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Collective monograph

DISEASES OF CRUCIFEROUS CROPS AND ADAPTIVE STRATEGIES FOR ITS CONTROL

(GENERALISATION OF UKRAINIAN AND WORLD EXPERIENCE)

2023

IZDEVNIECĪBA
BALTIJA
PUBLISHING

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Riga, Latvia
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UDK 635.1/8
DI785

Title: Diseases of cruciferous crops and adaptive strategies for its control (generalisation of Ukrainian and world experience)
Subtitle: Collective monograph
Scientific editor and project director: Anita Jankovska
Authors: Yaroslav Tsytsiura, Pavlo Vergeles, Sergiy Amons, Svitlana Okrushko
Publisher: Publishing House "Baltija Publishing", Riga, Latvia
Available from: http://www.baltijapublishing.lv/omp/index.php/bp/catalog/book/375
Year of issue: 2023

Diseases of cruciferous crops and adaptive strategies for its control (generalisation of Ukrainian and world experience) : Collective monograph. Riga, Latvia : Baltija Publishing, 2023. 580 p.

ISBN: 978-9934-26-358-3

DOI: https://doi.org/10.30525/978-9934-26-358-3

The monograph details and systematises the results of scientific research, including the authors' own research, on the prevalence, harmfulness, biology, development cycle and pathogenesis of major diseases of cruciferous crops. The factors that contribute to the formation of epiphytoties of cruciferous crops diseases from the standpoint of hydrothermal, soil and agrotechnological factors are formulated and described in detail, taking into account the peculiarities of phenostage and physiological development of different types of cruciferous crops. The history of the study of each pathogen and different views on its etiophysiology in conjunction with the biological parameters of growth and development of the main cruciferous species are described in detail.

The basic components of the complex of measures to regulate the prevalence and harmfulness of each pathogen separately and in their integrated combination in agrocenoses of cruciferous crops are highlighted, taking into account the world and national experience based on the generalisation of a number of scientific studies over a eighty-year period.

The authors of the monograph aimed to summarise the development, prevalence and harmfulness of major cruciferous diseases in Ukraine and the world from the perspective of the results of studies of this issue by scientists from different countries and to summarise the recommendations of Ukrainian and world science (including the results of their own research) on the fundamental and effective technologies for their control in agrocenoses of major cruciferous species, covering a significant period of research on this issue.

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INTRODUCTION

The right fungal disease management strategy prevents significant losses without additional investment.

Depending on the weather conditions, prevention and protection methods can vary significantly. Even seemingly insignificant factors can have a significant impact on the spread and development of diseases.

Measures to protect crops from pests are an integral part of the overall system of agricultural practices for growing a particular crop. Modern methods and means of plant protection are divided into breeding and genetic, agrotechnical, biological, physical and mechanical, chemical, and others. They are carried out in a certain sequence and make up a system that makes it possible to effectively combat pests, reduce damage from them and thereby ensure significant crop safety and improve its quality. The pest control system is aimed at eliminating sources of infection and suppressing pests in the most vulnerable period of their development, before they cause significant economic damage, and at maximizing yields with high product quality, while excluding environmental pollution.

In plant protection technology, considerable attention should be paid to the phytosanitary condition of crops. Signaling the timing of protective measures is considered an important part of this technology. Therefore, survey work to identify pests plays an important role in technological schemes.

Among the complex of harmful plant diseases of major field crops in Ukraine, fungal diseases dominate, with a prevalence ranging from 60 to 100%. Most pathogens belong to highly specialized fungal species that persist for a long time on plant residues and are a source of infection for many crops in crop rotation. This can cause epiphytoties, increase biological contamination of agroecosystems and create environmental risks [1–3].

It is known that cultivated plants characterized by high resistance to phytopathogenic microbes create significant selective pressure on their populations and select highly pathogenic and aggressive forms [4]. Excessive, often scientifically unjustified, anthropogenic impact on agroecosystems leads to intense environmental pollution. It is known that cultivated plants characterized by high resistance to phytopathogenic

microbes create significant selective pressure on their populations and select highly pathogenic and aggressive forms. Plants susceptible to such microorganisms ensure rapid growth of their populations. It has been proven that, regardless of disease resistance, certain varieties of cultivated plants can increase the reproductive capacity of pathogenic microbes, which leads to a significant increase in the intensity of the phytopathogenic background, a factor of biological pollution of agroecosystems. Growing such plant communities on production crops requires increased use of chemical plant protection products against diseases, which causes chemical pollution of agroecosystems. This leads to a significant deterioration in the quality of plant products due to the accumulation of metabolic products of phytopathogenic microorganisms and chemical elements and a decrease in the biological safety of agrocenoses [5].

It is difficult to overestimate the role of cruciferous crops in the agricultural sector of the economy of both the world and Ukraine, as this group of crops accounts for at least 25% of the gross product of the crop production industry. At the same time, the decrease in the productivity of their agrophytocenoses from a complex of diseases can reach more than 50% [6].

On the other hand, successful protection of cruciferous crops from major diseases is not possible without constant monitoring of the agrocenosis, without a thorough knowledge of the biology, physiology and development cycle of the pathogen. This especially applies to the basic concepts of the factors that limit its spread, regulate the severity of the disease and determine the set of measures that guarantee the prevention of a particular type of pathogenesis [7–9].

The authors of the monograph are convinced that the generalization of world and domestic experience over a long period of years on diseases of major cruciferous crops and specific recommendations for building a system of their protection against the most common diseases will allow both students and production practitioners to deepen their knowledge of this important area of successful cruciferous crops cultivation and will allow everyone to choose their own version of the strategy for regulating the number and prevalence of pathogens in the agrocenoses of this species group of crops.

To conclude our foreword, I would like to quote one of the scientists in the field of phytopathology [10] «Nothing limits the harmfulness of a

particular pathogen as much as knowledge of its strengths and weaknesses, and especially the ability to skillfully use these strengths and weaknesses to your advantage».

In conclusion, it should be noted that the authors of the monograph aimed to summarise the development, prevalence and harmfulness of major cruciferous diseases in Ukraine and the world from the perspective of the results of studies of this issue by scientists from different countries and to summarise the recommendations of Ukrainian and world science (including the results of their own research) on the fundamental and effective technologies for their control in agrocenoses of major cruciferous species, covering a significant period of research on this issue.

The authors also hope that the summarised information presented will be useful for the scientific community, which develops effective technologies for controlling pests for different representatives of the numerous cruciferous species.

CHAPTER 1. PREVALENCE, SPECIES STRUCTURE OF CRUCIFEROUS DISEASES AND THEIR HARMFULNESS

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DOI: https://doi.org/10.30525/978-9934-26-358-3-1

1.1. Importance, species structure of the main cruciferous crops and their fungal diseases

Oilseed cruciferous crops occupy more than 29.39 million hectares of agricultural land in the world with a total yield of 17 quintal/ha on average. The ability to survive and grow at low temperatures allows them to be successfully grown in cool agricultural regions, in the highlands and as a winter crop in the subtropics. Small round seeds of oilseeds contain more than 40% of oil in terms of dry matter, and after oil extraction, they are used to produce meal containing more than 40% of high-quality protein. In Western countries, the meal is used exclusively as feed for livestock and poultry, and in many countries it is used as an organic fertilizer for field crops.

The Brassicaceae family includes approximately 3.500 species in 350 different genera of many important crops that produce high-quality edible and industrial oil and vegetables. Based on the evidence that some types of vegetables were widely used in the Neolithic era [11–12], and direct references to rapeseed and mustard in ancient Indian Sanskrit writings of 2000-1500 BC [13]. Vegetable and oil cruciferous crops may have been among the first plants domesticated by humans. Greek, Roman and Chinese writings from 500-200 BC also mention these crops and their medicinal value [14]. Oilseed rape was introduced in China and Japan around the time of Christ [15] although its cultivation began in the thirteenth century in Europe, its industrial use was not widespread until its excellent qualities as a food and technical oil were recognized [16]. The use of cruciferous

crops as edible vegetable oil in Western countries is relatively recent. Unlike most other oilseeds, rapeseed comes from several species of the genus Brassica [17], including *B. napus* L., *B. rapa* L. (*B. campestris* L.) and *B. juncea* (L.) Czern. & Coss. which are known as rapeseed, rape and mustard, respectively.

Since prehistoric times, many cruciferous species have been cultivated for their edible roots, stems, leaves, buds, flowers, and seeds. Although the cultivation of this group of crops began in Europe as early as the 13th century, their industrial use did not become widespread until the 1930s when the qualities of cruciferous vegetable oils were established for lubrication and biofuel use [18]. It began to be used as edible oil even later, as the nutritional properties of previous cruciferous varieties were technologically poor, and the high content of erucic acid and glucosinolates gave the oil an unpleasant bitter taste. Varieties low in glucosinolates and erucic acid were developed through conventional breeding and were originally produced in Canada under the trade name 'Canola', defined as an oil that should contain less than two percent erucic acid and less than 30 micromoles of glucosinolates per gram of air-dried, oil-free meal. Since then, canola has become a generic term for these "double low" varieties in North America [19].

Rapeseed is mainly grown in temperate climates (Figure 1). In recent decades, rapeseed production has increased in all major growing regions: Canada, Europe, China, India and Australia [20]. *Brassica napus (winter)* and *B. rapa (spring)* are two types of rapeseed grown in different parts of the world. Globally, there is no discrimination between *B. napus* and *B. rapa* on the harvested seed market. There are varieties of both types for spring and fall sowing, which gives producers a choice of two types of crops*:* spring oilseed rape *(Brassica rapa)* and winter oilseed rape *(Brassica napus)*. In most cases*, B. napus* is more productive than *B. rapa,* but *B. rapa* matures earlier [21]. Winter rapeseed (*B. napus* var. *biennis*) is grown in regions where the crop does not die in winter, but where the regions are classified as Cfb and Dfb. In regions with harsh climatic conditions, spring rape and other types of spring cruciferous crops are grown in winter. Rapeseed is a highly profitable crop if managed properly, and the advantages of growing rape over cereals in crop rotations are widely reported [22–24].

The benefits of cruciferous crops include soil improvement, which leads to increased nutrient and water absorption. In addition, as a preceding crop, cruciferous crops suppress cereal diseases [25].

Cruciferous crops are often grown in short crop rotations: in Europe, in arable crop rotations – once every three years, and in Canada – every second year [26]. The introduction of high-yielding varieties has increased the profitability of rapeseed production, but some diseases and insect pests have a negative impact on this production. In a global study conducted in 2019 [27], The main biotic constraints have been reported to be caused by soil pathogens such as Plasmodiophora brassicae (clubroot) and Verticillium longisporum (Verticillium wilt), as well as stem pathogens such as Sclerotinia sclerotiorum (sclerotinia stem rot), Lepthospaheria maculans and L. biglobosa (blackleg or stem cancer (phomosis)), Alternaria spp. (black spot, dark spot (alternaria) of leaves and pods), Pseudocercosporellae capsellae (white leaf spot) and Pyrenopezizia brassicae (light leaf spot). Some of these diseases are recorded only in certain regions, while others, such as sclerotinia stem rot, cause significant yield reductions in all major cruciferous growing regions of the world.

The high frequency of cruciferous crops in crop rotations increases the risk of breeding and spreading soil-borne diseases by moving contaminated soil through machinery to new fields, such as tuber blight, which has become a serious constraint on vegetable cruciferous production worldwide [28]. The growing spread of clubroot as a disease in the main production regions of Canada, the UK, Germany, Poland, the Czech Republic, China and other countries is the result of the practice of narrow crop rotations due to the growing demand for rapeseed oil [29–30]. Increased production of oilseeds and cruciferous vegetables due to increased demand for products requires strategies that combine different means of control, including pathogen avoidance, pathogen exclusion, host plant protection and host plant resistance [31]. Knowledge of the epidemiology of plant diseases is important for choosing the most effective management method or combination of methods to control crop diseases.

Each pathogen has a unique, often complex life cycle, and producers must make informed decisions to avoid disease outbreaks. Crop protection management is multifaceted, and growers must consider a number of factors, such as variety selection and agronomic practices. Often, the use

of chemical pesticides is the only direct measure to limit the negative impact of plant disease during the growing season. The EU Directive on the Sustainable Use of Pesticides (2009/128/EC) encourages integrated disease management, which involves a plant protection strategy that combines preventive measures such as forecasting disease outbreaks, crop rotation where the target crop is grown at intervals of several years, and variety selection in combination with direct measures such as pesticide use.

Thus, the commonly used names are [33] for B. napus – rapeseed, canola, oilseed rape, rape, rape, rape, and Argentine rape; for *B. rapa* – spring rape, and Polish rape; and for *B. juncea* – white mustard, oriental mustard, and Indian mustard (Figure 1.1). In China, all three species are grown, but the main source of rapeseed is winter rape. In India, rapeseed and mustard can be considered rapeseed, while in North America and Europe, spring and winter rapeseed, white and black mustard, and various forms of radish are distinguished. Other oilseeds of the Brassicaceae family include *B. rapa* L. var. *toria* (rapeseed, toria), *B. rapa* L. var. *brown Sarson* (rapeseed, brown Sarson), *B. rapa* L. var. *yellow Sarson* (rapeseed, yellow Sarson), *B. nigra* (L.) Koch (black mustard), *B. hirta* Moench (*Sinapis alba* L.) (white mustard), *B. carinata*, *A. Braun* (*Abyssinian mustard, Ethiopian mustard*), *B. tournefortii* Gouan (wild turnip), *Eruca sativa* Mill. (*E. vasicaria* spp. sativa (Mill.) Thell.) (taramira), *Camelina sativa* Crantz (red flax, false flax, Dutch flax, goldenrod), *Crambe abyssinica* Hochst. ex. O.E. Schulz and *C. hispanica* L. (crambe species), *Raphanus sativum* d. var. *oleifera* Metrg. (oil radish). Traditional varieties of rapeseed grown in many countries contain 22–60% erucic acid in the oil, and the high content of glucosinolates reduces the feed value of the meal. Since the late 1970s, the Canadian varieties *B. napus* and *B. rapa* have been genetically modified to increase the content of erucic acid and glucosinolates, and in 1979 these "double low" varieties were named "canola". Thus, the previously mentioned term "canola" refers to a canola variety that contains less than 30 pmol/g of one or any combination of the four known aliphatic glucosinolates (gluconapine, progoitrin, glucobrassic-canapine and napoleiferin) in the defatted meal, and less than 2% of the fatty acyl content of the oil is erucic acid. Recently, varieties of white mustard (*B. juncea*) of the canola type have also been developed in Canada.

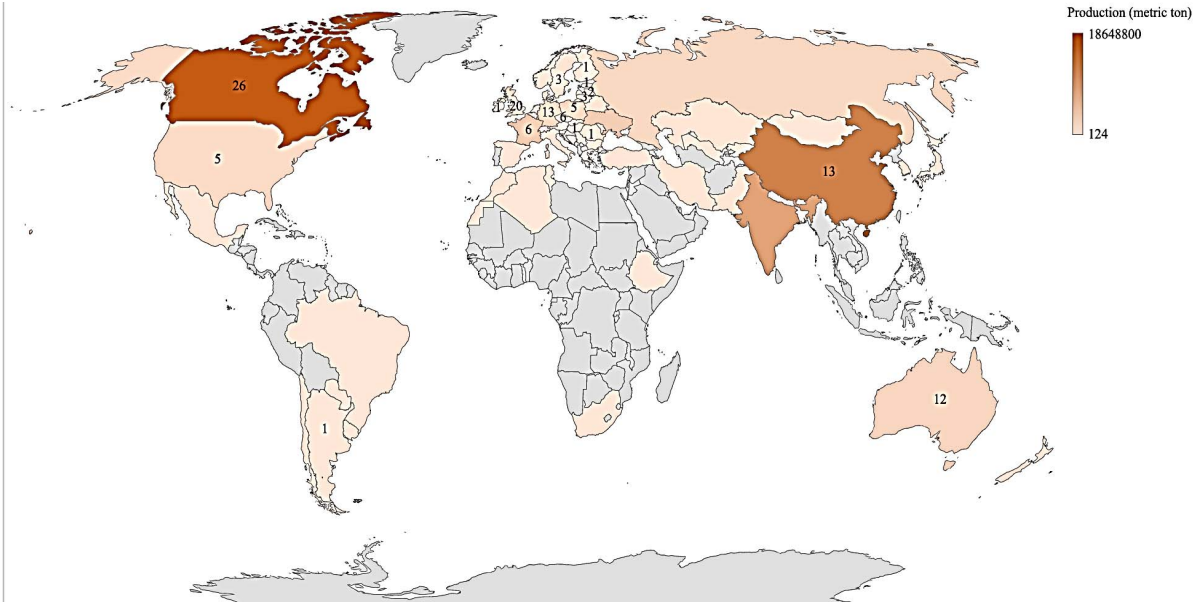

Figure 1 – Geographical location of articles on cruciferous crop diseases and global rapeseed production. Countries where research is being conducted, included in the systematic map, are marked with numbers indicating the number of studies conducted by each country. The color indicates the countries that produced rapeseed in 2022 [32]

The main groups of cultivated vegetables from the cruciferous family in the world practice of inventions are cabbage (*B. oleracea* L. var. *acephala*), including white cabbage, green cabbage, dwarf Siberian cabbage, narrow-stemmed cabbage, trochunda; cabbage (*B. oleracea* L. var. *captitata*, var. sabauda, var. bullata), including cabbage, Brussels sprouts and Savoy cabbage; kohlrabi (*B. oleracea* L. var. *gongylodes*. var. *botrytis*, var. *italica*), including cauliflower, broccoli, bush cabbage (B. oleracea L. var. fruticosa), cow cabbage, Chinese cabbage (B. alloglabra L.) and radish (*Raphanus sativus* L.) (Figs. 1.2, 1.3, 1.4).

Rapeseed oil is a relatively new oilseed crop, with commercial acreage growing in the United States, Poland, and some other countries. The oil is a potential raw material for the rubber and plastic industries.

Rapeseeds, including *B. campestris, B. juncea, B. napus*, and *B. carinata*, are an important group of oilseeds that account for almost 13.2% of the world's edible oil needs. Together, they cover about 29.39 million hectares with an annual production of 53.01 million tons worldwide. They are highly adaptable and often grown in different agro-climatic conditions around the world. Over the past two decades, the area and production of these crops have increased significantly, with total production almost tripling.

Other studies summarize that the Brassicaceae family includes 338 genera and 3709 species and contains many plants of economic importance as vegetable or perennial food crops, as well as industrial crops and animal feed crops. First, *B. napus* is one of the world's most important oilseeds. In recent years, global rapeseed production has exceeded 63.7 million tons, making it the world's second most important source of vegetable oils [36–37]. Secondly, *B. juncea* is both a condiment and an oilseed crop grown in areas with moderate to high temperatures, arid and short growing seasons, such as northern and western China, areas of northeastern Europe and arid regions of South Asia [38]. In addition, there are smaller areas of condiment and oil mustard, including mainly Indian mustard, but smaller areas of black mustard (*B. nigra*) and isolated areas of *Ethiopian mustard* (*B. carinata*) [39]. Third, until the 1950s, *B. nigra* was the dominant mustard crop. However, it was later commercially replaced by B. juncea in mustard production. In Europe and Asia, B. nigra was a rare crop in Europe and Asia, but has become more widespread in temperate areas [40]. In addition, there are several other cruciferous species that are regionally important

oilseeds, including spring rape, brown and yellow sarson, and toria (all *B. campestris*), taramira and arugula (*E. sativa* or *E. vesicaria*) [41] camelina (*Camelina sativa*).

Figure 1.1 – Cabbage family: 1 – flower; 2 – fruit; 3 – inflorescence; 4 – field cabbage; 5 – rape; 6 – field mustard; 7 – seed radish [34–35]

There are also important species of Brassicaceae that are used on a wide scale for fodder and vegetable production, including rapeseed (B. napus) [43], cabbage (*B. oleracea* var. *acephala*), radish, turnip (*B. rapa* var. *glabra*), rutabaga or swede, *Brussels sprouts* (*B. oleracea* var. *gemmifera*), cauliflower and Asian vegetables (*B. rapa* subsp., such as subsp. rapa and var. *pekinensis*) [44–45].

There is a steady upward trend in the global acreage of cruciferous crops, especially rapeseed. The upward trend of rapeseed production in the EU

countries continued in 2023 season. In particular, the harvest is expected to reach 19.6 mln tonnes compared to 19.1 mln tonnes a year earlier. The increase in the harvest of oilseeds is due to the expansion of the planted areas to the maximum level in the last 5 years – 5.94 mln ha, compared to 5.85 mln ha in 2022. Experts forecast the main increase in the area in France to 1.31 (1.23) mln ha and in Germany – to 1.15 (1.08) mln ha. Against this background, the production of the oilseed in these countries may increase to 4.55 mln tons (+1% per year) and 4.4 mln tons (+3%), respectively. In addition, analysts forecast the expansion of rapeseed acreage in Denmark and Sweden, which will also result in the increase of oilseeds harvest in this region. In turn, in the Baltic countries, rapeseed acreage will decrease by about 7%. At the same time, the production of rapeseed in this region this year may increase to 1.74 mln tonnes compared to 1.59 mln tonnes harvested in 2022. Rapeseed became widespread in Ukrainian farms after 2000, when its acreage increased more than 5 times, outpacing similar trends in sunflower. Seed production volumes have increased in recent years. This is primarily due to the growth of green energy and favorable external conditions on the global agricultural market. Another reason is the use of new, highly efficient technologies for growing the crop and high-quality seed material by producers, as well as the availability of satisfactory weather and climatic conditions for growing it in most regions of the country. There were also purely economic reasons, including high profitability of production and stable demand for rapeseed from domestic exporters and processing companies (Table 1.1).

Figure 1.2 – Types of cabbage (1 – red cabbage; 2 – white cabbage; 3 – cauliflower; 4 – kohlrabi; 5 – Peking cabbage; 6 – Brussels sprouts)

Figure 1.3 – Types of cabbage [42]

Table 1.1

Dynamics of changes in rapeseed acreage in all categories of farms in Ukraine [46]

Years	Winter and spring rape		The share of winter rapeseed, %
	(spring rape), thousand hectares	winter rape, thou hectares	
1990	89.7	84.2	93.9
2000	214.3	111.5	52.0
2010	907.4	800.5	88.2
2015	682.4	661.4	96.9
2018	1041.5	973.4	93.5
2019	1282.4	1252.5	97.7
2020	1126.6	1095.4	97.2
2021	1009.5	975.9	96.7

A significant increase in production was achieved not only due to the growth of sown areas, but also due to a significant increase in the productivity of its cultivation. In 2021, according to preliminary data,

the average yield of rapeseed reached the highest level in the history of statistical observations and amounted to 2.94 t/ha[46]

Most farms grow winter rapeseed, which has recently accounted for about 97% of all rapeseed acreage. At the same time, in 2000, the share of winter rapeseed varieties was only 52%, and in 2010 it increased to 88.2%. In 2021, this share was already almost 97%, with spring rapeseed accounting for 3% of the area.

Over the past 20 years, rapeseed production has grown at a record pace. While in 2000, about 132 thsd tonnes of rapeseed were produced, in 2021, according to preliminary data, 2557.2 thsd tonnes were already produced on the harvested area of 994.9 thsd hectares (98.5% of all sown areas) (Table 1.2).

Table 1.2

Dynamics of rapeseed production in all categories of farms in Ukraine [46]

Years	Harvested area, thousand hectares	Production volume, thousand tons	Yield, t/ha of harvested area
1990	89.6	130.2	1.45
2000	156.7	131.8	0.84
2010	862.5	1469.7	1.70
2015	671.1	1737.6	2.59
2018	1039.3	2750.6	2.65
2019	1279.2	3280.3	2.56
2020	1112.5	2557.2	2.30
2021	994.9	2924.1	2.94

In some regions, the average yield approached the record level of 3.6-3.8 t/ha. At the same time, in 13 of them, the yield level is below the average for all regions in general. In this case, agribusinesses are using a fairly effective intensification strategy to increase rapeseed production instead of expanding the acreage, as is the case with sunflower.

As you know, the key factor behind the growth of domestic rapeseed production is the increasing demand for it from the global agricultural market. Thus, according to the analysis of the latest USDA Oilseeds: World Markets and Trade for October 2021, in 2019/20 and 2020/21 marketing seasons there was an increase in the global market demand for rapeseed

and its products. This trend in the domestic market directly influenced the dynamics of the planted areas, which, due to relatively favorable weather conditions and higher average yields, led to the increase in the production and supply of rapeseed. The EU, Canada, China, and India are the major producers of rapeseed globally. According to the forecasts of USDA analysts, in 2021/2022 marketing season the total production in these countries will be about 52.6 mln tonnes or 78% of the global level. The main share of supply on the global rapeseed market is formed by the EU countries, where the forecasted production will reach almost 17.1 mln tonnes. At the same time, imports of rapeseed from China, Japan and the EU will decrease this marketing season. For domestic exporters, an important niche of the global agricultural market is not only seeds, but also their processed products, such as oil and meal. The analysis of the last two export destinations listed above indicates that the global domestic consumption of rapeseed oil and meal will remain at a fairly high level, which will lead to an increase in trade in these products in the future (Table 1.3).

The largest consumers of rapeseed are expected to be the EU (21.5 million tons), China (16.8 million), India (8.5 million) and Canada (almost 8 million tons).

Rapeseed is one of the most marginal and export-oriented crops. During the analyzed period of 2015-2021, the volume of rapeseed exports from Ukraine to the global agricultural market increased almost 8 times, and the revenue reached USD 4.2 billion. Exports of rapeseed oil have also increased in recent years (Table 1.4).

In 2021, the value of rapeseed oil exports amounted to $400.7 million, which is more than 5 times higher than in previous years. Currently, the interest of processing companies in rapeseed is growing.

Mustard production is also important for agricultural production. As noted above, several types of mustard have been introduced into the culture. Sarepta mustard (*Brassica juncea* L) originates from Southwest Asia. It is grown in India, Pakistan, Russia, Ukraine, Kyrgyzstan, and the North Caucasus. It grows as a weed in crops, along roads and near housing. Other types of mustard – white mustard (*Sinapis alba* L.), black mustard (*Brassica nigra* Koch.) are annual cultivated plants. Black mustard is cultivated in the southern part of Western Europe and West Asia, while white mustard is cultivated in Central and Northern Europe.

Table 1.3

Global balance of supply and demand in the market of rapeseed and its products (thousand tons), 2019–2021[46]

The marketing year	Rapeseed meal			Rapeseed oil			Rapeseed seeds		
	2019/20	2020/21	2021/22	2019/20	2020/21	2021/22	2019/20	2020/21	2021/22
China	9138	9442	9648	6039	6240	6377	13485	14000	14000
India	4170	4478	4657	2660	2854	2964	7400	8500	8500
Canada	5654	5936	4350	4434	4528	3350	19607	19485	13000
Japan	1280	1280	1270	1000	1000	991	4	4	4
EU	12027	12654	11913	8862	9324	8778	15241	16289	17100
Other countries of the world	7112	7272	6866	5025	5135	4849	13338	14229	14753
The world – in general	39381	41062	38704	28020	29081	27509	69075	72507	67357
Import									
China	1910	1900	1280	1940	2400	1600	2558	2800	2200
India	0	0	0	78	50	80	0	0	0
Canada	6	8	10	20	19	20	155	125	200
Japan	5	5	5	42	20	30	2242	2350	2200
EU	468	466	450	468	314	400	6211	5853	4975
Other countries of the world	5575	5839	5146	3246	3422	3276	4753	5304	4619
The world – in general	7964	8218	6891	5794	6225	5406	15919	16432	14194
Exports									
China	14	5	10	4	3	5	0	0	0
India	950	1100	1000	6	5	5	0	0	0
Canada	4904	5321	3950	3429	3439	2700	10043	10518	6300
Japan	6	0	0	2	2	2	0	0	0
EU	617	751	650	345	723	525	332	173	150
Other countries of the world	1230	1178	1329	2061	2214	2125	5530	6455	7761
The world – in general	7721	8355	6939	5845	6386	5362	15905	17146	14211
Domestic consumption									
China	11034	11337	10918	8146	8192	8200	15985	16450	16800
India	2950	3360	3600	2770	2720	2970	7600	8400	8510
Canada	710	652	436	1007	1013	985	10719	10760	7967
Japan	1288	1288	1275	1040	1035	1025	2305	2305	2285
EU	12000	12250	11950	8900	9040	8800	21700	22800	21525
Other countries of the world	11326	11799	10730	6257	6276	6083	12725	12944	12226
The world – in general	39308	40686	38909	28100	28276	28063	71034	73659	69313

Table 1.4

Exports and imports of rapeseed and rapeseed products in Ukraine [46]

Period	Product item	Export value, thousand dollars	Import value, thousand dollars	Trade balance, thousand dollars
2015	Rapeseed seeds	570107	19613	550494
	Rapeseed, mustard oils	109815	844	108971
2016	Rapeseed seeds	392474	22783	369691
	Rapeseed, mustard oils	68718	871	67847
2017	Rapeseed seeds	881549	32263	849286
	Rapeseed, mustard oils	51483	1492	49991
2018	Rapeseed seeds	49642	9656	59986
	Rapeseed, mustard oils	1386	606	780
2019	Rapeseed seeds	1247696	37605	1210631
	Rapeseed, mustard oils	118654	2246	116408
2021	Rapeseed seeds	4197365	138138	4059227
	Rapeseed, mustard oils	400723	9724	390998

It is mainly used to make Dijon mustard. Black mustard differs from Sarepta mustard by having clearer yellow corolla petals and smaller seeds. Mustard is a crop of multidirectional industrial importance due to its diverse use. The global production structure of mustard seeds is divided as follows: about 500 thousand tons are consumed for culinary purposes and about 2.7 million tons for production needs. It is grown to produce high-quality edible oil and green fodder for animals. In addition, mustard is widely known as a green manure crop because it has the unique ability to absorb hard-to-reach forms of nutrients from the soil and convert them into easily digestible forms. A by-product of fatty oil production (regardless of whether it is obtained by pressing or extraction), mustard meal, is of great interest to processors. After additional degreasing and grinding, it is converted into mustard powder, a product that is valued almost on par with oil. Mustard powder is the main ingredient in table mustard and mayonnaise, various sauces and condiments, marinades and canning mixtures. Its natural antiseptic properties due to its specific chemical composition and the presence of essential oil allow food producers to refuse to add artificial

preservatives to their recipes, which simultaneously reduces production costs and attracts consumers. The same conclusion has been reached by nutritionists from Canada, whose latest research shows that mustard seed processing waste can be used as a source of natural food preservatives. The extraction of sinapic acid from mustard seed meal can provide more choices for consumers when it comes to products containing preservatives [47].

Unfortunately, global mustard production cannot be accurately estimated. For example, India, a powerful world leader in mustard seed production, keeps statistical records under the item "Mustard + rapeseed" without separating this crop.

Ukraine has always been in the top five in terms of mustard production, but its local markets are not well integrated into the global turnover of mustard seeds and processed products, including due to differences in cultivated seed types and remoteness from the center of global production – the Asia-Pacific region [48].

Over the past ten years, global mustard acreage has fluctuated between 0.7 and 1.1 million hectares. For a long time, Canada has been the main player in the global food mustard market, accounting for up to 70% of export and import operations. The United States is also among the world's leaders in mustard production. However, statistics show that Americans do not have enough mustard of their own, so they still export it from Canada. Europe also faces a shortage of mustard. EU countries annually import up to 100 thousand tons of mustard seeds. This should be taken into account by Ukrainian farmers, especially since European purchase prices are much higher than in Ukraine.

Mustard of the highest quality that meets the developed standards is classified as food grade, and mustard that is not suitable for human consumption is classified as technical grade. Accordingly, Canada and the United States produce high-quality mustard, while the countries of the Black Sea region (Ukraine) produce ordinary food mustard. And the countries of the Indian continent (India, Nepal) grow both ordinary, food and technical mustard.

Ukraine is among the world's top ten countries in terms of mustard planted area. Ukraine's share of this seed production is 2% of global production, which is quite high and makes it one of the most important players in the global market (it is exported to 23 countries). Moreover,

the demand for Ukrainian mustard is higher due to its taste. This season, Germany and Hungary were the main importers of Ukrainian oil mustard.

The availability of markets, fertile land, moderate climate conditions, and a rich scientific base are the main advantages for growing this promising crop. Ukraine has the opportunity to successfully compete with the European market.

Thanks to increased professional capacity and favorable soil and climatic conditions, Ukraine has the potential to become a global leader in mustard production. At the same time, given the latest trends in climate change, there is a need to develop varietal mustard cultivation technologies for specific soil and climatic conditions.

Most of the mustard is grown in the southern regions of Ukraine, with about 26% of its crops, in particular, in Kherson region (15 thousand hectares). A significant part of the mustard area is also concentrated in Zaporizhzhia (8.7 thousand hectares) and Luhansk (8 thousand hectares) regions. Previously, Crimea, Luhansk and Donetsk regions were the main regions for growing mustard. Military actions have changed the trends of the Ukrainian market. However, Ukraine's weather and climate conditions allow for mustard to be grown throughout the country. The average yield of mustard is much higher compared to the rest of the world: from 1 to 1.2 t/ha of gray (Sarepta) mustard, 1.5 to 2.5 t/ha of white mustard for seeds and up to 30 t/ha of green mass.

With modern cultivation technologies, mustard can yield a harvest that is almost as good as rapeseed, and its production helps to "save farmers' nerves" in terms of the risks of unsatisfactory overwintering of rapeseed wedges in adverse weather conditions in winter. A vivid example of this is the situation that occurred in the 2011/12 season, when the degree of winter rape death reached 90–100%.

The winter mustard type has a much greater ability to maximize the use of autumn and winter moisture reserves, which is the main element of the soil water balance. Accordingly, domestic breeders have created modern varietal populations of mustard containing plants of winter, transitional, and varietal types, which, under favorable wintering conditions (relatively mild winters without sharp daily temperature changes), are able to produce high yields.

It is noted [49], that two types of mustard are most commonly used in production: gray or Sarepta mustard and white mustard, which belong to

different botanical genera. The seeds of both types are used to produce oil, mustard powder and alcohol, table mustard, etc.; the green mass is used as green manure or fodder. In recent years, due to the extremely high demand on the foreign market, black (French) mustard has also started to appear in the structure of sown areas.

The relatively greater popularity of gray mustard among other types of this crop is primarily due to its biological and ecological properties – drought resistance and the ability to form economically viable yields in areas with a high hydrothermal coefficient. Accordingly, the main areas under this type of mustard are concentrated in the Steppe and Southern Forest-Steppe. White mustard, which is more moisture-loving and cold-resistant, is grown in the northwestern regions of the country.

White mustard, compared to gray mustard, forms more leaves, accumulates biomass more intensively and in larger quantities, which is important when used for green manure. It has valuable phytomeliorative properties: its root secretions convert inaccessible, hardly soluble forms of potassium and phosphorus nutrients in the soil into available ones, and white mustard is also an excellent honey plant. The crop has a short growing season – 60–90 days before seeds are produced and 45–50 days before green mass is harvested. After 50–60 days, this crop provides a yield of 20.0–35.0 t/ha of green mass. The aboveground biomass contains 130–175 kg of nitrogen, 40–48 kg of phosphorus, and 50–187 kg of potassium. If the plants are plowed in the flowering phase, 3–5 tons of absolutely dry matter containing 120–130 kg of nitrogen, 180–190 kg of phosphorus, 130–140 kg of potassium, and 80–120 kg of calcium are introduced into the soil.

There are many advantages to using green manure crops. First of all, green fertilizers (green manure) are a source of significant soil replenishment with organic matter. The crop has a positive impact on soil structure and plays a significant phytosanitary role in reducing weeds, diseases and pests of agrocenoses. This contributes to a sharp reduction in the amount of crops treated with chemical plant protection products, which ensures the production of environmentally friendly products. Each hectare of mustard crop area leaves an average of 8.2 t/ha of plant mass after harvest, which, due to the absence of compounds in its chemical composition that inhibit bacterial decomposition, mineralizes very quickly, enriching the soil with

organic matter. Mustard can produce more than 850 kg of organic matter per hectare.

The technology of growing white mustard for green manure involves placing the crop on weed-free fields after cereals, legumes and row crops. For white mustard, it is advisable to apply mineral fertilizers at a dose of $N_{60-90}P_{45-60}K_{45-60}$. The post-harvest sowing period for mustard is the end of July in the northern regions and the first or second decade of August in the central and southern regions of Ukraine. It is sown in the early stages in the usual line method. The seeding rate is 15–20 kg/ha, and the seeding depth is 1.5–3 cm. It is sown with grain seeders.

Mustard is an excellent precursor for the vast majority of crops due to its agro-ecological properties. Due to its fast growth rate, mustard is sown even in late terms (late July – early August), after harvesting grain crops. Given these features of mustard biology, it is grown as both a main and intermediate crop. In addition, it improves the phytosanitary condition of the field. Mustard root secretions contain organic acids, which, when interacting with the soil, can convert a number of mineral nutrients into more accessible forms for the next crop and for their own needs.

The crop has a powerful phytosanitary effect – it reduces the accumulation of diseases such as cereal root rot, late blight, rhizoctonia, scab, and potato fusarium in the soil. It also radically reduces the infestation of the soil with wireworms. This is very important for monoculture grain growing.

The global market for mustard seeds is projected to be worth USD 1,084.8 million by 2032, up from USD 718.9 million in 2022, representing a USD of 4.2% [50]. During the period under review, global mustard production peaked in 2014, but declined slightly from 2015 to 2021. The countries with the highest production volumes in 2021 were Nepal, Canada and Ukraine, which together accounted for 64% of global production. From 2012 to 2021, production in Russia grew the most (average annual growth rate was +14.9%), while production in other world leaders grew at a more modest pace. In 2021, the average yield of mustard seeds in the world fell to 1.54 t/ha, which is -8.2% less than a year earlier. However, in general, the yield had a relatively even trend. The growth rate was the fastest in 2020, when the yield increased by 17%. During the study period, the average yield of mustard seeds reached a record high in 2016 – 2.3 t/ha, but from 2017 to 2021, the yield remained at a lower level.

Despite the increased use of modern agricultural techniques and methods, future yields may still be affected by unfavorable weather conditions. In 2021, the total harvested area under mustard in the world increased to 1.2 million hectares, which is 17% more than in the previous year. For the period from 2012 to 2021, the average annual growth rate of the planted area was +2.6%, but the trend shows some noticeable fluctuations that were observed throughout the analyzed period. The highest growth rates were recorded in 2018, when the area increased by 31%. The global harvested area peaked at 1.24 million hectares in 2019, but in the period from 2020 to 2021, the harvested area was slightly lower [51].

It should be noted that in 2021, Ukrainian agricultural producers supplied 35.4 thousand tons of mustard seeds to foreign markets, which is twice as much as in 2013. According to the Ukrainian Agribusiness Club, Ukraine is one of the largest exporters of mustard in the world. Canada, Germany, and India also supply large volumes of mustard seeds to foreign markets.

The main buyers of mustard are Germany, the United States, France, Nepal and Poland. Ukraine ranks fourth in terms of mustard production in the world. The largest volumes of mustard seeds are harvested annually in Canada (200 thousand tons), Nepal (150 thousand tons), Russia (90 thousand tons), Ukraine (40 thousand tons) and Myanmar (40 thousand tons). The sixth and seventh place is shared by the Czech Republic and China with an annual production of about 20 thousand tons of mustard seeds [52].

Mustard is very capricious and does not forgive mistakes. Farms that follow the technology closely get yields of up to 20–22 centner/ha. Of course, when everything coincides with the weather, and the agronomist is always on hand. Professionals understand that the optimal successful limit is a yield of 15 centner/ha. After this figure, the farm becomes a champion. If the farm has a high production culture, the grain doesn't even need a photo separator during processing, and the quality and purity immediately meet the standards. For those who do not strain themselves, invest little in cultivation and lose a lot during harvesting, the payback comes after 5–7 centner/ha. The most realistic way to achieve this is for farms that plan their crop rotation on a 5-year scale [53].

Mustard must be present in it, and it must return to the same place in at least 3 years. For example, in the Netherlands, 10% of the area must be allocated to mustard, and if everything goes well, it is used as a product,

otherwise it is used as green manure. Farms that will go through ups and downs due to weather conditions and other disasters will generally get a better financial result in such a system than those who decide to survive only on industrial crops.

Oilseed radish (*Raphanus sativum* d. var. *oleifera* Metrg.) (Figure 1.4) should be mentioned separately in terms of the prospects for the cruciferous market, which has long been considered a rare plant. However, since the mid-1970s, it has been used in spring post-mowing and post-harvest crops in the system of conveyor production of green fodder. Very quickly, this crop conquered new areas for various purposes not only in the former Soviet Union, but also in Poland, Germany, the Netherlands, and Finland. The culture was firmly established as an extremely plastic and high-yielding species, capable of growing from early spring to late autumn both in monoculture and in grass mixtures of various compositions, forming from 30 to 70 t/ha of leaf mass balanced in terms of digestible protein content in 40–50 days of vegetation.

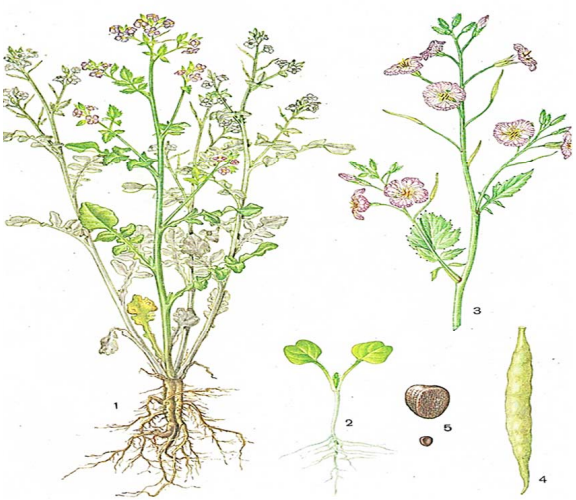

Figure 1.4 – General view of oilseed radish [54]: 1, 2 – plants in the phases of flowering – fruit formation and germination; 3 – the upper part of the stem in the flowering phase; 4 – fruit; 5 – seeds (the upper position is enlarged)

Multi-purpose study of this crop in different soil and climatic zones made it possible to formulate the main positive features that the crop potentially possesses: unpretentiousness to growing conditions and predecessor in crop rotation, high productivity and nutritional value, productive post-harvest and post-harvest use, high intensity of the root system functioning, relative tolerance to changes in sowing dates, fast growth rates, high positive reaction to mineral fertilization, high competitiveness to segetal vegetation, possible.

Unfortunately, in recent years, the area under oil radish in Ukraine has been 12–15 thousand hectares in single-species sowing and 45–50 thousand hectares in various feed mixtures. For comparison, in Russia 200–250 thousand hectares, Lithuania 100–120 thousand hectares, Poland 160 thousand hectares [55]. The reason for this, despite the multifaceted economic "portrait" of oil radish, is that the technology of its cultivation for fodder and seeds, optimized for the right-bank Forest-Steppe, is not sufficiently scientifically substantiated, given the ongoing climate change and degradation processes in the soil cover of Ukraine. As a result, when introducing new varieties of intensive oil radish into production, there is a need to establish optimal sowing dates, seeding rates and fertilization for sustainable production of fodder and seeds. In addition to rapeseed species, mustard species, radish species, and a wide range of vegetable cruciferous plants, the Brassicaceae family includes approximately 120 weed species, most of which are universal agricultural weeds such as field mustard (*Sinapis arvensis*), ragweed (*Thlaspi arvense*), while various species of *R. sativus* and wild radish (*R. raphanistrum*) form crop-weed complexes; some of these weed species have a natural ability to exchange genes and form transgenic forms with field crops [56–57].

It is reported [58], that the cabbage family (Brassicaceae) has been of interest to researchers for many decades, not only for its benefits to human health, but also in plant protection research due to the production of secondary metabolites such as glucosinolates and wax production on the leaf surface [59]. In addition, they are grown worldwide for the production of food and animal feed, edible oil, biofuels and biofumigants [60]. The family Brassicaceae includes many cultivated plants (e.g. *Brassica oleracea, B. napus, B. júncea, Armoracia rusticana* and many others), ornamental plants (e.g. Aubrieta, Iberis, Lunaria, Arabis, Draba and others)

and plants used as models in botanical sciences, such as *Arabidopsis thaliana*, *A. lyrata, A. halleri, B. napus*, *Capsella rubella, Thellungiella halophila, Arabis alpina* and others [61].

There is considerable potential to increase production and productivity of oilseeds and cruciferous vegetables through the selection of improved varieties that are resistant to biotic and abiotic stresses. Among the biotic factors that limit yields, diseases such as Alternaria, white rust, downy mildew, sclerotinia stem rot, and powdery mildew are serious.

It is noted that under the influence of the development of diseases such as downy mildew, Alternaria, Phomosis, and Cylindrosporium, the content of carotene, dry matter, fiber, and ash in the affected leaves increases, but the content of vitamin C, protein, fat, and sugar decreases significantly. The amount of amino acids in the affected rapeseed leaves, depending on the intensity of disease development, decreases by 1.4–2.7 times, in particular, essential amino acids by 1.5–2.9 times and substitutable amino acids by 0.13–2.6 times. The shortfall in seed yield from diseases, depending on the variety and technology of its cultivation, ranges from 15 to 70% or more, while its sowing and technological qualities are significantly impaired.

When rapeseed pods are damaged, the oil content in the seeds, depending on the pathogen, decreases by 1.3–3.4 times, the specific gravity of palmitic, stearic, erucic, eicosic, and linolenic acids increases significantly, while the specific gravity of oleic and linoleic acids decreases.

The most common and damaging infectious diseases of cruciferous plants in Ukraine are snow mold, black leg (rhizoctonia), downy mildew (peronosporosis), black spot (alternaria), stem cancer, or root neck necrosis (phomosis), white rot or sclerotinia (white stem disease), gray rot (botrytis), light spot (cylindrosporium), verticillium wilt (verticillium), fusarium wilt (fusarium), root bacteriosis in winter rape, mucilage bacteriosis in spring rape. Less common diseases in rapeseed are white spot (ring spot or gray stem), powdery mildew, common mosaic clubroot, wrinkle mosaic, black ring spot, turnip yellow virus, greening of flowers, etc. [62].

The diseases of cruciferous crops are ranked in the following order in terms of their harmfulness: Alternaria, Phomosis, Cylindrosporium, Root Bacteriosis, Snow Mold, Peronosporosis, Blackleg, White Rot, Gray Rot, White Spot, Fusarium Wilt, Verticillium Wilt.

The global monitoring of cruciferous diseases has identified 15 diseases that, according to scientists, pose the greatest threat to the productivity of modern varieties of cruciferous crops, primarily rapeseed [64] (Table. 1.5–1.6). Biotic stresses caused by these diseases mainly affect leaves (10 diseases) and stems (7 diseases), while only 2 diseases affect rapeseed pods and seeds.

Plasmodiophora, sclerotinia stem rot and stem cancer, phomosis, powdery mildew, peronosporosis, white rust, and Alternaria are recorded in all analyzed regions of the world.

Table 1.5

The most common diseases of cruciferous plants (global dimension) [63]

Disease	Pathogen	Root	Seedlings	Leaf	Stem	Buds/ flowers	Pods/seeds
Alternariosis	*Alternaria* spp.		x	x	x		x
Clubroot	*Plasmodiophora brassicae*	x					
Peronosporosis	*Peronospora parasitica*			x			
Fusarium wilt	*Fusarium oxysporum* f.sp. *conglutinans*				x		
Gray rot	*Botrytis cinerea*			x			
White leaf spot	*Pyrenopeziza brassicae Pseudocercosporella capsellae*			x			
Mycotic spotting	*Mycosphaerella brassicicola*			x			
Powdery mildew	*Erysiphe cruciferarum*			x	x		x
Sclerotoniosis	Sclerotinia sclerotiorum				x	x	
Complex of seedling diseases	*Rhizoctonia, Fusarium*, *Pythium* spp.	x	x				
Phomosis	*Leptosphaeria* spp.			x	x		
Sclerotonyosis	*Sclerotium rolfsii*	x	x		x		
Verticillium	*Verticillium longisporum*	x			x		
Viruses	*Turnip yellows virus Turnip mosaic virus*			x			
White rust	*Albugo candida*			x		x	

The causative agent of the disease, Sclerotinia sclerotiorum, is a devastating pathogen that can affect more than 400 plant species [64]. Its sclerotia can survive in the soil for more than 4 years (Table 1.6), which narrows the choice of crop rotation and increases the risk of sclerotia accumulation in the soil. During periods of cool and humid weather during flowering, ascospores can form and spread, usually on the lower parts of the stems under the canopy, but can also be spread by wind, insects or rain splashes to upper leaves, pods or neighboring plants [65].

Clubroot, caused by *Plasmodiophora brassicae*, has gained in importance over the past two decades as a major threat to rapeseed production worldwide. In Europe, awareness of this disease has increased only in the last 10–15 years.

Table 1.6

The top 10 most significant biotic threats in the form of cruciferous crop diseases to the cultivation of cruciferous crops in Australia, Europe, China and Canada at present [66]

Rating	Australia	Europe	China	USA Canada
1	Phomosis	Sclerotoniosis	Sclerotoniosis	Clubroot
2	Sclerotoniosis	Phomosis	Phomosis	Sclerotoniosis
3	White leaf spot	Альтернаріоз	Downy mildew	Phomosis
4	Downy mildew	Downy mildew	Powdery mildew	Downy mildew
5	White rust	Powdery mildew	Alternaria	Alternaria
6	Viruses	Verticillium	White leaf spot	Powdery mildew
7	Powdery mildew	White rust	Viruses	Viruses
8	Clubroot	Clubroot	Clubroot	Seedling disease complex
9	Alternaria	Seedling disease complex	Seedling disease complex	White leaf spot
10	Seedling disease complex *	White leaf spot	Verticillium	Verticillium

* A complex of seedling diseases consisting of Rhizoctonia, Fusarium, Pythium spp.

The average yield loss is 0.03 t/ha for every 1% increase in infection, while the potential total yield loss can reach 100%, with current field research estimates ranging from 5 to 60% [67–69]. Dormant *P. brassicae*

spores from infected root nodules remain in the soil for more than 4 years in the absence of host plants. Previous studies have shown that the half-life of dormant spores is 3.6 years [70]. In addition, a significant increase in the density of spores in the soil after modern tillage systems has been reported. Clubroota spreads mainly by moving soil containing dormant spores through agricultural machinery or through water erosion [71].

Stem blight, or blackleg, is one of the most important diseases and is associated with yield losses of 5 to 50% in Europe, Canada and Australia, where *Leptosphaeria maculans* or *Leptosphaeria biglobosa* are widespread [72–77].

L. biglobosa, which is less aggressive than *L. maculans,* is the only leptosperm species that can cause significant seed yield losses of 10 to 37% [78]. It is noted that mechanical damage and nutritional damage by cabbage root fly, cabbage stem flea and rapeseed stem weevil can significantly increase the incidence, volume of affected tissue and severity of phoma stem cancer in susceptible varieties [79–80]. While the inoculum survival time on residues in Europe is 4 years, in Western Australia, longer survival is expected – up to 4 years [81–82]. Airborne ascospores are the main source of inoculum for epidemics, and the release of ascospores is virtually unchanged in the temperature range from 5 to 20 ^{0}C, but increases significantly during precipitation [83]. The limited spreading distance, mainly within 14 cm, is estimated to be due to spraying during rain [84]. However, the spores can be carried by the wind up to 10 km away [85].

Thus, based on the global dynamics, it can be concluded that alternaria, downy mildew, white rot, phomosis, verticillium, and clubroot are the most common diseases in cruciferous crops. Less common are powdery mildew, grey rot, cylindrosporosis, white spot and others.

During the period under review, Ukraine has allocated [86]fungi from 4 classes (12 genera from spring rape plants and seeds, 11 genera from winter rape). The most numerous group was made up of fungi of the class Deuteromycetes (imperfect), which amounted to 58% on spring rape and 55% on winter rape. The smallest number of fungi of the class Zygomycetes (zygomycetes) was noted: 8% on spring rape and 9% on winter rape. The number of fungi of the classes Oomycetes and Ascomycetes was low – 17 and 18% on spring and winter rape, respectively.

It is reported [87] also that the spread and development of downy mildew and Alternaria in the forest-steppe zone of Ukraine on spring and winter rape during 1985–2005 were 58–80% and 4–25%, respectively, and phomosis – 24–50% and 3.0–14.0%. Epiphytotypes of downy mildew and Alternaria were observed in 1986, 1989, 1993, 1995, 1998, 2001; phomosis – in 1986–1989, 1993, 1995, 1998, 1999, 2000, 2001 and 2004. The prevalence of these diseases in these years was in the range of 60–100%, and the development of 15.0-35.0%. The shortfall in rapeseed yield, depending on the intensity of the development of individual diseases, ranged from 10.0 to 80.0%.

The largest number of harmful diseases of rapeseed are caused by representatives of the class Deuteromycetes. Diseases caused by fungi of the Oomycetes and Zygomycetes classes do not cause significant damage to the crop. From the class Ascomycetes, rapeseed is damaged by the fungus *Sclerotinia sclerotiorum* (Lib.) de Bary, the causative agent of white rot (Table 1.7, Figs. 1.5–1.6).

The dependence of the frequency of occurrence on the level of GTK and relative humidity in spring rape was noted in *Erysiphe communis* Grev., *Fusarium oxysporum* (Schlecht.), *Sclerotium bataticola* Taub. and fungi of the genus Alternaria.

In dry years (at low values of GTC: during the growing season – 0.29–0.52, April-May – 0.34 in combination with low relative humidity – 56–58%) it significantly decreased in the pathogens of powdery mildew, Fusarium, Alternaria and increased in the pathogen of ash rot.

Another study notes [92], that in the conditions of the phytopathological site of the Agronomic Research Station of the NUBiP of the Right-Bank Forest-Steppe Zone of Ukraine, the most harmful diseases of rapeseed are downy mildew, phomosis, alternaria, powdery mildew, root bacteriosis, etc. At a certain stage of the rapeseed plant's vegetation, diseases cause significant damage.

For example, downy mildew appears on cotyledons, young leaves, and is widespread in the budding phase. The first signs of phomosis and Alternaria were recorded on rapeseed plants when 3–5 rosette leaves were present in the autumn sowing. The massive manifestation of diseases on rapeseed was noted in the flowering phase. Powdery mildew appears in the pod setting phase on late spring rapeseed crops.

Root bacteriosis is especially dangerous in the fall and spring periods in winter rape and largely depends on the state of plant vegetation in the fall. For the first time, clubroot was also detected on rapeseed crops, which is one of the harmful diseases of cabbage crops.

Table 1.7

Classification of phytopathogenic fungi isolated from rapeseed plants and seeds [88–89]

Class, order, family	Gender	Type	Disease
Oomycetes, Peronosporales, Peronosporaceae	*Peronospora* Cda	*Peronospora brassicae* Gaeum. *f. brassicae* (Gaeum.) Dzhan	Downy mildew
Albuginaceae	*Albugo Pers.*	*Albugo candida* (Pers.) Kuntze	White rust
Zygomycetes, Mucorales, Mucoraceae	*Mucor* Mich. emend. Ehrenb.	*Mucor mucedo* Fres. *emend.* Bref	Moldy seeds
Ascomycetes, Helotiales, Sclerotiniace	*Sclerotinia* Fusc.	*Sclerotinia sclerotiorum* (Lib.) de Bary	White rot (sclerotinosis)
Erysiphales, Erysiphaceae	*Erysiphe* Link.	*Erysiphe communis* Grev. *f. brassicae* Hammar L.	Powdery mildew
Deuteromycetes, Hyphomycetales, Moniliaceae	*Aspergillus* Michtli et Fr.	*Aspergillus niger v. Tiegh*	Moldy seeds
	Penicillium Link.	*Penicillium viridicatum* Westl.	
	Botrytis Micheli	*Botrytis cinerea* Pers.	Gray rot
Dematiaceae	*Alternaria* Nees.	*Alternaria brassicae* (Berk.) Sacc.	Alternariosis
		A. brassicicola Wilts. (Schw.)	
Tuberculariaceae	*Fusarium* Link.	*Fusarium oxysporum* (Schlecht.) Snyd. et Hans	Фузаріоз
Sphaeropsidale s, Sphaeropsidaceae	*Phoma* Fr.	*Phoma lingam* (Tode) Desm.	Phomosis
Phomaceae	*Sclerotium* Taub.	*Sclerotium bataticola* Taub.	Ash rot

Studies have shown that the above diseases and their manifestation on rapeseed plants depend on the biological characteristics of pathogens, as well as on the weather conditions of the autumn and spring period. Taken together, their manifestations pose a significant threat to rapeseed plants, which is manifested in a decrease in the yield of green mass and seeds and a deterioration in the quality of oil.

In the conditions of a phytopathological station [96] also found a leafy form of phomosis in the form of elongated light gray spots covered with numerous black dots. Over time, as the leaves age, the spots darken, crack, and fall off. On winter rape, the first signs of the disease were detected 55–60 days after sowing in the phase of 4–5 rosette leaves. The first symptoms of the disease were observed on the lower leaves. The maximum development of phomosis was found 20 days after the detection of disease symptoms.

Figure 1.5 – Alternaria in spring oilseed rape (caused by Alternaria brassicae) [90]

We noted particularly severe damage when the average daily temperature decreased from 15 to 10 ^{0}C, and the air humidity increased to 85–95%. Under such conditions, there is an intensive formation of pseudothecia on the lower leaves in the form of bags with sackspores (*Leptosphaeria maculans*). At the same time, there is a tendency to increase the damage to rosette leaves by the phomosis pathogen on weakened plants due to lack of nutrients in the soil. Such plants do not survive wintering and die prematurely (Figure 1.7).

Figure 1.6 – Gray rot on winter rape pathogen: *Botrytis cinerea*) [91]

In spring rape, the first signs of the phomosis pathogen were detected on the lower leaves at the end of the budding phase. The intensity of the disease growth depended on environmental conditions and varietal characteristics of rapeseed plants. The artificially created microclimatic conditions due to the forest belt significantly enhanced the development of phomosis, and this was especially noticeable in susceptible varieties of spring rape. Later, the development of the phomosis pathogen spread to the pods in the form of gray dry spots, on which black pycnidia were formed. The seeds in the affected pods were small and much smaller than healthy ones.

The most dangerous period for pod infection is the flowering phase. When artificially infected with picnic fungus during the flowering period, the pods show massive infection with the disease. The fungus penetrates through the stigma of the pistil. The first signs of the disease appear at the ends of the lower pods, Analysis of the affected pods showed that about 84% of the seeds were brown, the rest were underdeveloped. It is known that the seed infection can remain viable for up to 4 years.

Figure 1.7 – Gray rot on white mustard caused by a pathogen: *Botrytis cinerea*) [92]

The life cycle of phomosis is also described, taking into account the hydrothermal regime of the Right-Bank Forest-Steppe zone of Ukraine. According to observations [93–94] pseudothecia develop on rapeseed plant debris in the form of a stroma of intertwined mycelial hyphae. Ascomata and antheridia are established in the stroma, and the sexual process takes place. Ascogenic hyphae with bags formed on them grow. The stroma tissue is torn, resulting in cavities. In each of them, several bags with bagospores are formed. Pseudothecia are oval in shape, 360–500 microns in diameter.

At the first stages, they are immersed in the plant's carpel, later they appear on the surface, covered with a dark-colored film. The bags are elongated, club-shaped, 90 x 10 or 138 x 16 microns in size, with pseudoparaphyses around them. Sumps are yellowish, elongated ovoid with 3–5 septa, 30–70 x 4–9 μm in size. The formed pseudothecia remain until spring. At a temperature of 4–8 ^{0}C, the ascites begin to germinate, and growth tubes are formed. Formed hyphae penetrate into the tissue through the stomata of growing leaves of winter rape. Unlike sumcospores, pycnospora germinate at a temperature of 16 ^{0}C. Hyphal infection occurs at 100% relative humidity. During the growing season of rapeseed plants, the phomosis pathogen is spread by pycnospores and sumps.

In the conditions of the phytopathological site of the Agronomic Research Station of NUBiP (Zone of the central regions of the Right-Bank Forest-Steppe of Ukraine) [97] the first symptoms of Alternaria

(*A. brassicae*) were detected on plants of winter rape (in autumn) and spring rape (in spring). The first signs were observed in the phase of 3–5 leaves in the form of dark brown, almost black individual small spots. A yellow or light green border often formed around the spots. Later, the affected tissue is covered with a black coating in the form of small-dotted sods, especially on the stems, branches, and pods. Affected pods are deformed and cracked. Seeds from the affected pods are small and underdeveloped.

In the conditions of the Right-Bank Forest-Steppe of Ukraine, the marsupial and pycnidial stages of the fungus that causes Alternaria were not found. In most cases, A. brassicae overwinters as mycelium on plant residues or wintering plants of winter rape.

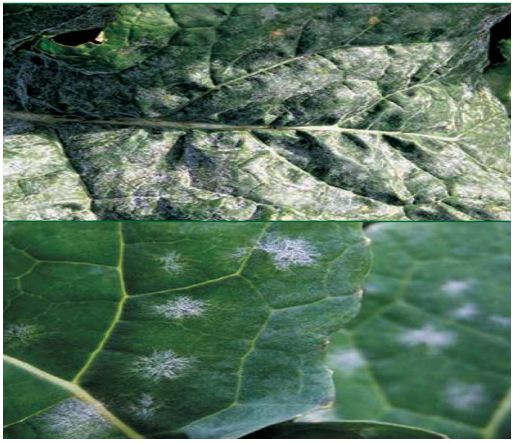

Figure 1.8 – Powdery mildew (pathogen: *Erysiphe communis* f. Brassicae, Syn. *Erysiphe cruciferarum*) [96]

In the spring, when the average daily temperature is +5 ^{0}C and the relative humidity is 90%, conidia appear, which infect young, growing leaves of winter rape and then settle on spring rape plants. The disease damage increases in the budding phase at the beginning of flowering. During flowering, the conidia penetrate the ovary, resulting in massive damage to the pods. The fungus can also be preserved by mycelium in seeds for up to 12 years [95].

The dynamics of alternaria spread and harmfulness in the conditions of the experimental field of VNAU was studied [96]. Field recordings in the conditions of the VNAU experimental field showed that Alternaria on spring rape was manifested on all parts of plants: cotyledons, leaves, stems, branches, pods. Dark brown, almost black, or light gray, rounded, zonal spots with a diameter of 1–15 mm appeared on cotyledons and leaves. A yellow or light green border was observed around the spots.

Later, the affected tissue of the spot was covered with black or gray bloom in the form of small dotted sods. On the stems, the spots were of different sizes and shapes, dark, shiny, often merged and covered a large surface of the stem or branches.

On pods, Alternaria appeared as black small shiny spots. In case of early pods damage, deep black ulcers appeared, diseased pods were usually deformed, seeds in them were small and underdeveloped. When spots or ulcers appeared on the seams of the valves, the pods cracked and the seeds spilled out, which led to significant yield losses.

The peculiarities of the dynamics of cruciferous diseases development were also studied in the experimental field of Vinnytsia National Agrarian University. Thus, the dynamics of damage to spring rape crops had its own characteristics. The year 2017 was more favorable for the development of disease signs during the rosette-flowering period, and the year 2016 was more favorable for the development of the disease on plants in the second half of the growing season during the period of fruit formation and fruit formation, which was reflected in the prevalence and development of the studied disease (Table 1.8). Thus, dry weather with low air humidity, which was observed in May-June 2016, did not contribute to the development of the disease, due to which at the end of the spring period the disease prevalence was only 2.3% with a development intensity of 0.08%, and vice versa, an increase in total moisture, especially during the period of pod and seed ripening, led to an increase in the total disease prevalence to 26–29% with a development intensity of 8.0–8.6%.

On the contrary, for the conditions of 2017, during the summer period, the prevalence of the disease increased in the third decade of May – first decade of June, where this figure was 8.6% with an intensity of its development of up to 3.7%, and during the period of ripening of fruit elements, these figures were significantly lower.

Thus, the development of Alternaria on spring rape in the conditions of the research area is facilitated by intense precipitation during June and July and high humidity under the cover of plants. According to our observations, the gradual spread of the disease during this period was facilitated by increased air humidity under the cover of plant leaves and heavy dew at night, because precipitation in June was less than normal (especially in 2017), and in July and early August, during the maturation phase of plants, their amount was even less (Table 1.8).

The same studies also found that Alternaria has a significant impact on the main structural parameters of spring rape yield.

The data in the table shows that the development of Alternaria on plants, which is estimated by points 1–3, does not significantly affect the length of the pod. It is equal to 10.7–11.3 cm in both healthy and diseased plants.

However, with the development of the disease with a score of 5, the length of the pods in diseased plants compared to healthy plants is significantly reduced and is 7.0 cm, or 3.7 cm less than in the control variant.

Table 1.8

Spread and development of Alternaria on spring rape variety Maria in the experimental field of VNAU, 2016–2017 [101]

Year	Indicators	Accounting dates, decades						
		June			July			August
		I	II	III	I	II	III	I
2016	Distribution, %	4	17	21	24	26	29	0
	Development, %	0.1	2.9	4.8	6.2	8.0	8.6	0
2017	Distribution, %	4.2	8.6	11.0	16.5	21.3	16.5	0
	Development, %	0.3	3.7	5.6	7.8	9.7	10.4	0

The slight development of Alternaria on the pods (within 1–2 points) does not significantly affect the formation of the number of seeds in the pods, which ranges from 18.3–18.6 pcs. per 1 pod. At a damage score of 5, the number of grains in a pod compared to the control (healthy pods) decreases almost twice – to 9.2 pcs.

It was noted that the development of Alternaria on the pods contributes to their premature cracking, which causes the loss of spring rape yield as a result of shedding. At the same time, slightly affected pods (score 1 and 2),

as a rule, do not open prematurely and their number in the total mass varies as in healthy plants within 3.1–5.0 pieces per 1 plant. However, with the development of the disease, which is estimated by a score of 4–5 compared to the control, it increases almost 13 times, reaching 39.5 pieces per 1 plant.

The development of Alternaria on pods most significantly affects the individual weight of seeds. With the superficial development of the disease on the pods (score 1), the weight of 1000 seeds in the affected plants does not change significantly compared to healthy plants (score 0), being in the range of 4.4–4.3 g. And with a score of 5, respectively, it decreases almost three times – 1.6 g.

Under these conditions, a natural and statistically significant decrease in the total yield of spring rape in comparison of control and plants with a damage score of 5 is observed – with a difference of 19.7 quintal/ha to the control, which actually corresponds to the natural level of spring rape yield according to the price of the point and the score of gray forest soils in the soil cover of the experimental field (Table 1.9). The regression analysis performed in the Statistica 6.0 block program allowed us to form a mathematical model of the reduction of spring rape yield (yield shortfall (Y)) in relation to a certain plant infection with Alternaria (X). This dependence is expressed by the following equation for two phases of accounting: for the flowering phase: $Y = 0.237 X + 0.208$; for the green pod phase: $Y = 0.831 X – 0.562$.

Thus, the yield loss of spring rape depends on both the weather conditions of its vegetation and the phase of intense pathogen damage. At the same time, greater yield losses should be expected when plants are damaged during the period of intensive formation of fruit elements (green and yellow-green pod phase).

Thus, the presented studies have shown that Alternaria is a rather significant factor in reducing the yield of spring rape crops. The intensity of its development depends to a large extent on the optimal ratio of high humidity at high temperatures of a moderate interval. The very harmfulness of the disease in terms of reducing the seed yield increases when the fruit elements are affected, especially during the period of already formed seeds in the pods and the beginning of their intensive ripening, which corresponds to the phase of green-yellow-green pods.

Table 1.9

Harmfulness of Alternaria depending on the intensity of damage to rapeseed plants of Maria variety in the experimental field of VNAU (average for 2016–2017) [101]

Intensity of pods damage in points	Pod length, cm	Number of seeds per pod	Number of opened pods without seeds per 1 plant, pcs.	Weight of 1000 seeds, g	Seed yield, centner/ha	Yield reduction compared to control, centner/ha
Score 0 – healthy plants	10.7	18.3	3.1	4.4	24.3	0.0
Score 1 – up to 20 surface small spots on the pod	10.5	18.6	5.0	4.3	22.8	1.5
Score 2 – more than 20 surface spots on the pod (background)	11.3	18.3	5.0	4.3	20.8	3.5
Score 3 – with 1 or 2 deep ulcers	10.1	15.8	19.9	3.3	15.3	9.0
Score 4 – with 3 or 4 deep ulcers	8.5	13.0	35.7	2.3	8.7	15.6
Score 5 – with more than 5 deep ulcers	7.0	9.2	39.5	1.6	4.6	19.7
SSD_{05}	*0.8*	*1.8*	*2.0*	*0.11*	*1.7*	–

Rapeseed powdery mildew – the causative agent is the marsupial fungus Erysiphe communis var brassicae – was found on late spring rape crops in the form of a white spider web coating on stems, leaves, and pods. Later, the leaves curl up and dry out. The pods of severely affected plants turn yellow early, their seeds are immature and small (Figure 1.13).

During the entire growing season, the powdery mildew pathogen forms conidial sporulation. It is only in the fall that dark brown spots – cleistothecia – appear on the dead stems of rape. Conidiophores on the mycelium are arranged vertically with single ellipsoidal conidia at the top. Conidia are 28–35 x 11–19 μm in size. Kleistothecia are dark brown, globose, 85–90 μm in diameter. They have branched appendages at the top. Each cleistothecium contains 4–8 pear-shaped sacs with 4–8 elliptically discolored asci measuring 19–25 x 9–14 μm. According to the results of

the research, it was found that this fungus overwinters on rapeseed residues in the vast majority of mycelium and only in some cases, depending on weather conditions, in cleistothecia. The massive manifestation of powdery mildew on spring rape plants was noted in the phase of complete pod setting.

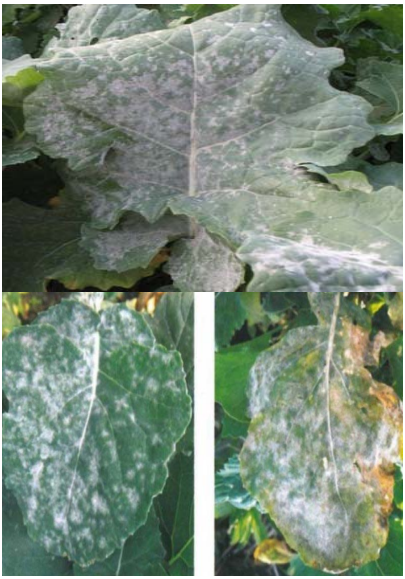

Figure 1.9 – Powdery mildew on spring rape [97]

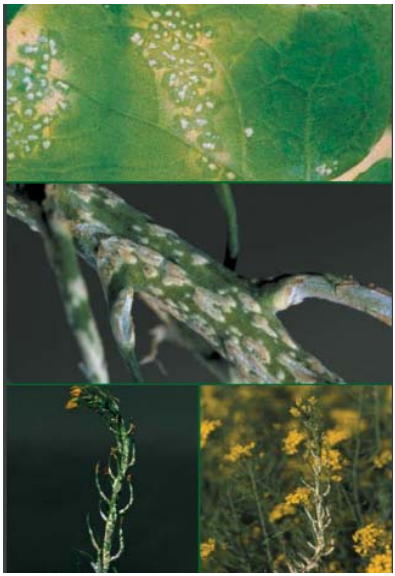

Figure 1.10 – White rust (Cause: *Albugo candida*, Syn. Cystopus candidus) [98].

The frequency of occurrence of other isolated pathogens did not depend on meteorological indicators. During 10 years of research, the frequency of downy mildew (downy mildew) in spring rape crops was high, while the frequency of white rot, phomosis and seed mold was low. The fungus Albugo candida (Pers.) Kuntze showed a periodicity of manifestation – 1 year in 3 with a low frequency of bridging (Figure 1.14).

The frequency of occurrence of Albugo candida (Pers.) Kuntze and Botrytis cinerea Pers. fungi on winter rape was found to depend on the GTC

Figure 1.11 – Rapeseed stalks affected by gray mold [99]

Figure 1.12 – Signs of verticillium wilt on the stem of spring rape [103]

and relative humidity. These pathogens were observed on winter rape crops, respectively, with a low and medium frequency of occurrence according to the GTK in April-May, exceeding 1.35, in combination with relative humidity of 62% and above. In the same years, the frequency of Phoma lingam (Tode) Desm. increased from medium to high in winter rape crops.

Regardless of weather conditions, in all years of the study, the manifestation of pathogens was noted in winter rape crops: sclerotinia (white rot) and Fusarium – with an average frequency of occurrence, downy mildew, powdery mildew and Alternaria – with medium and high frequency of occurrence (Table 1.10–1.11, Figure 1.9–1.13).

Figure 1.13 – Cylindrosporosis (White leaf spot, pathogen: *Cylindrosporium concentrium*, Syn. *Gloeosporium concentricum)* [103]

The fungi Aspergillus Michtli et Fr. emend. Ehrenb. are a constant component of rapeseed mycoflora. The frequency of their occurrence in all years of the study is low.

In another study, 22 species from four classes were identified as a result of the inventory of the species composition of spring and winter rape mycorrhizal flora: oomycetes – 1; zygomycetes – 1; ascomycetes – 2 and imperfect – 18 (Tables 1.14–1.15). In all the years of research, regardless of the prevailing weather conditions, a high frequency of occurrence was found in the pathogen of Fusarium wilt, powdery mildew, phomosis and downy mildew (Figure 1.14–1.16).

During the study of pathogen localization sites, it was found that mycoses are most often isolated from affected stems – 55.0%, root system – 44.0% and seeds – 41.0% (Table 1.15).

During pod formation, the intensity of phytopathogen infection of Athora hybrid plants increased, and symptoms of these diseases were also found on stems and pods in addition to leaves. The severely affected pods in the control variant of the experiment, where fungicides were not used, cracked. In 2020, during this period, the development of such a disease as Alternaria was the highest compared to others and amounted to 22.5%, in 2021, the highest was the development of diseases such as powdery mildew – 22.5% and Alternaria – 20.1%. In addition to Alternaria, in 2020, at the end of the growing season, the development of phomosis increased to 16.6%, downy mildew – to 18.1%, powdery mildew – 10.6% and sclerotinia – to 9.7%. In 2021, in addition to Alternaria and powdery mildew, the development of phomosis increased to 10.5%, downy mildew – to 10.1%, and sclerotinia – to 4.2%

In assessing the development of the species structure of cruciferous diseases in agricultural formations of Vinnytsia region, an example is the result of surveys of winter rape crops in one of the agricultural formations on the Athora variety. The dynamics of the development of the main phytopathogens on plants of the winter rape hybrid Athora was studied by conducting surveys of the degree of their damage four times during the growing season, namely in the phases of leaf rosette formation, stemming, early flowering and pod formation. The data of the surveys are presented in Table 1.16.

Table 1.10

Frequency of fungi occurrence on spring rape depending on the HTC and air humidity, 2013–2022 [100]

Pathogen	Frequency of occurrence									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1	2	3	4	5	6	7	8	9	10	11
Peronospora brassicae Gaeum. *f. brassicae* (Gaeum.) Dzhan	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++
Albugo candida (Pers.) Kuntze	–	+	–	–	–	+	–	–	–	+
Mucor Mich. emend. Ehrenb.	+	++	+	+	+	+	+	+	+	++

(End of Table 1.10)

1	2	3	4	5	6	7	8	9	10	11
Sclerotinia sclerotiorum (Lib.) de Bary	+	++	+	+	+	+	+	+	+	+
Erysiphe communis Grev. *f. brassicae* Hammar L.	+++	+++	+++	++	+++	+++	+++	++	+++	+++
Aspergillus Michtli et Fr.	+	+	+	+	+	+	+	+	+	+
Penicillium Link	+	+	+	+	+	+	+	+	+	+
Botrytis cinerea Pers.	–	+	–	–	–	–	–	–	–	–
Alternaria brassicae (Berk.) Sacc.	+++	+++	+++	+	+++	+++	+++	+	+++	+++
A. brassicicola Wilts. (Schw.)										
Fusarium oxysporum (Schlecht.) Snyd. et Hans	+++	+++	+++	++	+++	+++	+++	+	+++	+++
Phoma lingam (Tode) Desm.	+	+	+	+	++	+	+	–	+	+
Sclerotium bataticola Taub.	–	–	–	++	–	–	–	++	–	–

Note: + – low incidence of the pathogen (up to 10% of plants are affected); ++ – medium incidence of the pathogen (up to 50% of plants are affected); +++ – high incidence of the pathogen (more than 50% of plants are affected); – no pathogen.

Table 1.11

Frequency of fungi occurrence on winter oilseed rape depending on the HTC and air humidity, 2013–2022 [101]

Pathogen	Frequency of occurrence									
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
1	2	3	4	5	6	7	8	9	10	11
Peronospora brassicae Gaeum. *f. brassicae* (Gaeum.) Dzhan	++	+++	++	+++	+++	+++	+++	+++	++	+++
Albugo candida (Pers.) Kuntze	–	+	–	–	–	+	–	–	–	+
Mucor Mich. emend. Ehrenb.	+	+	+	+	+	+	+	+	+	++

(End of Table 1.11)

1	2	3	4	5	6	7	8	9	10	11
Sclerotinia sclerotiorum (Lib.) de Bary	++	++	++	++	++	++	++	++	++	+
Erysiphe communis Grev. *f. brassicae* Hammar L.	+++	++	++	++	+++	++	+++	+++	++	+++
Aspergillus Michtli et Fr.	+	+	+	+	+	+	+	+	+	+
Penicillium Link	+	+	+	+	+	+	+	–	+	+
Botrytis Micheli	–	++	–	–	–	++	–	–	–	++
Alternaria brassicae (Berk.) Sacc.	++	+++	+++	+	++	+++	+++	++	++	+++
A. brassicicola Wilts. (Schw.)										
Fusarium oxysporum (Schlecht.) Snyd. et Hans	++	++	++	++	++	++	++	++	++	++
Phoma lingam (Tode) Desm.	++	+++	++	+	++	+++	++	++	++	+++

Note: + – low incidence of the pathogen (up to 10% of plants are affected); ++ – medium incidence of the pathogen (up to 50% of plants are affected); +++ – high incidence of the pathogen (more than 50% of plants are affected); – no pathogen.

Table 1.12

Ecological niches of spring rape pests [102]

The causative agent of the disease	Ecological niches			
	underground and root organs	leaves, stems	generative organs and seeds	leading system
Root rot	+			
Fusarium	+	(+)	(+)	(+)
Alternaria		+	+	
Peronosporosis		+	(+)	
Sclerotinia	+		(+)	
Viruses		+	+	

+ – main ecological niche, (+) – additional ecological niche.

Table 1.13

The main pathogens of white mustard seeds, 2012–2022

Species name of the pathogen	Average plant infestation, units/m²	Disease progression, %
Downy mildew *Peronospopa brassicae* Gaeum.	2.8	24.5
Powdery mildew *Erysiphe communis* Grev. f. *brassicae* Hammare L.	1.5	14.3
White rust *Cystopus candidus* Pers.	1.3	11.5
Dry rot (phomosis) *Phoma lingam* Desm.	1.0	6.5
Fusarium wilt *Fusarium oxysporum* Sch–lecht.	0.5	2.5

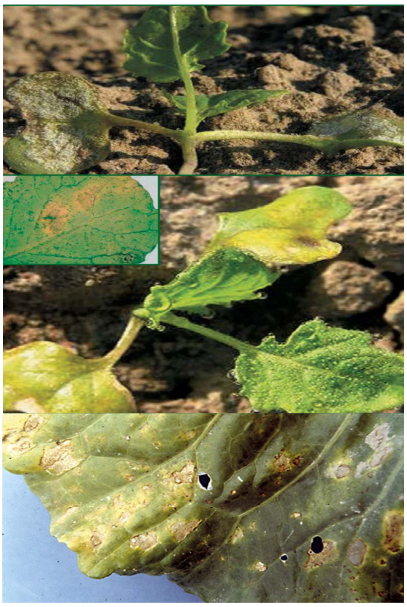

Figure 1.14 – Peronosporosis, downy mildew (caused by Peronospora parasitica) [96]

Figure 1.15 – Phomosis (pathogen: *Phoma lingam, Syn. Plenodomus lingam)* [96]

The first signs of such fungal diseases of winter rape as phomosis and downy mildew appeared on plants already in the phase of leaf rosette formation in the fall and the development of downy mildew in 2020 was already quite high – 7.3%, in 2021 it was slightly lower – 5.1%, the development of phomosis was 2.8% in 2020 The first signs of plant damage by such phytopathogens as powdery mildew, alternaria and sclerotinia pathogens were observed in the spring in the stemming phase and the development of powdery mildew during this period was the highest – 5.5 in 2020 and 10.6% in 2015, Alternaria development was 5.8% and 4.6%, respectively, and sclerotinia – 1.3 and 1.1%, respectively. During the flowering period of Athora hybrid plants in 2020, the highest development was noted for such a disease as Alternaria – 9.7%, and in 2021 for such a disease as powdery mildew – 15.1% (Table 1.16).

Figure 1.16 – Black leg (pathogen: *Olpidium brassicae, Pythium debaryanum, Rhizoctonia aderholdii)* [96]

Table 1.14

Distribution of isolated fungi by systematic groups and frequency of their occurrence on spring and winter rape, 2019–2022 [102]

Class, order,. family	Gender	Frequency of occurrence			
		2019	2020	2021	2022
Oomycetes, Peronosporales, Peronosporaceae	*Peronospora* Cda	++	+++	++	+
Zygomycetes, Mucorales, Mucoraceae	*Mucor* Mich, emend. Ehrenb.	+	+	+	+
Ascomycetes, Helotiales, Sclerotiniace	*Sclerotinia* Fuse.	–	++	+	–
Erysiphales, Erysiphaceae	*Erysiphe* Link	+++	+++	++	+
Deuteromycetes, Hyphomycetales, Moniliaceae	*Aspergillus* Michtli et Fr.	+	+	+	+
	Botrytis Micheli	–	+	–	–
	Penicillium Link	+	–	+	+
	Trichoderma Pers. et Fr.	+	+	–	–
	Verticillium Nees	+	–	–	–
Dematiaceae	*Alternaria* Nees	++	++	+	+
	Cladosporium Link	+	+	+	+
Tuberculariaceae	*Fusarium* Link	+++	++++	+++	+++
Sphaeropsidales, Sphaeropsidaceae	*Phoma* Fr.	++	+++	++	++
Myceliales, Myceliaceae	*Sclerotium Tode.*	+	++	++	+

Frequency of occurrence; + – single (up to 10% of plants are affected); ++ – medium (up to 50% of plants are affected); +++ – severe (more than 50% of plants are affected).

Table 1.15

Species composition and localization of pathogenic mycorrhizal flora of spring and winter rape, 2013–2022 [102]

Diseases	Pathogen	Location of the localization				
		root	stem	leaf	pod	seed
1	2	3	4	5	6	7
Alternariosis	*Alternaria alternata* (Fr.) Keissler; *A. brassicae* Sacc; *A. brassicicola* Wilts; *A. cheiranthi* (Fr.) Bolle; *A. consortiale* (Thiiem.) Hughes	+	+	+	+	+

(End of Table 1.15)

1	2	3	4	5	6	7
Powdery mildew	*Erysiphe communis* Grev.var *brassicae* Hammar L.	–	+	+	+	–
Peronosporosis	*Peronospora brassicae* Gaeum. *f. brassicae* (Gaeum.) Dzhan	–	–	+	–	–
Phomosis	*Phoma lingam* (Tode) Desm.	+	+	+	–	–
Tracheomycosis wilting	*Fusarium oxysporum* (Schlecht.) Snyd. et Hans	+	+	–	–	+
	Verticillium dahliae Klebahn	+		–		–
White rot	*Sclerotinia sclerotiorum* (Lib.) de Bary	+	+	–	–	–
Ash rot	*Sclerotium bataticola* Taub.	+	+	–	–	–
Gray rot	*Botrytis cinerea* Fr.		–	+	–	
Rot of seedlings Плесневение семян	*Fusarium* Link	+	+	–	–	–
	Penicillium Link	+	+	–	–	–
	Penicillium Link	–	–	–	–	+
	Aspergillus Micheli	–	–	–	–	+
	Trichoderma viridi Pers.	–	–		–	+
	Cladosporium herbarum Link	–	–	–	–	+
	Mucor Micheli emend Ehrenb.	–	–	–	–	+

Table 1.16

Dynamics of major diseases on plants of winter rape hybrid Athora (control – without fungicides)

Period of accounting	Disease development, %.									
	2020 p.					2021 p.				
	Alternariosis	Phomosis	Sclerotinosis	Perono-sporosis	powdery mildew	Alternariosis	Phomosis	Sclerotinosis	Perono-sporosis	powdery mildew
Formation rosettes leaves	–	2.8	–	7.3	–	–	2.5	–	5.2	–
Stemming	5.8	8.7	1.3	9.3	5.5	4.6	6.6	1.1	6.2	10.6
Beginning of flowering	9.7	10.3	6.9	16.2	8.3	9.9	8.7	2.3	8.3	15.1
Formation of pods	22.5	16.6	9.7	18.1	10.6	20.1	10.5	4.2	10.1	22.5

Figure 1.17 – *Verticillium wilt* (Verticillium wilt and stem rot, pathogen: *Verticillium dahliae)* [96]

Figure 1.18 – Klubroot (pathogen: *Plasmodiophora brassicae)* [96]

Thus, in 2020–2021, research on the degree of damage to winter rape plants by the main fungal phytopathogens without fungicidal protection (control) showed a high development of diseases such as Alternaria and downy mildew, an average level of diseases such as powdery mildew and phomosis, and a relatively low level of diseases such as sclerotinia, but the harmfulness of which is high even at this level of development.

The most common disease in winter and spring rape is Alternaria. The incidence of winter rapeseed in the northwestern regions ranges from 40-100%, and 35.0–81.0% in spring rapeseed; in the central and southern regions – 16–58 and 11–32%, respectively. Pods affected by Alternaria ranged from 15.0–26.0% [103].

It was found that Fusarium is also one of the most common and harmful diseases, which leads to significant plant death during the growing season [104]. In particular, her research on the Otradnensky variety found that in

Figure 1.19 – White leaf spot (causative agent: *Pseudocercosporella capsellae)* [96]

the seedling stage, losses from Fusarium can amount to 15% of the crop. The largest losses in rapeseed yield are associated with the disease at the beginning of flowering. It is noted that the disease is usually focal and spreads radially across the field during the growing season. Fusarium can also manifest itself in an acute form, causing plant death within 2–3 days [105]. The development of the disease is facilitated by hot, dry weather in the first half of the growing season [106].

The fungus causing Fusarium can grow at temperatures ranging from 10 to 35 °C. The optimum temperature for it is 18–27 °C and soil moisture content of 40–70% (of the total moisture capacity). In the field, the minimum soil temperature during the development of the disease is 16–18 °C, and the maximum is 35 °C. The development of the disease is enhanced by a lack of potassium in the soil [107].

The study on the influence of weather conditions on the infection of spring rape with Fusarium was conducted by S.I. Parshintseva (2001) [108].

According to her data, during the rosette phase of rapeseed, a 4.8°C decrease in temperature leads to a 1.0–1.6% decrease in Fusarium damage to plants. During the budding-flowering period, an increase in air temperature by 1.7°C causes an increase in the incidence of 5.5% and 26.8% in moderately susceptible and susceptible samples, respectively. During the ripening phase of rapeseed, there is also a direct dependence of damage on temperature. Thus, the author found that in all phases of rapeseed plant development, the highest temperature value corresponds to the maximum damage rate.

When comparing the damage rates and precipitation, the following was noted: the inverse relationship is observed only in cases where the amount of precipitation for the period under study differs significantly from the average summer. Sufficiently dry weather during the rosette phase did not lead to a significant increase in Fusarium damage. The greater the amount of precipitation during the budding phase, the lower the damage was and vice versa. The dependence of Fusarium damage to rapeseed plants on the amount of precipitation in the ripening phase was the same as in the rosette phase. Sources of infection are infected soil and seeds, in which the pathogen is stored mainly in the form of chlamydospores, which can remain viable in the soil for up to 11 years [109]. In the conditions of the Steppe zone, in addition to Fusarium, a great danger to rapeseed is Alternaria or black spot [110]. The main causative agent of Alternaria is the fungus Altemaria brassicae Sacc., but Altemaria brassicicola Witts. (Schw.), Altemaria alternata Keissler. are also found (Figure 1.20–1.23). However, many researchers tend to believe that Altemaria alternata Keissler is a common component of leaf surface microflora and therefore it is usually referred to as a saprophyte on rapeseed. High relative humidity (more than 95%), frequent precipitation with wind at a temperature of 22 ^{0}C during the period of filling and maturation of rapeseed contribute to the development of the disease.

Alternaria is a widespread disease in rapeseed growing areas. It manifests itself in the form of dark brown or light gray, rounded spots on stems, leaves and pods. The first signs of the disease can be found on the rosette leaves of cruciferous plant species. The causative agent of the disease is the fungus Alternaria brassicicola (Sehn), which is common and causes dark spotting. Alternaria brassicae is the causative agent of gray spot.

Figure 1.20 – Signs of damage to pods of spring and winter rape by Alternaria [101]

Figure 1.21 a – Alternaria brassicae Sacc: 1 – affected plant; 2 – affected pods, 3 – affected seeds, 4 – conidia [101]

Figure 1.21 b. – Signs of alternaria infection [96]

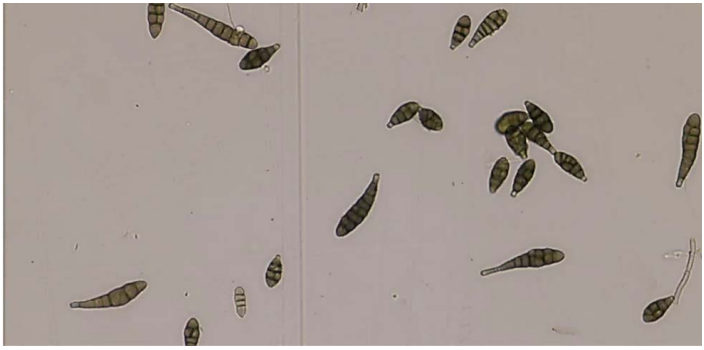

Figure 1.22 – Alternaria conidia [117]

The fungi belong to the class Deuteromycetes, order Hyphomycetales. *A. brassicicola* hyphae are 1.5–7.5 µm thick, conidiophores are olive-brown in color, solitary or in bunches of 2–12 pieces, simple, straight with a membrane. Their length is 70 and thickness is 5–8 µm. Conidia are dark

brown or olive in chains of 20 or more, sometimes they are branched, inversely club-shaped with 1–11 transverse and 6 longitudinal membranes, warty when aged, 18–130 µm long, 8–20 µm wide. *A. brassicae* has hyphae 4–8 µm thick. Conidiophores are produced in bunches of 2–10 pieces. They are simple, straight or cranked, slightly expanded at the base. They are membranous, white-gray-olive, 170 mm long and 6-11 mm thick. Conidia are solitary, sometimes in a chain of up to 4, obovate with 6–15 transverse and 1-8 longitudinal septa of gray-olive color, 75–350 x 20–30 µm in size. Conidia of *A. brassicae* germinate at 15 ^{0}C, and conidia of *A. brassicola* at 23 ^{0}C. Relative humidity is most favorable above 95%. The degree of damage to cabbage is directly related to the amount of precipitation during the flowering period. The main source of infection is the leaves of the testes with conidia, which infect it in the spring. The infection begins on the lower pods of the plant, and then gradually develops upward. Pathogen conidia spread en masse during the threshing of affected plants. They are also carried by the wind up to 2 km or more, affecting spring rape and other cabbage crops.

During periodic changes in dry and wet weather, the development of the disease can cause up to 20% or more of the yield loss. The affected pods are smaller in length, and the number of seeds per pod is correspondingly

Figure 1.23 – Signs of alternaria infection in spring rape [115]

smaller. The seeds are small, gray, and the weight of 1000 seeds is reduced by 28%. Seed germination is reduced by 27%, and seed oil content is reduced by 12%. Pathogens persist on plant debris, in seeds, and on the leaves of winter cruciferous plant species affected in the fall in the form of mycelium and conidia. Sick seeds can retain infection on the surface for up to 2 years and internal infection for up to 12 years.

Those varieties that show increased resistance to Alternaria have fewer stomata per unit area. In addition, the reduced number of conidia on the same spots in a resistant, as opposed to susceptible, variety of cruciferous plant species in a ratio of 1:3 [111].

Resistance can also be manifested by the presence of waxy coating on the leaves of cruciferous plant species.

The resistance of cruciferous plant species to Alternaria is influenced by the conditions of its cultivation, the application of high doses of phosphorus and potassium fertilizers, as well as spring foliar fertilization with nitrogen fertilizers [112].

The use of antagonist fungi in soil and hyperparasites against the pathogen has prospects for the development of biological defense [113].

Alternaria, or black spot, is caused by imperfect fungi from the genus Alternaria Nees in the class Deuteromycetes of the order Hyphomycetalesy of the family Dematiaceae.

Andersson & Olsson [114] four species of Alternaria were recorded on oilseed rape. The main species on oilseed rape in Europe is *Alternaria brassicae* Sacc, but *A. brassicicola* Witts (Schw.), *A. raphani* Groves et Skolko [115–119].

Alternaria alternata (Fr) Keissler is a common component of leaf surface microflora [120]. It is usually classified as a saprotroph on rapeseed, although some isolates can be pathogenic to the related genus *Brassica campestris* [121]. Pre-inoculation of rapeseed leaves with non-pathogenic isolates of *A. alternata* reduces *A. brassicae* infection [122–123].

Alternaria is widespread everywhere, especially in areas with sufficient moisture In the UK, it is the most economically important disease. In France, black spot significantly reduces yields once or twice every five years. Alternaria pathogens can infect plants throughout the growing season, with the greatest damage occurring when infection occurs at the end of flowering or during pod development [124].

In wet weather, the disease becomes an epiphytotic disease and can cause premature "ripening" of plants, which is manifested in pods cracking and the formation of underdeveloped seeds. The affected seeds inside the burst pods shrivel up and fall out immature in dry weather, and rot in wet weather. When the pods are damaged, the mycelium penetrates deeply into the seed embryo, as a result, they underdevelop and their germination rate decreases by 10–15% [125].

The pathogen *A. brassica* reduces the content of chlorophylls, carotenoids, total sugars and the sum of phenols, but increases the content of proteins. A significant decrease in the content of total sugar in diseased leaves is most likely due to its consumption during pathogenesis [126–127].

A number of factors contribute to the intensive growth of alternaria [128]:

– increase in the area under rapeseed and other cabbage crops, which in some areas provide a year-round cycle of susceptible host plants;

– widespread use of herbicides, which reduces wax coating on the leaves and increases susceptibility to leaf diseases;

– a tendency to early sowing in the fall.

The species composition of oilseed rape Alternaria pathogens was determined in laboratory conditions for the conditions of Ukraine. *Alternaria alternate* (Fr.) Keissler, *A. brassicae* Sacc, *A. brassicicola* Wilts, *A. cheiranthi* (Fr.) Bolle and A. consortiale (Thiiem.) Hughes were isolated from the affected leaves and pods. The most common species were *A. alternata* and *A. brassicicola*. Less frequently – A. brassicae.

Regarding *A. consortiale* (Thiiem.) Hughes, it should be noted that by the end of the spring rape vegetation, some researchers recorded surface necrosis on the stems of single plants weakened by Fusarium wilt and ash rot. The spots are initially narrow, elongated into longitudinal strips (0.2×3–5 cm) from black-olive to ash-gray, clearly defined, which subsequently increase to 3-6 cm long and 1–1.5 cm wide, acquiring an eye-shaped shape, do not merge, and are surrounded by a dark gray border. The necrotic tissue in the center of the spot lightens and turns gray, covered with very small and closely spaced black dots – microsclerotia. The fungus was isolated on CGA at a temperature of 24–25 °C. Colonies are gray in color, mycelium is septate. The conidia are acrogenic (apical), shifting sideways as the conidiogenes continue to grow. Conidia vary in shape: almost spherical, quadrangular to oblong-oblong, sometimes with short

legs. The fungus is identified as *A. consortiale* (Thiiem.) Hughes. There are also reports in the literature that fungi of the genus Alternaria can form microsclerotia and chlamydospores [129].

The annual inspection of the phytosanitary condition of spring rape, brown mustard and white mustard crops revealed the following diseases with a prevalence of more than 10.0% [130]:

– Peronosporosis, or downy mildew (the causative agent of – *Hyaloperonospora brassicae* Gäum. Göker, Voglmayr, Riethm., Weiss & Oberw).

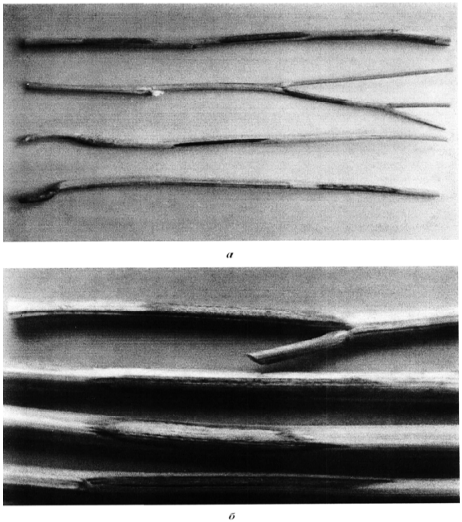

Figure 1.24 – Necrosis on spring rape stems caused by *Alternaria concortiale*: a – general view, b – enlarged spots with microsclerotia of the pathogen

Phytopathological examination of winter rape and mustard crops showed that the plants are affected by the following diseases [96]:

– Peronosporosis, or downy mildew (the causative agent is *Hyaloperonospora brassicae* Gäum. Göker, Voglmayr, Riethm., Weiss & Oberw.)

– Powdery mildew (pathogen – *Erysiphe communis* Grev. f. brassicae Hammar L.).

– Alternaria (causative agents – fungi of the genus Alternaria Nees).

– Phoma rot in the form of stem cancer (pathogen – *Leptosphaeria maculans* (Desm.) Ces. et. De Not).

– Sclerotinia, or white rot, in the stem form (causative agent – *Sclerotinia sclerotiorum* (Lib.) De Bary).

As for alternaria of cruciferous plants, the pathogen is first observed on the leaves in the form of dark brown, almost black, or light gray rounded zonal spots with a diameter of 1 to 15 mm. The color and size of the spots depends on the type of pathogen. A yellow or light green halo is observed around the spots. Later, a black or gray coating in the form of sod and small dots appears on them. This coating is a conidial sporulation of pathogens. Most often, the disease manifests itself shortly before harvesting [131].

On the stems, spots of various sizes and configurations, often elongated in the direction of the axis, dark, shiny, often merging with each other, cover a significant surface of the stem or branches. Pedicels may be affected by Alternaria. The spots on the pods are dark, small, shiny. In case of early infection, deep black depressed spots, ulcers, stretch marks form on the pods, the pods are deformed, seeds develop in them, or do not form at all. If the top of the pod is affected or the spots are located along the seam of the valves, the pods crack prematurely, which leads to seed loss. With prolonged development of the disease, when the pods or stems are covered with spots, and the pods are deformed, wrinkled and brittle, their condition is further aggravated by secondary damage by the fungus Botrytis cinerea Pers. The disease on seeds progresses in winter [132].

The disease is favored by high relative humidity (above 95%), frequent precipitation with wind, at a temperature of 22 °C during filling and ripening; seeds and thickened crops. If the temperature is below 18 °C, conidia germinate poorly. The disease is also caused by changes in wet and dry weather [133].

The conditions necessary for the development of the disease and its maximum harmfulness are warm (17–25°C), humid weather during flowering and pod filling. Infection with *A. brassicae* can occur in a relatively short period in the presence of dripping moisture. The minimum time for infection is 6 hours at 22 °C [135], according to other sources – 4 hours at 25 °C [136]. There are also sources that indicate that it takes at least 16 hours to become infected with Alternaria, and

48–72 hours for optimal infection. Infection with both species of *A. brassicae, A. brassicicola* is limited to alternating wet (above 95% relative humidity) and dry (70–80% relative humidity) periods of 16 and 8 hours, respectively. Conidia of *A. brassicicola* are abundantly formed within 20 hours at an average temperature of 13 °C and above [137].

Figure 1.25 – Signs of Alternaria on irpaccus in early spring during the process of crop vegetation recovery [134]

A. brassicae spores germinate at 0–35 °C, with an optimum of 15–20 °C, and mycelium grows at 0-30 °C, with an optimum of 20–25 °C. At 50 °C, spores and mycelium die within 10 minutes. Spores germinate at a relative humidity of > 90%, the optimum for germination and infection is 96% relative humidity. Ultraviolet light promotes sporulation in most cases [138].

The duration of the incubation period of Alternaria of rapeseed (*A. brassicae* pathogen) decreases with increasing moisture time from 6 to 24 hours and increasing temperature from 6 to 15 °C. The duration of

the incubation period also decreases with increasing leaf age. The degree of alternaria development depends on the spore concentration and leaf age [139].

Rapeseed leaves are more susceptible to Alternaria than rapeseed leaves due to the smaller thickness of the waxy coating, which prevents infection [140].

A phytotoxin specific for cabbage was isolated from A. brassicae. Sensitivity to the toxin corresponds to the sensitivity to the pathogen [141]. This toxin can be used for selection for resistance especially in tissue culture [142].

Infection of rape leaves with Alternaria species causes an increase in the content of indole and aromatic glucosinolates, it is assumed that the accumulation of glucosinolates: in the infected plant can limit the spread of the developing *A. brassicae* infection and inhibit further infection, especially in young plants.

The pathogens persist in the form of conidia and mycelium on the affected leaves of winter rape, on plant residues of cruciferous crops, cruciferous weeds, in soil, and seeds. Affected leaves are a source of inoculum for pod infection [143].

There is evidence that seed infection has little effect on seedling emergence, but there is a close relationship ($r = 0.76$) between the level of seed infection and subsequent infection of seedlings with Alternaria [144].

In case of surface denial, the seeds retain the infectious origin of the pathogens for up to two years, and in case of internal infection – up to 12 years. During the growing season of rapeseed, fungi are spread by conidia, which are transferred from plant to plant with rain drops. *A. brassicae* is a semi-saprotroph, penetrates the plant only through wounds and various insect damage [145]. Peronosporosis, or downy mildew, is no less harmful. The causative agent of the disease is the lower fungus *Peronospora brassicae* Gaeum (class Oomycetes, order Peronosporales, family Peronosporaceae), a parasite that weakens plants. Its mycelium spreads between the cells of plant tissues, but one or two conidiophores with conidia that form plaque come out through the stomata to the surface. The conidiophores are dichotomously branched, with terminal, strongly curved branches extending at an acute angle. In addition to conidial sporulation, spherical, 25–30 microns in diameter, oospores with a yellow-brown reticulate membrane are formed in the affected plant tissues [146].

Downy mildew is considered the most common disease of rapeseed and rape. The disease is common in England, Germany, China, Ukraine and Poland [147]. (Figure 1.26–1.28).

In particular, it is the most common disease in Poland. In the fall, about 30% of the leaves are affected, in the spring – 20–80% [148]. Dangerous in areas with sufficient moisture [149]. The pathogen affects almost all cruciferous plants. It is particularly severe on rape, which often spreads to rapeseed. With the intensive development of the disease, the shortage of green mass of rapeseed can be 15–25%, and seeds – 10–15% [100]. With moderate development of this disease, the yield loss of rapeseed can reach 10–20%, and in years of epiphytic development – up to 40–50%. If infection occurs in the cotyledon phase, plants may die [102].

Figure 1.26 – Tissue necrosis on rape seedlings caused by downy mildew [96]

Figure 1.27 – Signs of downy mildew [96]

Figure 1.28 – Plaque of the pathogen peronospora on rape seedlings [96]

Downy mildew is found in almost all areas of cucurbits growing in Ukraine, as well as abroad. It is a very harmful disease. The causative agent of downy mildew, *Peronospora brassicae* G., can reduce the yield of green mass and seeds of cruciferous plant species by 15–20 centner/ha or more during epiphytotic years [150]. It is known from the literature that downy mildew is very common on cruciferous plant species in England [151], Canada [152], India [153], France [154], Denmark [155], Sweden [156–157] and other countries. In Ukraine, downy mildew occurs in all areas of cruciferous plant cultivation [158–167].

Downy mildew appears on the cotyledons and leaves of cruciferous plant species in the form of brown-green and yellow spots. In the morning, in the presence of dew, or in rainy weather, a faint, delicate white coating is visible on the underside of the leaf, which later acquires a gray-purple hue. The spots often merge, forming significant lesions of the leaf blade, the leaves turn yellow and die prematurely. On the stems and pods, the spots are rounded or elongated, light brown, slightly depressed into the tissue, later covered with a light purple coating [168] (Figure 1.29).

Works by M.P. Polyakov, E.N. Vladimirskaya [169] it was noted that in the northern regions downy mildew on cabbage crops appears in the spring (April-May), then disappears and only reappears in August and September. By V.K. Kupriyanova [170] downy mildew manifests itself first on cotyledons and first leaves, with age the resistance of plants to the disease increases and only at the end of the growing season the plants are again affected by downy mildew, especially physiologically old leaves.

For the first time, a complete characterization of the signs of the disease on cabbage crops was described by S.N. Dorogin [171]. He claimed that cabbage plants are affected by downy mildew throughout the growing season. In affected plants, blurry yellowish spots appear on the cotyledons and on the first leaves. The pathogen often affects the entire leaf blade. On the underside of the leaf, a grayish-white loose coating appears in the places of spots – conidial sporulation of the fungus. Often, white rust develops on cabbage plants affected by downy mildew [172].

On young cabbage pods, downy mildew appears as grayish elongated spots, often covered with a weak scattered coating. In addition, such pods are heavily affected by Alternaria. On pods affected by downy mildew and Alternaria, the seeds are small and have low germination [173].

Downy mildew of radish caused by the oomycete Hyaloperonospora brassicae f. sp. raphani is a serious problem in the culture of radish, an edible root crop of the Brassicaceae family (Figure 1.30).

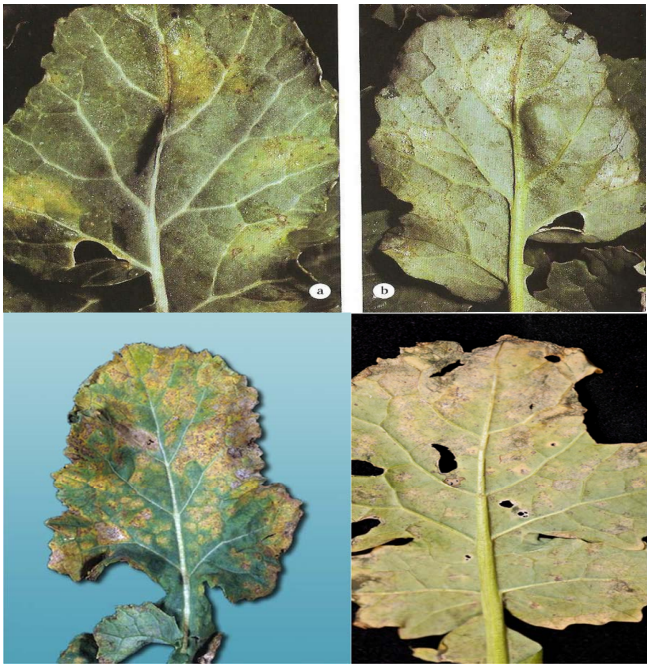

Figure 1.29 – Peronoporosis (The causative agent is a fungus *Perenospora brassicae)* [96]

The genus Hyaloperonospora (Division Oomycota; Family Peronosporaceae) is a group of biotrophic oomycetes responsible for DM disease in their respective Brassicaceae crops. Radish DM is caused by *Hyaloperonospora brassicae* f. sp. raphani, an obligate airborne pathogen that is highly dependent on air temperature and humidity. Favorable conditions for radish infection and disease spread are daytime and nighttime moderate/cool temperatures of 20 °C and 10–15 °C, respectively, associated with high humidity (RH > 80%). The first symptoms are yellow or brown spots on the upper surfaces of cotyledons and mature radish

leaves, combined with white sporulation on the corresponding abaxial epidermis. These spots eventually become necrotic and the leaf dies. VD also affects radish roots, which develop black areas with H. brassicae sporulation, scarring and cracking, making them unsuitable for sale. Foliar protection is important as the roots are infected by conidia washed from cotyledons and young leaves (Figs. 1.31–1.37).

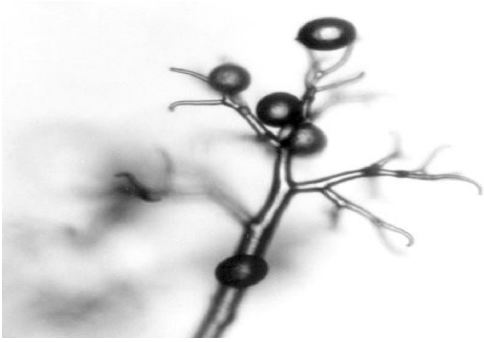

Figure 1.30 – Conidia of *Hyaloperonospora parasitica* [174]

V.P. Yagodkina [183] noted that cabbage crops are heavily affected by downy mildew. The disease causes the death of a significant part of the leaf surface of plants – the affected leaves curl and dry out. G.V. Boos and Z.V. Tymoshenko [175] note the great harmfulness of downy mildew in cabbage. By affecting blood vessels, the pathogen causes general damage to plants [176].

In the forest-steppe of Ukraine, in some years, vascular damage by the downy mildew pathogen was also observed on plants of winter cruciferous plant species. The development of the disease is facilitated by cloudy, rainy weather, when high relative humidity is created [177].

A.F. Salnikova [178] notices the rapid spread of downy mildew on cabbage in favorable conditions, which affects the entire array within a week. Spots appear on the affected plants that merge. The stems dry up and die. Leaves curl, dry out, branches break, the stomata darken and become covered with a grayish-white coating, the seeds become tiny, and their weight decreases sharply.

V.F. Peresypkin [188] indicates the lack of special research in the study of downy mildew of rapeseed.

The causative agent of downy mildew is *Peronospora brassicae* Gacéum, belongs to the class Oomycetes, order Peronosporales, family Peronosporaceae. It was isolated by E. Goiman [179] from a prefabricated form *P. pachestika.*

In the areas affected by *P. brassicae*, mycelium develops and spreads in the intercellular tissues of plants. The mycelium of *R. brassicae* is colorless, unicellular, repeatedly branched, develops intercellularly, and haustoria penetrate into the cells of the host plant, which absorbs the cell contents. At the same time, the affected cells of the host plant die along with the mycelium, but its branching is detected in neighboring parts of the plant [181].

The grayish-white coating on the affected plant tissues is conidia with conidiogenes, which come to the surface through the stomata one or two at a time from the underside of the leaf. The conidiophores are dichotomously branched and colorless. At their tops, ellipsoidal, unicellular, colorless conidia, 12–23 x 11–23 in size, are formed. Conidia size 250–450 x 6–9 μm [180].

During the growing season, the downy mildew pathogen is spread by conidia, which, after maturation, are easily separated from the conidia and transported in different directions by wind, water, insects or other means. Air movement in the summer is one of the main factors in the spread of the infection. Once in a drop of water, conidia germinate and form a hyphal process that penetrates the stomata into the plant.

Conidia formation occurs in the early morning in the presence of dew. They germinate at a temperature of 8–12 ^{0}C. The optimum temperature for the development of the disease is 10–15 ^{0}C [184–185].

In addition to conidial sporulation, rounded, 25–30 μm in diameter oospores with a yellowish mesh shell are formed in the affected plant tissues. Oospores are formed as a result of the fusion of oogonia and anisotrophs. They are covered with a double shell and lie deep in the tissues of the affected organ. The reason for the formation of oospores is unfavorable climatic conditions in the fall.

In the spring, overwintering oospores germinate into hyphal sprouts that infect young plants. Moisture is an important condition for oospore germination.

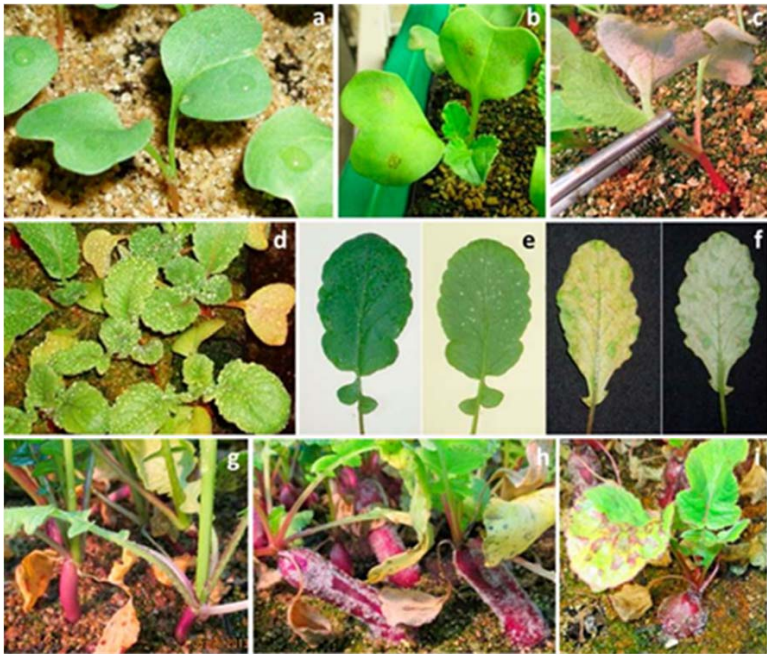

Figure 1.31 – Symptoms on plants of cruciferous species inoculated with H. brassicae at the seedling stage. Resistance: no host response and sporulation or slight necrosis on the adaxial surface of the cotyledon/leaf and root. Susceptibility: sporulation scattered over the entire abaxial surface of the cotyledon/leaf and root, or abundant and dense sporulation scattered over the entire cotyledon/leaf/root. a – Drop inoculation of cotyledons at 6-day intervals. b – Resistant cotyledons (class 1) 7 days (days after inoculation). c – Cotyledons of the pathogen sample – necrosis and lack of sporulation (class 1) 12 days. f – Adaxial and abaxial surface of a nonresistant sample with dense sporulation (class 6) 12 days. g – Daikon long red radish root of a resistant sample (class 1) 12 days. h – Long red radish root not resistant to damage (class 4) 12 days. i – Red round radish root not resistant to damage (class 4) 12 days [185]

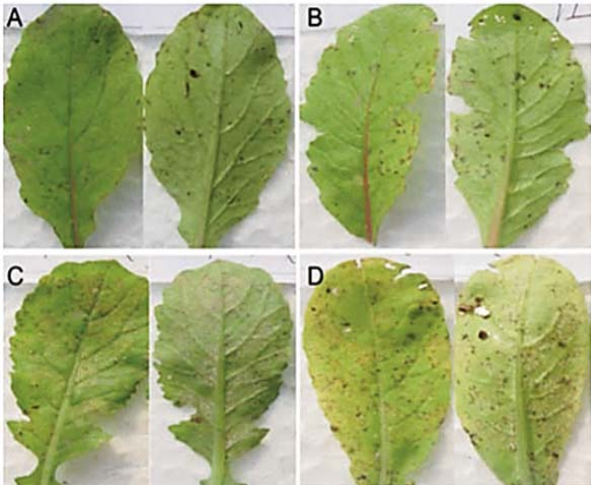

Figure 1.32 – Symptoms of a radish leaf inoculated with downy mildew spore suspension at the seedling stage. Resistance: no host response and no sporulation (A), or slight necrosis localized to the upper cotyledon/leaf surface (B). Susceptibility: sporulation is scattered over the entire lower surface of the leaf (C), or abundant and dense sporulation is scattered over the entire leaf (D) [181]

Figure 1.33 – Daikon leaf affected by downy mildew [182]

Figure 1.34 – Stem of an oil radish seed plant with dark downy mildew lesions [192]

Figure 1.35 – White sporulation inside necrotic lesions on radish seed pods [192]

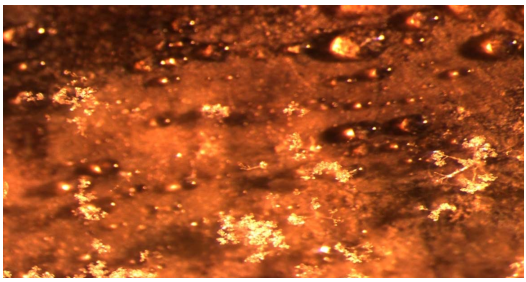

Figure 1.36 – Downy mildew spores forming on daikon stems, with magnification [192]

Figure 1.37 – *Hyaloperonospora brassicae* on wild radish; A-C: Symptoms and signs on stems and stems and inflorescences, D: Sporangia with sporangia, E-F: Sporangia. – Bars = D = 50 µm, E-F = 20 µm [183]

Oospores are preserved in plant debris. However, some authors disagree with this statement. Thus, according to V.K. Kupriyanova [186] *P. brassicae* cannot overwinter in the form of oospores on plant debris in the soil. She argues that the primary damage to plants occurs by mycelium, which is stored in the shell of the affected seeds. A number of authors confirm this opinion. They report that 10% of affected cabbage seedlings with downy mildew were obtained by sowing diseased seeds in boxes with sterile soil. But Anisimov [187] rejects the possibility of transmission of downy mildew by seeds. When the affected seeds were harvested and sown in disinfected soil, the cabbage seedlings were not affected by the disease. Research by F.W. Wang [188] was proved that *P. brassicae* is an obligate parasite, very sensitive to light, which acts on the fungus through the plant, and that high humidity is less important for the emergence of the disease compared to light.

The study of the resistance of new varieties and hybrids of cruciferous plant species to downy mildew is one of the top priorities. In his research

conducted in an artificial climate, Johnson R. [189] studied the resistance of different varieties of cruciferous plant species to downy mildew. Resistance was determined by the degree of damage to cotyledons in the germination phase, with artificial infection of plants with the pathogen downy mildew. Such winter cruciferous plant varieties as Vestal, Dippes and FON-Rehbers showed high resistance to the disease, while Metador and Margot were not resistant. In experiments conducted in 1964, 1965 and 1968, high resistance to downy mildew was found in the Report variety. Such experiments make it possible to assert that there are great opportunities for breeding work with winter rape in order to obtain varieties resistant to downy mildew.

The study of the impact of downy mildew and other major diseases on rapeseed was conducted by the National Agricultural Institute of Botany in England [190]. It has been noted that a number of cruciferous plant varieties have resistance genes against downy mildew.

In order to protect cabbage and other cabbage crops from downy mildew at different times, different authors have recommended separate measures. Dorogin S.N. suggested that the seeds of cruciferous plant species should be treated with a formalin solution (1:300) to prevent downy mildew infection, as well as to destroy plant residues and preventive spraying of plants with a 1% solution of Bordeaux liquid. A.F. Salnikova [202] given that the pathogen can overwinter in the form of oospores in the tissues of the affected organ, she recommended destroying plant residues after harvesting cruciferous plant species by plowing to full depth with a plow with a skimmer.

V.I. Timchenko [191] against seed infection recommends heat treatment of seeds in water at a temperature of 48–500 C for 20 minutes with subsequent cooling. In his opinion, it is advisable to spray vegetative cabbage plants with a 1% solution of Bordeaux liquid.

E.D. Vasylieva [192] against downy mildew of cabbage studied the effectiveness of polycarbacin and copper chloride at 0.5% concentration. In the variant where plants were treated with polycarbacin, the disease practically did not develop. The quality of the seed yield increased in the treated cabbage plants. Similar results were obtained when spraying winter cruciferous plant species with polycarbacin at 0.4% concentration [193].

A study of the effectiveness of chemicals against downy mildew on cabbage crops was conducted in the United States. Researchers studied various systemic fungicides on cabbage against downy mildew. The most effective was a systemic fungicide with the active ingredient dimethyl gylnenil and methoxy cetyl alanine methyl ester.

According to Jonson (1994) [194], on partially resistant oilseed rape material to the pathogen peronospora, necrosis was detected on the back of the leaf with minor conidia formation, and only a small number of very susceptible lines affected most of the leaves during the flowering period; this level of susceptibility reduced the yield [195].

When pods are affected by P. brassicae, the weight of 1000 seeds decreases in winter rape by 1.5 and in spring rape by 1.6 times; seed oil content – by 10.8–16.9%, respectively. The content of palmitic acid in oil from seeds of affected winter rape increases by 1.4 and spring rape – by 0.6; stearic acid – by 1.4 and 1.2; linolenic acid – by 3.5 and 1.8; erucic acid – by 2.0 and 0.4; eicosenic acid – by 1.0 and 1.4%, respectively. The content of oleic acid, respectively, decreases by 7.9 and 4.2; linoleic acid – by 1.4 and 1.2% [196].

The disease manifests itself in the spring, more often 8-10 days after germination on the cotyledons and the first leaf of spring rape. Brownish-green, yellow blurry spots appear, on the underside of which a weak scattered coating develops, at first it is white, and then acquires a gray-purple hue [197]. Individual spots have an angular irregular shape with a darker border, equally visible on both sides of the affected leaves [198]. Later it spreads to all new leaves of adult plants. According to N. Hornig (1979) [199], young leaves of rapeseed plants are affected by downy mildew only occasionally, and according to Anderson and Olsson (1961) [200]. In the later stages of rape plant growth, the impact of the pathogen conidia is limited to old leaves. As a result of the merging of spots, large areas of damage occur, the leaves turn yellow prematurely, dry up and fall off. Due to a decrease in the assimilation surface of the leaves, the plants grow more slowly and lag behind healthy ones. The disease on young plants is manifested by deformation of the leaf blade.

Spots also form on the stems and pods. They are round or elongated, light brown, slightly depressed, and in wet weather their surface is covered

with a white and later light purple coating. In case of severe damage, the pods are underdeveloped and sometimes do not form seeds.

In the spring, pathogens multiply well in the following conditions: alternating long cold, highly humid periods with warm, moist ones. In the main cultivation areas, dry weather occurs in the 2nd half of the growing season and the development of the disease stops if the cool weather persists, the mycelium moves from the leaves to the inflorescences and greatly reduces seed setting. The infection is spread by spores that are in a drop of water and enter the tissues through the closing cells of the stomata. The causative agent of this disease has races that differ in aggressiveness, but, in general, the development cycle of downy mildew is not yet well understood [201].

Optimal conditions for the development of downy mildew are 10–15 °C in rainy or very humid weather. Development slows down or stops when the weather is warmer and drier.

Optimal conditions for the spread of *P. parasitica* spores are 5–15 °C and relative humidity of 90-98%. This temperature is optimal for infection, however, infection occurs only at a relative humidity of 98% or more [209].

According to [201], conidia germinate at 8–12 °C, and plaque is best formed at 10 °C, usually at night or early in the morning when it is dewy. It is believed that the causative agent of downy mildew develops best at low temperatures of 8–16°C, in humid air and low light. According to N. Hornig [212], under optimal conditions for plant growth, it is unlikely that they will be affected. Under unfavorable growth conditions, the pathogen causes only periodic growth inhibition.

It should be noted that the same plant species are affected differently by pathogen strains collected from different ecological and geographical zones.

In winter, the infection persists in the affected plants: residues in the form of oospores, which in spring are the primary source of infection of rapeseed. It is indicated[128] the possibility of overwintering of the fungal oospores in the upper soil layer. The fungus can be located in the form of mycelium in the seed coat of rapeseed. However, more often the mycelium is preserved on wintering winter rape plants. In the spring, conidiophyte carriers with conidia are formed again on this mycelium, carried by wind and rain drops. The conidia are used to infect plants in the spring. Thus, the type of infection with this pathogen is aerogenic-droplet.

The causative agent of sclerotinosis, or white rot, is the marsupial fungus Sclerotica sclerotiorum (Lib.) de Vagu (Syn: *S. libertiana* Fuckel, *S. kaufmanuiana* Tichomirov, *S. varians* Pers., *S. ovatum* Schum., *S. brassicae* Pers., WetzeUnia sclerotiorum (d. By.) Korf et Dumont), which parasitizes more than 300 plant species belonging to 64 families of monocots and dicots in addition to rapeseed [153].

Sclerotinia sclerotiorum is a disease found everywhere. Its causative agents are pea-sized sclerotia lying in the soil at a shallow depth. They develop above-ground saucer-shaped reservoirs with spores (apothecia). Sclerotia germination and apothecia formation depend on soil temperature and moisture. From the end of April to the beginning of May, spores are released from the apothecia and carried by the wind over short distances. They are not allowed to spread to neighboring fields. The disease starts from the leaf bed (Figure 1.38–1.40).

The disease occurs on all cruciferous crops, often developing in foci. Young plants are not affected by sclerotinia. On adult plants, signs of the disease appear as watery spotting at the base of the stem, near the soil surface. The growing spotting causes semi-mildewy rot on the lower, aging leaves In wet weather, the tissues soften and rot, and then become covered with a dense, white, cotton-like coating. Large, hard, black sclerotia appear on the fungus coating, in the core of the stem. In dry conditions, the spotting on the stems is dry, light, and has a characteristic concentric structure. Plants affected by sclerotinia often break down and die. Yields from the remaining plants are very low.

Figure 1.38 – Signs of rape sclerotinia in drought conditions [96]

Figure 1.39 – Rapeseed stalks affected by sclerotinia [96]

The fungus Sclerotinia sclcrotiorum (Lin) DeBy forms black, rough, hemispherical, often glued sclerotia. Disk-shaped, light white apothecia are formed on them, containing cylindrical club-shaped asci with 8 unicellular, ovoid ascospores in each.

The pathogen persists for a long time in the form of mycelium or sclerotia in plant debris and soil, without losing its viability. Sclerotia germinate with mycelium, which infects plants. In wet weather and in the light, sclerotia form apothecia with ascospores, which, when released into the soil, give rise to mycelium, which develops saprotrophically and infects plants.

The disease is most pronounced when cruciferous species are grown monoculturally, on fertile, cold or moderately warm and moist soil. The optimum temperature required for infection is 15–23°C. Favorable conditions for the development of the disease are created in crops with a high planting density.

According to the currently existing classification, the fungus S. sclerotiorum de Vagu belongs to the higher fungi, class Ascomycetes, subclass Euascomycetidae, group of orders Discomycetes, order Helotiales of the family Sclerotiniaceae, genus Sclerotinia Fuckel. In Australia, another stem rot pathogen affecting rapeseed, *S. minor*, has been described [202].

In the UK, severe damage to winter oilseed rape by stem cancer was first observed in 1977–1978 in eastern England [203]. Crop losses reached 50% [204]. In the 80s, the disease was noted every year, but, in general,

not with a very high intensity [205–207]. Sclerotinia increased in the late 70s in Europe due to the rapid growth of rapeseed areas and shortened crop rotations [208].

The increased risk of severe white mold damage to canola in the UK is due to the growing area under the crop, the inclusion of other susceptible crops in the rotation and the growing financial pressure on farmers to plant canola more often in the same field [209]. During the survey of rape in 1986–1990 in the UK, sclerotinia was noted on less than 12% of the fields, and the disease was recorded mainly in the south-east of England [153].

The increase in sclerotinia damage in France is associated with an increase in the area under rapeseed and the inclusion of other susceptible crops, such as sunflower and legumes, in the crop rotation [210]. In northern Germany, rapeseed yield losses due to stem rot reached 50% [211].

Winter rape sclerotinia is the most frequent and damaging disease of rape in Belgium. The disease leads to uneven maturation of plants, difficulties in harvesting and sometimes a decrease in yield by more than 1 t/ha [212].

In Poland, stem cancer was first described in the late 70s [213]. The disease has spread rapidly across all regions; countries that grow rapeseed [214–216].

Commercial production of rapeseed in the southeastern United States began in 1989. The most harmful disease is the stem end rot. In the first year of canola cultivation in some areas, the incidence was 30–50%, in subsequent years it approached 100% [217].

When pods were damaged by *S. sclerotiorum*, the weight of 1000 seeds decreased in winter rape by 2.9 and in spring rape by 2.2 times, seed oil content – by 22.6-23.9%, respectively. The content of palmitic acid in the oil increased by 4.1 and 1.2; stearic acid – by 2.6 and 1.7; linolenic acid – by 4.0 and 3.6; erucic acid – by 5.0 and 5.9; eicosenic acid – by 2.6 and 4.2%, respectively. The content of oleic acid, respectively, decreases by 16.9 and 12.0; linoleic acid – by 1.4 and 4.6% [153].

White rot manifests itself on stems, leaves, flowers, pods in the form of mucous wet spots, which are later covered with a thick cotton-like white coating; in dry weather, the coating disappears, the affected tissue becomes discolored, soaked, diseased leaves die, and stems and stalks usually do not develop or are underdeveloped. All plant organs become discolored, hence the second name of the disease – white stem rape. In the affected areas,

black sclerotia are formed on the surface and inside the stem and pods, often similar in size and shape to rapeseed seeds. In case of early infection of the stems in the area of the root collar, the plants dry out [109].

The first wave of the disease is in the rosette stage, when infection occurs as a result of mycelial germination of sclerotia through contact of leaves with the soil [98].

Sclerotia of S. sclerotiorum in the soil layer (3–5 cm) germinate in April with the formation of apothecia. This occurs under moist conditions and soil temperatures of 6–10 °C; apothecia do not form in dry conditions. If a long dry period follows the formation of aphotocysts, they dehydrate, shrivel up, and produce few or no spores.

The period of existence of the aphothecia coincides with the peak of flowering. Spores are released in dry weather and light winds, cloudy and rainy weather makes it difficult for spores to escape [218].

Figure 1.40 – Sclerotinia or white rot (the causative agent is the fungus *Whetzelinia (Sclerotinia) sclerotiorum)* [96]

Ascospores germinate at 20 °C in the presence of droplet moisture and 94% relative humidity or without droplet moisture but with 100% relative humidity. at high humidity – 21 hours. Spores do not germinate at a relative humidity of 84% and below, even in the presence of dripping moisture. However, heavy rains are undesirable, as ascospores are unable to be released or washed away by the soil [81].

S. sclerotiorum infection of rapeseed stems is caused by petals that are infected first, falling on the stem or in the leaf axil and serving as a source of food for germination of ascospores. Ascospores that fall directly on the leaf surface do not develop and die. The appearance of signs of damage depends on the temperature: after 5 days at 15 °C and after 14 days at 5–8 °C [219].

During white mold infection, the pathogen produces large amounts of the necrosis-forming toxin oxalic acid [220].

Tolerance and barriers to permeability of the toxin in the organs of rapeseed plants are related to its mode of action and the structure of the host leaves [221].

In the UK, there are two main epidemiological phases of the disease, the first of which occurs in May and is associated with winter crops, the second occurs 4–6 weeks after the first and is associated with spring crops [222].

The source of infection is sclerotia of the pathogen in plant residues and seeds (as an impurity). Sclerotia can persist in soil for up to 8 years [153].

The number of sclerotia in the soil increases significantly after a severe pathogen damage to sensitive crops and decreases under conditions unfavorable for the development of the disease, and the half-life of the pathogen in these cases is approximately 2.5 years. The formation of aphoticia on winter rape is greatest when plant residues are crushed in the field in the previous season. The emergence of aphotic plants is accelerated by cultivating the crop without plowing with minimal tillage and is delayed by the spring application of a large dose of fertilizer [109].

Under conditions of high atmospheric humidity and high soil moisture, gray rot can occur on rapeseed. Damage is concentrated at the base of the stem in the form of light watery spots. Under favorable conditions, the disease can cover the entire young plant, including the top, causing it to rot. All affected plant tissues are covered with a delicate, gray, spore-forming coating of the fungus. During a drought, the disease dies down, the stems break at the site of damage, and the plant dies. Harvesting is complicated

and is accompanied by high losses. The fungus Sclerotinia fuckeliana De By has a conidial stage Bonyiis cinerea Pers. that develops bundles of large, branched sporophytes, on top of which, on swellings, ovoid, unicellular conidia are formed. Many small dark-colored sclerotia are formed on the mycelium. Apothecia with elongated mace-like asci and 8 ellipsoidal unicellular spores in each are formed on the sclerotia.

The pathogen persists in the form of mycelium and sclerotia in the affected plant residues, on which in spring a dense spore-forming coating of the fungus with conidia is formed, which carry out secondary infection during the growing season.

The causative agent of phomosis, or dry rot of cabbage, is the fungus *Leptosphaeria maculans* (Desm.) Ces. et. De Not (class Ascomycetes, subclass Loculoascomycetidae, order Pleosporales, family Leptosphaeriaceae, conidial stage Phoma lingam (Tode) Desm. – class Deuteromycetes, order Sphaeropsidales, family Sphaeropsidaceae) [223].

Phomosis is a long-known and widespread disease on cabbage crops. Phomosis was first described as a harmful disease of cabbage in 1849 in France, and was discovered in Germany as early as 1791 [224–225]. In France, during 1976–1979, widespread spread of the disease was also observed on winter cruciferous plant varieties. Depending on the weather conditions, phomosis in some years caused great damage to cabbage crops, especially in areas of high humidity and moderate temperature during the growing season [153].

In Ukraine, the massive appearance of phomosis on crops of cruciferous plant species was registered in the early 80s. The most intense damage to plants was observed in 1988, 1990, 1995, 1997, 2001, 2007, 2011, 2014 and 2019, which were very similar in terms of agroclimatic conditions and characterized by moderately warm and humid autumn, mild and short winters with significant changes in thermal conditions at the end, early spring, and significant precipitation during budding and flowering [227] (Figs. 1.41–1.42).

Phomosis on cabbage crops manifests itself from germination to pod ripening, i.e. throughout the growing season. First, discolored areas appear on the seedlings of cruciferous plant species. Then discolored small dots become visible on the plant tissue – these are pycnidia. In a day, the latter turn brown, the tissue is torn, and the spores are sprayed. The affected area of the cotyledon turns into a natural phomose burn. On diseased seedlings,

a narrow ulcer of 1-3 mm of dead epidermal cells forms along the stem. The tissue becomes discolored, colorless pycnidia are formed under the epidermis, which rapidly increase in size and darken in 1–2 days. On the 7–10th day after the disease onset, the plants lie down. On adult plants, phomosis appears as gray dry spots. Often solid areas of affected leaf tissue are formed. The spots are oval in shape with a purple border. Dark dots – pycnidia – are clearly visible against the gray background. Around the spot, the leaf tissue turns yellow. On the stems directly at the attachment points of leaf petioles, the affected tissue becomes rotten and the plant dies. Stem damage at the soil surface level is often called root cancer or root neck necrosis. Plants are stunted, acquire a chlorotic or bluish color, and often most of them wither and die [87].

The root system of adult plants is often affected in the form of dry rot. This phenomenon is especially common on cabbage. The affected root looks like a chopped off piece. Over time, the tissue becomes slimy and softens, and the vessels become woody. A plant with such a root becomes anthocyanin-colored. The lower leaves dry up, while the upper part lives on for a long time. Spots in the form of elongated brownish ulcers form along the pods. The affected pod often contains diseased seeds. It is believed that the most dangerous period for pod infection is the flowering phase. The disease develops before the pods are formed. Affected pods are underdeveloped, deformed, crack prematurely, seeds spill out [208].

Figure 1.41 – Rapeseed stalks affected by phomosis [96]

The harmfulness of the disease is manifested in the thinning of seedlings, which is caused by the death of young seedlings. Premature death of diseased leaves leads to a decrease in the assimilation surface of cruciferous plant species, resulting in a decrease in the weight of 1000 seeds, and deterioration of the fodder quality of green mass [228].

When sowing affected vegetable seeds, seedlings with signs of phomosis on the root collar or cotyledons are formed. With severe damage, the seeds do not germinate. The yield shortfall can be 50% or more [229].

By research [55] was found that the harmfulness of phomosis depends on the source of infection, its size, and environmental conditions. Seeds can be infected when threshing affected cabbage plants. Such sown seeds produce seedlings affected by phomosis by 43–82%.

The foliar form of phomosis is also dangerous. Single spots from the affected leaves are carried by the wind to healthy areas. Affected plants are stunted and many of them die. Research has shown that early and late sowing of vegetable crops is more severely affected by phomosis compared to the optimal sowing time [230].

Thickened crops of cruciferous plant species are more severely affected by phomosis than optimal ones, since the intensity of plant damage is correlated with the diameter of the stem. The thinner the stem, the more severe the phomosis [243].

In the spring, damaged plants of winter cruciferous species are much more severely affected by harrowing than without harrowing. To a certain extent, the placement of cabbage crops plays a role in reducing the damage caused by phomosis. It is advisable to place cabbage crops at a distance of 1000 meters from each other [231]. Interesting studies were conducted by researchers N.A. Naumov [174; 232], Burkhina E.K. [233] on cabbage seed crops. Severely affected cabbage seedlings planted in the ground died early. And the slightly affected ones developed poorly. Pre-sowing treatment of cabbage seeds reduced the spread of diseases, including phomosis [234].

The causative agent of phomosis has a mycelium that is articulated, whitish, sometimes dark brown, 2–8 microns thick. Due to the accumulation of nutrients, fruiting bodies – pycnidia – are formed in the places of interweaving of mycelial hyphae. The surface of the pycnidia is spherical, with a thick sclerotial membrane. Pycnidia have a convex pad at the base and a crescentic cavity at the top. They range in diameter from

45 to 390 microns in the form of dark dots on the surface of the affected organ. In the middle of them, small, 1.7–2.4 x 4.2–5.6 μm, unicellular, colorless, ovoid or elongated cylindrical pycnospora develop. When ripe, at high humidity, pycnidia secrete pinkish-purple mucus with pycnospores. The latter, once on the plant, form a seedling that penetrates the tissue and infects it. The fungus can grow at temperatures from 2 to 40 ^{0}C. Low temperatures of 2–6 ^{0}C delay development, the optimum temperature is 20–25 ^{0}C.

In addition to pycnidial sporulation, phomosis develops in the form of perithecia, in which bags with baggies of asci are formed. Perithecia are rounded, 360–500 microns in diameter. The ascospores are colorless, have 5 membranes, 4–9 x 30–70 μm in size. In the marsupial stage, the fungus is called Leptoshaeria maculans Ces. De Not. Under natural conditions, the mycelium develops between and within the cells of plant tissues. The affected plant tissue dies, and gray spots with dark dots form.

A.F. Salnikova found that when seeds and leaves of all cabbage crops are artificially infected, cabbage is most severely affected, followed by rapeseed and other crops. When seeds are artificially infected, the first sign is the formation of necrosis with pycnidia on the seedlings [59].

According to a number of researchers, the pathogen can penetrate the host plant only through damaged tissue. However, it has been established that pycnospora, once on healthy tissue, can also damage it Under optimal conditions of 21–25 ^{0}C and sufficient humidity, the incubation period is 7–8 days. Pycnidia appear only at a relative humidity of 60–90% [118].

When plants are artificially sprayed with a solution containing pycnospora during the flowering period, the pods are severely damaged. The fungus penetrates through the stigma of the pistil. The first signs are detected at the lower end of the pods and at the base of the pedicels. The analysis of the seeds obtained from the affected pods shows that about 84% of the seeds are brown, the rest are underdeveloped [153]. Diseased seeds from affected pods of cruciferous plant species are not suitable for sowing without treatment. The phomosis pathogen can persist in the soil for up to 3 years. Seeds can also be a source of infection [92].

Phomosis is spread during the growing season of rapeseed plants by wind, rain, insects, including aphids.

The disease occurs on all types of cruciferous plants. The entire aboveground mass is affected – cotyledons, leaves, stems, peduncles, seeds. On the seedlings, the disease symptoms develop in the form of a black pedicel or light brown spotting on the cotyledons, which gradually covers the plants to the top and causes their death The most characteristic signs are manifested on the root collar, which is necrotic and often cracked. On the stems of older plants, a brown, dry stripe develops from the underground part to the base of the lowest spreading leaves. Affected plants turn yellow and wilt, and their external signs are similar to those of a burn. In case of early infection, the plants die, and in case of late infection, they produce very few seeds. Sometimes large gray-brown spots 1–1.5 cm in diameter, covered with small black pycnidia, form on the leaves. Gray-brown ellipsoidal spots with a dark border appear on the testes. Affected peduncles are deformed, cracked and form small seeds covered with black dots, from which pink exudate is abundantly released in wet weather. The presence of black dots (pycnidia) on all affected parts of plants is a distinctive feature.

Pseudothecia of the fungus are black and hemispherical. Ascospores are yellow-brown, filamentous, with 5 transverse septa. Pycnidia are dark brown or black, of various sizes. Pycnospores are hyaline, unicellular.

The fungus overwinters in infected plant residues and infected seeds, where it remains viable for up to 4–7 years, depending on storage conditions. Pseudothecia with ascospores formed on overwintered plant debris carry out primary infection. The pathogen is spread by conidia through rain drops, irrigation water, wind, soil, insects or mechanical contact.

Conditions for the development of the disease. The causative agent of phomosis is a relatively weak pathogen that develops strongly in monoculture cultivation of cruciferous crops on waterlogged soils, at high air humidity (over 70–80%), temperature 21–25 ^{0}C and mechanical damage to the sprouts.

Isolates of Phoma lingam from oilseed rape can vary greatly in aggressiveness and therefore they were divided into two groups: aggressive (A) and non-aggressive (NA). On certain media, NAs have much faster mycelial growth and color liquid cultures, and in liquid culture they produce the host-specific toxin syrodesmine. Both groups also differ in the isozymes of pectinase, malate dehydrogenase, and glucose phosphate isomerase. There are differences in the morphology of their pseudothecia,

ascospores released from their pseudothecia germinate differently. These and other differences have led to the suggestion of a new species name for NA isolates, for which the designation NAV *L. biglobosun* is proposed for possible further intraspecific differentiation, and for A isolates – *L. maculans* [235].

It is assumed that syrodesmine, as a host-independent phytotoxin of *L. maculans*, can contribute to the increase in the areas of damage caused by the pathogenic fungus [236].

In studies of virulence types of *L. maculans* in rapeseed fields, a highly virulent type was found in all studied rapeseed tissues, and a weakly virulent type was present only in leaf tissues [237].

The new species of L. biglobosum differs from the aggressive dry rot pathogen *L. maculans* by the toothed disk-shaped ascocarps with enlarged apices. Ascocarps of both species were produced on canola stems when inoculated with compatible strains of Phoma anamorphs or isolates from individual ascospores at distances of 1 cm with further co-growth. Both species showed bipolar heterothallism. Of the Leptosphae species with 5-septate ascospores infecting cabbage, none fit the characteristics of L. biglobosum. The species *L. lindqnistii* on sunflower had ascospores with 1, 2, rarely 3 septa, but also had as an anamorph Phoma [238].

Aggressive and non-aggressive isolates of *Ph. lingam* behave neutrally when combined sexually [239].

Ph. lingam produces a number of secondary metabolites, including phytotoxic ones. Recently, unique isolates of the pathogen, Leyard-2 and Meifei-2, have emerged in western Canada that are neither highly nor weakly virulent. This new group of isolates is virulent to B. juncea, a species traditionally resistant to blackleg, and poses a new threat to high quality canola lines. The profile of secondary isolates was obtained. The new group requires a separate classification. Its phytotoxins and secondary metabolites and their biosynthetic pathways are being studied [240].

Ph. lingam has a very wide range of host plants from the cabbage family [241]. Field mustard is a host of highly virulent forms of stem cancer pathogens [242].

In the case of artificial infection, rapeseed was susceptible to *Ph. nigricans* isolated from a widespread weed often associated with rapeseed – field bentgrass (*Thlaspi arvense* L.), so this pathogen poses a

potential threat to rapeseed [243]. Strong phomosis damage is observed in regions with intensive rapeseed production [244].

In 1966–1967, phomosis led to large crop losses in France and became a major disease in England and the Netherlands [245]. French linear varieties Oleopus, Titus, Tonus proved to be highly susceptible to phomosis during the epiphytotic epidemic of 1966–1967 [246].

In Australia, due to the severe defeat of phomosis in the early 70s, rapeseed cultivation almost stopped [247–249]. In the areas of intensive cultivation of winter rape in northern Germany, the most harmful disease of this crop was phomosis [250].

Large yield losses of spring rapeseed due to phomosis noted in Canada [251], osses due to the shortfall in rapeseed harvest as a result of the disease annually exceed $ 30 million [252].

On a global scale, phomosis, or stem cancer, is the most harmful disease of rapeseed [253–256]. One percent of infected seeds can cause epiphytosis. There is a high degree of correlation between the number of spores and the level of damage and reduction of rapeseed yield [257].

Phomosis occurs both on seedlings and on adult rapeseed plants. On the hypocotyl of seedlings, as well as on the cotyledons, various shapes of watery spots are first found, which later dry up and become light gray or ash-colored. Scattered dark dots – pycnidia of the pathogen – can be seen in the lesions. In older plants, the lower part of the stem blackens, and phomosis at this stage initially resembles a black leg, but it does not cause continuous blackening around the stem. Over time, the bark of the stem in this area lightens and turns gray. The affected tissue is covered with dark dots – pycnidia of the pathogen.

The stems dry out, become rotten, and the plant dies. With the later development of the disease, it manifests itself on the stems, usually at the base in close proximity to the axils of the petioles of the lower leaves, in the form of ulcers. With this manifestation on the stems, the disease is called stem cancer. The ulcers are oval in shape, slightly depressed, light brown to gray in color, often surrounded by a purple border. They can slowly grow and completely cover the stem. Stem damage at the soil level (root canker and neck necrosis) often spreads to the root system, causing black sores and root dry rot. Plants are stunted, acquire a dry chlorotic or bluish color, often lie down, and most of them wither and dry out. Phomosis develops

on leaves and pods in the form of gray dry spots, on pods they are slightly depressed, often with concentric zonation. Black pycnidia are clearly visible on the surface of the spots. In addition to localized damage, there is a diffuse development of the pathogen in plant tissues, in its disease is asymptomatic. During the growing season, the pathogen is spread by pycnospora and sumkospora [88].

It is assumed that in the field, phomosis infection occurs through damage, with plant sap stimulating the development of the fungus and, accordingly, promoting infection [258].

Rapeseed phomosis increases when damaged by insects (*Psylliodes chrysocephala* and Ceutorhynchus spp.) [8]. The maximum ascospore summer of L. maculans is observed in September. This is when 60–70% of ascospores are released. The number of flying spores is regulated by precipitation and temperature. Ascospores and pycnidiospora of *L. maculans* germinating on the surface of rapeseed leaves are introduced into its tissues through stomata without the formation of apsorias – 'intercellular' hemi-biotroph [259].

Most often, *Ph. lingam* is found in rapeseed varieties containing low amounts of erucic acid. Pathogenesis is facilitated by 100% relative humidity or dripping moisture on plants. Fomites are caused by excessively early sowing of winter rape and late sowing of spring rape. The intensity of phomosis damage increases in thickened crops [101].

Figure 1.42 – Phomosis (The causative agent is the fungus *Phoma lingam*) [96].

The pathogen overwinters in the form of mycelium and pycnospores on the leaves of winter rape, in the form of pycnidia and pseudothecia on plant debris and mycelium in infected seeds [19].

It is noted that one of the most serious diseases of spring rape is *Fusarium wilt* (Figure 1.43). The disease manifests itself on rapeseed plants at all stages of crop development. Symptoms can be observed on cotyledon leaves and leaves of the lower tier, then spreading to the growth point. The disease is intense during the period of emergence of seedlings before the formation of true leaves, then it dies down and is restored again and increases during the budding, flowering and until the end of the rapeseed growing season.

Fusarium wilt (caused by *Fusarium oxysporum* f. sp. conglutinans Schlecht,: Fr.), which occurs on many species of the family Brassicacae [260]. *F. oxysporum* is characterized by the presence of specialized forms dedicated to certain host plant species and physiological races affecting individual varieties of these species [261]. Three specialized forms have been described on species of the cabbage family: *F. oxysporum*.sp. conglutinans infects cabbage (*Brassica oleracea*) and is represented by two races (Foci and Foc2); *F. oxysporum*/.sp. matthhli infects levkoy (*Matthiota incand*) and is also represented by two races (Foml and Fom^2); *F. oxysporum*, sp. Raphani 28 (For) infects radish (*Rafanus sativus*), races not described (Figs. 1.43–1.45).

The disease first appears as small yellowish spots, which then grow larger and cover the entire leaf. When the leaf is viewed in the light, a reticulation is revealed. Then the leaves lose their turgor, dry up and fall off, and young plants die. Plants that get sick in the early stages of development, with a slow course of the disease, are characterized by shortened internodes. The growing new leaves of the upper part of the stem in the chronic course of the disease have a corrugated appearance (Figure 1.45). Leaves fall off on plants that are infected during the budding phase, and buds, flowers, and stems dry out. If the plant dries up during the fruit formation phase, it dies before harvesting, and the stem of such plants has a dark color.

Lightning blight usually occurs in the middle of summer or at the end of the growing season. The leaves on such plants lose their turgor without changing color, hang down, there is no characteristic reticulation, and the plant dries quickly. A distinctive feature of the disease at all stages of rapeseed development and with different disease progression is the browning of the stem wood, which is detected during cutting.

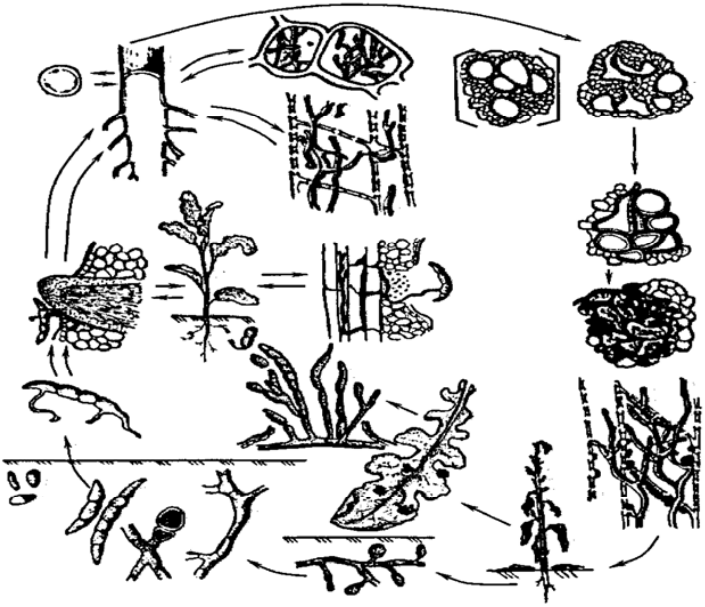

Figure 1.43 – Biological and infectious cycles of Fusarium oxysporum, which causes wilt of rapeseed [262]

Established [263], that *Fusarium oxysporum* usually overwinters as chlamydospores (thick-walled dormant spores) in the soil or on infected plant debris. Two other types of spores are also produced – macro- and microconidia. The spores germinate and penetrate the roots directly or through cracks created by new lateral roots by the expanding mycelium.

Figure 1.44 – Signs of *Fusarium wilt* in rape [264]

Figure 1.45 – Leaf chlorosis on rape leaves caused by *Fusarium wilt* [96]

Figure 1.46 – Rapeseed pods affected by *Fusarium wilt* [96]

Under conditions of moisture deficit, the symptoms will be more noticeable and easier to detect. Look out for these symptoms: yellowing, wilting, and dark brown or black discoloration of the vascular tissue, often seen on only one side of the stem or on branches, known as unilateral striation. Some plants may have orange-pink discoloration at the base

of the stem. Plants with a minor infection may also mature prematurely and be prone to shedding. There may be symptoms of plant cell or tissue death, discoloration of blood vessels, poor seed set, and premature drying. Stems and branches turn brown, but plants remain upright with intact roots. There are no visible lesions on the stems and roots. Plants are often stunted and have small pods without seeds.

The pathogen then infects the vascular tissue, which becomes discolored and clogged. The fungus produces microspores that move up the stem. The blockage of the xylem prevents water from moving up the stem, which leads to wilting of the plant. Spores also form on the above-ground parts of plants, which fall to the ground and re-infect the soil. Sometimes the seeds become infected through the vascular tissue, but usually the seeds die before this can happen. Fusarium oxysporum persists in the soil for a very long time, with spores lasting for more than 10 years. The pathogen is transported through the soil by wind, water flows, or on equipment.

Any conditions that cause stress to the plant increase the risk of infection. Fusarium wilt is influenced by environmental conditions, especially soil temperature and moisture. Warm temperatures above 16°C favor the development of the disease. Dry soils are favorable for the development of the disease. Factors that reduce root growth rate increase the plant's susceptibility to Fusarium wilt. Early planting in cool, moist soil contributes to the development of the disease.

According to the researchers, *F. oxysporum* isolates belonging to different specialized forms are genetically isolated, as each specialized form corresponds to a specific group of vegetative compatibility and a characteristic electrophoretic type of isozyme polymorphism.

The causative agent of Fusarium wilt of rapeseed, according to [8; 153], is no longer a highly specialized pathogen of *B. napus*, but is capable of infecting other members of the cabbage family. Based on the reaction of differentiator samples, it can be attributed to the cabbage-specific form, F. oxysporumf. sp. conglutinans. Genetic relatedness of isolates from different cabbage species virulent to rape is confirmed by the fact that they are vegetatively compatible. The strains tested on cabbage varieties with different resistance proved to be a race.

The damage caused by the disease depends largely on the time of its manifestation. Plants affected in the early stages of development (before

flowering) do not form a crop at all. When the disease develops in later stages, the number of pods, seeds per pod and weight of 1000 seeds decreases by 27–43, 20–35 and 28–37%, respectively. Fusarium losses due to attacks in the germination and rosette phases are partially compensated by the more powerful development of the surviving plants and an increase in their productivity. The largest yield losses are associated with rapeseed damage at the beginning of flowering. In production crops, there are usually only a few diseased plants. In the case of crop loss, there is no economic impact. However, the number of affected plants increases significantly when reseeding rapeseed [267]. The disease is found on young and adult plants. In the rosette and stemming phase, the leaves wither and the plants die. When the disease appears in later stages, in addition to symptoms on the leaves, there is damage to individual conductive bundles, which is manifested in the lightening (light green, then yellow color) of a part of the central stem, made above the damage, at the border of the bark and wood due to the penetration of the pathogen into the xylem vessels. There is no maceration of the bast, it only dries to the wood [268].

Plants that get sick during budding or flowering abruptly lose their turgor, the flower cluster droops, the stems dry out, become brittle and easily pulled out of the soil. Small underdeveloped pods may also form, and premature ripening occurs. In wet weather, a pink mycelium coating forms on the lower part of the stem of dried plants [269].

The disease is usually focal and spreads radially during the growing season. Fusarium can also manifest itself in an acute form, causing plant death within 2–3 days. Infection of plants occurs through the epidermal cells of the root sheath. The mycelium spreads through the vessels to the stem and leaves and is located along the walls of the vessel, in the intercellular spaces and sometimes enters the cell cavity. Mycelial hyphae in the vessels are thick (5–6 microns), and thin (1.5–3 microns) in the intercellular spaces and cells [270].

The fungus can grow at temperatures ranging from 10 to 35 °C. The optimum temperature for it is 18–27 °C and soil moisture content of 40–70% of the full moisture capacity. At a moisture content above 70%, development slows down and the mycelium forms a mass of chlamy dospores; at a moisture content of 40%, mycelial growth also slows down, but there is no abundant formation of chlamydospores [283].

The dynamics of the disease varies by season and depends on the temperature regime. This dependence is especially clear in the early stages of development. At low temperatures in April-May, the symptoms of the disease in most affected plants begin to appear only before flowering, and at higher temperatures, a significant proportion of plants are affected in the early stages. Varietal characteristics also have a significant impact on the dynamics of the disease. Susceptible samples vary significantly in the number of plants affected at different stages. Resistant ones get sick at later stages of development.

In some years, a significant negative correlation was noted between the percentage of Fusarium wilt damage and the content of erucic acid and glucosinolates in varieties [283].

The fungus forms one- and two-celled, colorless, rounded chlamydospores 3.5–7 μm in diameter with a thick shell, thanks to which it can easily tolerate sharp temperature fluctuations, does not die during severe freezing, and is not afraid of drying. When dry, they can withstand heat up to 8 °C. They can survive in the soil for up to 11 years. The infection enters the soil with plant residues. The main reservoir and accumulator of the infection is carrion, which explains why in crop rotations with a short rotation, the harmfulness of Fusarium can be very high, almost the same as in an infectious background The pathogen can be introduced to fields with soil clods, with irrigation water coming from infected fields [208].

There are contradictory opinions in the literature about the possibility of seed transmission of Fusarium wilt. Thus, V.F. Peresypkin [283] indicates the possibility of plant infection through seeds. However, L.G. Portenko [271] did not detect Fusarium pathogens in seeds from diseased plants, but does not deny the possibility of seed transmission due to surface contamination of seeds by small particles of affected stems. Some studies indicate the presence of the ash (charcoal) rot pathogen (*Sclerotium bataticola* Taub.) in the agrocenoses of cruciferous crops (Figure 1.47–1.49). The pathogen is a polyphage and affects more than 300 species of cultivated and wild plants. It affects sunflower in the southern regions of Ukraine, where it occurs every year, regardless of weather conditions. In years with dry and hot summers, sunflower infection can reach 90%.

The disease causes premature drying of the plants, and yields are reduced by 20–60%, which is due to a 25–35% decrease in the weight

of 1000 seeds. Oil content of seeds decreases by 2–8%, in addition, yield losses during harvesting increase due to brittleness and lodging of affected plants, and plants are more susceptible to ash rot in the budding phase. External signs of the disease appear in the second half of the sunflower growing season in the form of yellowing, drying of leaves and the formation of a brown spot in the basal part of the stem, which does not soften even in wet weather and gradually acquires a light ash color. Over time, the spot encircles the stem and spreads up the plant. Affected plants wither, dry out, the stem softens, the core dries up and it can completely crumble. The baskets and seeds are not affected and the disease is not transmitted with the seeds.

In appearance, the manifestation of charcoal rot resembles the root form of white rot, but differs from the latter by the ashy color of the affected tissues and much smaller sclerotia.

Numerous, small (50–150 microns in size) microsclerotia of the fungus are formed under the epidermis and in the stem core. In the soil in plant debris, they remain viable until the next year, and in the spring they germinate into mycelium, which penetrates directly into the seedlings and infects them.

Subsequently, during the sunflower growing season, the mycelium actively grows and spreads throughout the stem. In 10–15 days after flowering, the mycelium fills the plant's conductive system, which prevents the flow of water and nutrients.

The disease spread is facilitated by high soil temperatures (over +25...+30 °C), dry and hot weather, and the use of alfalfa as a precursor.

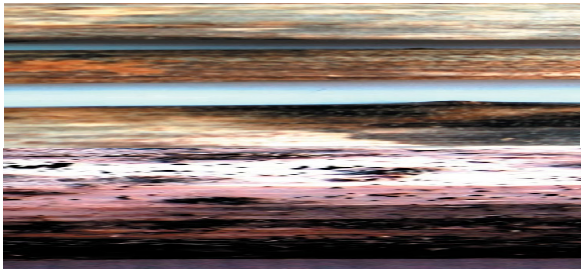

Figure 1.47 – Symptoms of ash rot on stems and roots of winter rape [96]

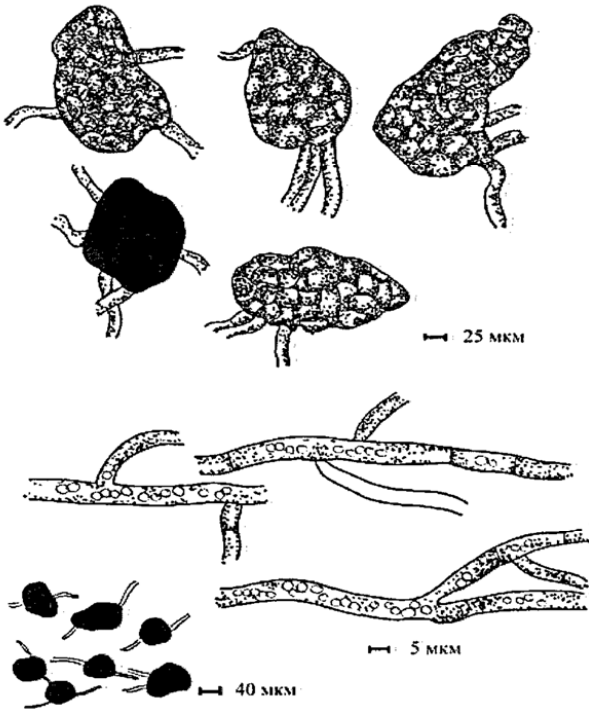

Figure 1.48 – Microstructures of Sclerotirum bataticola Taub. – the causative agent of ash rot of rape [10]

Verticillium wilt of Brassicacea species has attracted the attention of researchers relatively recently. Verticillum dahliae Klebahn (class Deuteromycetes, order Hyphomycetales, family Moniliaceae) as a pathogen of rape was first discovered in 1960 in Sweden [272]. It is now one of the most harmful diseases in this country. Its harmfulness is also high in Germany [8]. Evaluating 1992–1994 in Poland, verticillium was present in all surveyed fields [273], losses reached 30–70%. In the 80s, the disease was discovered in France [274]. Rapeseed verticillium is found in Ukraine. It causes damage in the production of cabbage family vegetables in Japan, and in recent years – in cauliflower growing areas on the California coast.

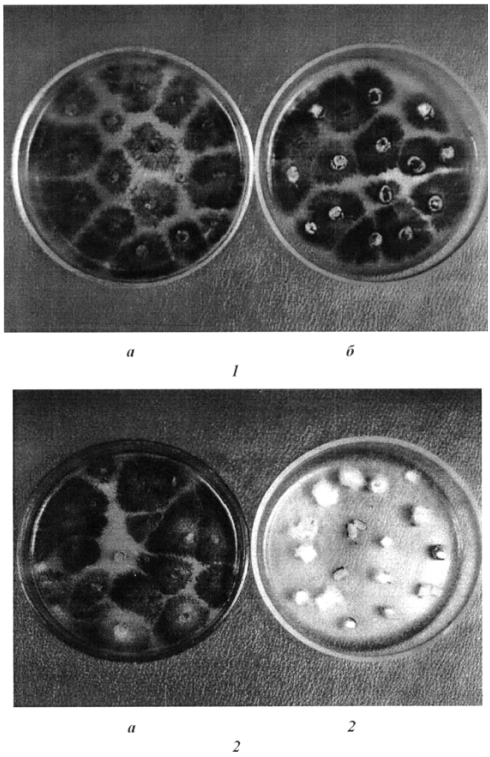

Figure 1.49 – Isolation of ash rot pathogen of rape from affected roots (a) and stems (b), where 1 – pure culture of *Sclerotium bataticola*, 2 – mixed infection with *Fusarium oxysporum* [284]

Studies of the virulence of V. dahliae of different origins for B. napus have been conducted. Isolates from rapeseed caused severe wilting of spring forms of this crop, a strong decrease in the yield of a single plant and the weight of 1000 seeds. Isolates from other host plants caused much less severe symptoms and did not affect yield. Plants infected with the potato isolate produced significantly higher yields than uninfected plants [275].

The causative agent of this disease was considered to be *V. Dahliae* [200]. However, a number of studies have shown that the conidia of pathogen isolates from affected plants of the cabbage family are almost twice as long

as those of typical *V. dahliae* isolates, so they were referred to as V. dahliae var. longisporium Stark. This species was described by Stark (1961) [289], who first isolated a long-spore isolate of the pathogen verticillosis.

A study of a large group of longisporous isolates isolated in Japan from cabbage plants showed that they differed significantly from typical V. dahliae isolates and were very similar in morphology, pathogenicity and polyphenol oxidase activity to diploid isolates (including the Stark isolate), so they were grouped into one group – "cabbage" isolates. From a comprehensive study of *V. dahliae* var. *longisporium*, *V. dahliae* and *V. alboatrum* (from alfalfa (L) and nonalfalfa (NL)), including cluster analysis of morphological, molecular and physiological characters, a significant separation of *V. dahliae* var. *longisporium* from two other species – pathogens of Verticillium wilt and it was proposed to give this species the status of an independent species – *V. longisporium* (C. Stark) Karapapa, Bainbridge & Heale [188].

Verticillium wilt is manifested at the end of the flowering phase in the form of gradual wilting or premature maturation of plants. In the lower and middle parts of the stem, as well as on the roots under the epidermis or bark, very small and closely spaced black dots can be found – microsclerotia of the pathogen. The stems and branches of diseased plants become discolored and light yellow. The leaves turn yellow, dry up and fall off. Seeds in the pods are formed in a small, poor quality, with low germination.

In the phase of pods filling and browning, healthy plants bend under the weight of the upper branches, while diseased plants are upright and stand out with their light color from the mass of healthy plants that still retain their green color. On the transverse sections of the stem or root of diseased plants, you can see the darkening of vascular bundles [187].

Infection with this disease occurs through the roots via the germinating mycelium of microsclerotia. For germination of *B. dahliae* microsclerotia, the temperature required is from 6 to 34 °C, and the optimal temperature is 15–28 °C [276].

Infestation of winter rape plants is possible as early as autumn, but on the main stem it occurs only in the spring before flowering. The first symptoms are noticeable before pod formation. It is often possible to observe plant damage simultaneously with necrosis of the root neck. The dynamics of the disease is accelerated and premature maturation of plants is observed.

The source of infection is post-harvest affected residues of rapeseed and other affected crops containing microsclerotia of the fungus.

With high atmospheric humidity and high soil moisture, gray rot may occur on rapeseed. Damage is concentrated at the base of the stem in the form of light watery spots. Under favorable conditions, the disease can cover the entire young plant, including the top, causing it to rot. All affected plant tissues are covered with a delicate, gray, spore-forming coating of the fungus. During a drought, the disease dies down, the stems break at the site of damage, and the plant dies. Harvesting is complicated and accompanied by large losses. The fungus *Sclerotinia fuckeliana* De By has a conidial stage *Bonyiis cinerea* Pers. that develops bundles of large, branched sporophytes, on top of which, on swellings, ovoid, single-celled conidia are formed. Many small dark-colored sclerotia are formed on the mycelium. Apothecia with elongated mace-like asci and 8 ellipsoidal unicellular spores in each are formed on the sclerotia. The pathogen persists in the form of mycelium and sclerotia in the affected plant residues, on which in spring a dense spore-forming coating of the fungus with conidia is formed, which carry out secondary infection during the growing season.

The causative agent of rape white spot is the fungus *Pseudocercosporella capsellae* (EU. et. er) Deigthon (class Deuteromycetes, order Hyphomycetales, family Moniliaceae). White leaf spot of rapeseed was first detected in France in 1985, and then in Canada. In Germany, the disease became widespread only in 1994. In addition to rapeseed, the pathogen can also affect ruddy (*Camelina pilosa*), and therefore it is necessary to take this disease into account when planning rapeseed cultivation in different regions of the world [277]. *P. capsellae* fungus can infect and cause disease symptoms on legumes [278].

Symptoms of the disease are noted on the leaves, but they could also appear on the stems and pods. The spots on the leaves may merge, causing a part of the leaf blades to dry out quickly [279].

The sexual stage of *P. capsellae* – *Mycosphaerella capsellae* (class Ascomycetes, subclass Loculoascomycetidae, order Dothideales, family Mycosphaerellaceae, genus Mycosphaerella) develops in the fall, and the ascospores formed during airborne transmission are the basis of primary infection. Further spread of the disease occurs with the help of conidia. Before the stem begins to stretch, 1–3 lower leaves are usually affected.

After the plants begin to grow in height, the disease spreads further, which is associated with two interdependent mechanisms: the vertical movement of conidia with rainwater to infect young upper leaves and the vertical movement of these infected young leaves due to the growth of internodes [280].

Relative humidity of no more than 80 percent or more is favorable for infection of rapeseed. The onset of infection usually coincides with the onset of precipitation. Conversely, excessively intense precipitation (40 mm in 3 hours) led to a decrease in infection, apparently due to the washing away of fungal spores. It is hypothesized that the rate of fungal spread is a linear function of temperature: incubation for 48 hours at 12 °C is equivalent to 32 hours at 18 °C. The risk period started 15–20 days after flowering and ended 2–3 weeks before harvesting [153]. The fungus *P. capsellae* is preserved on the affected plant residues in the form of thick-walled hyphae [153].

The causative agent of powdery mildew is the marsupial fungus *Ersyphe communis* Grev. f. *brassicae* Hammar L. (class Ascomycetes, order Erysiphales, family Erysiphaceae). Rapeseed powdery mildew is known in Germany, Hungary, France, England, Canada, Ukraine, Azerbaijan, Georgia and Armenia [166]. Powdery mildew is characterized by the appearance of a white, delicate, loose coating on the upper and lower sides of leaves, petioles, stems, and pods. Over time, it thickens and becomes covered with dark brown dots (cleistothecia), which gives it a dirty white or brown color. Severely affected leaves turn yellow and dry out [152].

The primary infection of plants is caused by the sowing of sowing spores released in the spring from cleistothecia that have overwintered on the affected residues. The airborne fungus infects rapeseed plants during flowering. During the growing season, the pathogen is spread by conidia [281].

Powdery mildew develops best at temperatures of 17–20 °C with periods of high humidity [8]. The pathogen persists on the remains of affected plants in the form of cleistothecia, and on overwintering plants – in the form of mycelium and fruiting bodies (Figure 1.50–1.52).

Powdery mildew appears on crops of spring cruciferous plant species, especially on late crops, in the form of a thick white coating on leaves, stems and pods. Affected leaves turn yellow and dry out. On the latter, you can find small dark dots – cleistothecia.

Figure 1.50 – Powdery mildew (the causative agent is the fungus *Erysiphe communis*) [96]

Figure 1.51 – *Powdery mildew* (beginning of winter rape plant infection) [96]

Figure 1.52 – *Powdery mildew* on the leaves of white mustard [96]

The causative agent of the disease is the marsupial fungus *Erysiphe communis* Zrev. f brassicae Hammare. It also affects cabbage, mustard and other cabbage crops. The pathogen's mycelium is multicellular and located on the surface of plant organs. It consumes nutrients with the help of haustoria, which penetrate into the cell. Initially, the fungus forms conidial sporulation, and at the end of the growing season, marsupial sporulation. Conidiophores are placed vertically on the mycelium. They contain colorless, single ellipsoidal conidia measuring 30–36 x 10–18 microns. With the help of conidia, the fungus spreads during the growing season of cruciferous plant species. Kleistothecia are dark brown, spherical, 65-180 μm, on average 90 μm in diameter, without notches when dry. They form branched appendages at the top. In the cleistothecia, 4-8 pear-shaped sacs are formed. Each of them contains 4–8 elliptical discolored asci measuring 19–25 x 9–14 microns. The fungus persists on the remains of affected plant organs of cruciferous plant species in the form of cleistothecia, from which bags with bagospores spread in spring and give rise to new plant infections [282].

The intensity of powdery mildew development on rapeseed increases with the alkaline reaction of the soil solution. This is due to the fact that at high pH in the soil, plants absorb less manganese, the content of which in the leaves is directly correlated with the intensity of powdery mildew development. There are different degrees of resistance to powdery mildew among rapeseed varieties. According to a number of researchers [283]. The most susceptible variety of cruciferous plant species to powdery mildew in Scotland was Dio. It formed an average of 42.4 conidia per 1 g of leaf tissue. High resistance to the disease was characterized by the varieties Winfred (I conidia/1g) and the sample C57E18 (1.7 conidia/1g).

In the conditions of the Agronomic Experimental Station of NUBiP, we found high resistance to powdery mildew in the varieties of spring rape Kalinovsky and Kletinny 8 [284]

The causative agent of light spot, or cylindrosporosis, is the fungus *Pyrenopeziza brassicae* (conidial stage of *Cylindrosporium concentricum* – class Deuteromycetes – order Melanconiales, family Melanconiaceae). The disease has been known since the beginning of the XIX century on cabbage, but only in the 70s of the XX century it was discovered on rapeseed. Cylindroporosis is found in all European countries [285]. Since the late 1980s, its harmfulness has been increasing in Germany [8], in the UK [286],

and causes yield losses of up to 50%. In the spring of 1983, the epiphytoty of cylinderspore on rape was noted in France [287].

With the onset of disease symptoms in November-January, the productivity of dry biomass of plants, seeds and other components of the winter rape crop significantly decreased. The manifestation of the disease in March did not have a significant impact on the evaluated parameters [288].

When pods are damaged by *C. concentricum*, the weight of 1000 seeds decreases in winter rape by 1.5 and in spring rape by 1.7 times, oil content – by 9.3–16.1%, respectively. The content of palmitic acid in the oil increases by 24–36 and 04%; stearic acid – by 2.3 and 1.0%; linolenic acid – by 2.7 and 1.4%; erucic acid – by 2.3 and 2.0%; eicosic acid – by 1.5 and 1.7%, respectively. The content of oleic acid decreases by 8.6 and 4.9; linoleic acid – by 2.6 and 1.6%, respectively [252].

Spores of the fungus, spread by the wind in the fall, cause irregularly shaped gray spots on the leaves, similar to frost damage or fertilizer burns. Gradually, shoots, buds and flowers of rapeseed plants are affected.

Infection with *C. concentricum* occurs within five days at a temperature of 5–15°C, and dripping moisture is required for the disease to develop. Under controlled conditions, necrosis developed with prolonged moistening of the leaf surface after inoculation for 16–18 hours and at a temperature of 12–18 °C. The latent period decreased from 17 to 9 hours with increasing duration of leaf surface moisture, while the number of necrosis also increased. A similar dependence was observed in the field, but the area of the affected surface was lower than that of plants in the greenhouse [289].

When rape leaves are damaged by the pathogen cylindrosporium, three aliphatic glucosinolates are induced in them in a greater proportion.

Variability in the virulence of *C. concentricum* was found in the UK [290].

The initial occurrence of the disease and the rate of its spread are higher when re-sowing rapeseed than after grain crops. Residual amounts of propyzamide, tebut and fluazifop-P-butyl herbicides increase the incidence of rape light spot [292].

Sources of infection are seeds and plant residues, on which the pathogen persists in the form of conidia, rarely marsupial sporulation (apothecia). Mycelium of the fungus can be stored in the living tissue of winter rape leaves under the cuticle [166].

The causative agent of clubroot is the fungus *Plasmodiophora brassicae* War. (class Plasmodiophoromycetes, order Plasmodiophorales, family Plasmodiophoraceae, genus Plasmodiophora). In many regions of intensive oilseed rape planting, the infected [293].

In Sweden, in the early 80s, large losses were recorded as a result of the defeat of rapeseed by this disease. In opinion [294] the main reason is a significant increase in sown areas.

Clubroot is rare in the UK, but all commercial winter oilseed rape varieties have been susceptible to the disease. The expansion of rapeseed crops to the north and west of the country, where soils are more acidic and fodder Brassicae are grown, has led to an increase in the disease88. Registered in Ukraine and Poland [2] (Figure 1.53).

Clubroot leads to a decrease in the density of productive stems, branching and the number of pods per plant [295]. Clubroot manifests itself on the roots of young seedlings and older rapeseed plants in the form of growths and swellings, which can sometimes reach significant sizes.

Figure 1.53 – Signs of clubroot on winter oilseed rape [100]

Figure 1.54 – Development of clubroot on the roots of cabbage seedlings [296]

Rapeseed is depressed, stunted; leaves turn pale green, droop in the heat, and are easily pulled out of the soil. Pods often do not form. In late autumn and especially at the beginning of the growing season in spring, plants dry out. The root system dies off, the growths rot, and most often the plants die [166]. Plants are infected by zoospores that penetrate the roots through root hairs or epidermal cells. Acidic and moist soils favor the release of zoospores.

The fungus is stored in growths in the form of dormant spores, then under the influence of soil microorganisms, the growths are destroyed and the spores enter the soil, where they can persist for up to 4–5 years [166]. According to other data, the pathogen was released from the soil 18 years after sowing a susceptible crop [297], but there is evidence that in 3–4 years the degree of infection decreases to a negligible value [298]. Diseases such as white rust – *Albugo candida* – also pose a potential danger [299–301], white leaf spot – the causative agent *Psedocercosporella capsellae* [125]; seedling diseases [302] (Figure 1.55).

Figure 1.55 – White rust on a rape leaf

Black leg. It is known in areas where cruciferous plant species are grown, mainly on heavy clayey black soils. Seedlings of cruciferous plant species are affected. Entire groups of plants lose

their turgor, turn yellow and dry out. The affected root collar becomes thin, turns dark in color, and later rots. The root system of affected plants of cruciferous plant species practically does not develop. The roots of the 2nd and 3rd orders die off. Affected plants are easily pulled out of the soil with a black leg [303]. The causative agents of this disease are semi-saprotrophic fungi from the genera Pythium Pringsh, Rhizoctonia D.C., Olpidium A. Br. These pathogens are found in the soil, multiply on various plant residues, and affect weakened seedlings of cruciferous plant species. With a strong development of the black leg, the crops of cruciferous plant species are greatly thinned out, especially in the early spring period on crops of spring cruciferous plant species [304].

White spotting. The disease is widespread on all cabbage crops, including rapeseed. It affects the leaves, rarely the stem and pods. The leaves form indeterminate grayish-white spots with a light green halo, which merge in wet weather, and the leaves curl and dry. In the affected areas, sporulation is formed in the form of small whitish pads. On the stems and pods, spots are formed in the form of elongated ulcers of grayish-white color with sparse pads. In the affected areas, the pods are bent, the seeds are small and underdeveloped. The causative agent of the disease is Cercosporella brassicae v.Hochn (Pseudocercosporella capsellae). Its mycelium is multicellular, developing in the middle of the host plant. Conidia are simple, in the form of bundles. Conidia are straight or curved, 50–130 x 4–4.5 μm in size, colorless, and have two or three septa. The fungal conidia spread mainly in wet, windy weather.

The first epiphytic development of white spot on spring rape was observed by I.L. Markov [4]. The fungus is preserved on the affected plant residues by mycelium and microsclerotia. The harmfulness of the disease is expressed by a decrease in the assimilation surface of plants, premature death of leaves, which leads to a decrease in the productivity of cruciferous plant species [305].

Root bacteriosis occurs in winter rape. Its development begins in late September or early October, with the formation of a cavity inside the root, near the root collar. As a result of the lesion, the core turns brown. According to external signs, the disease may not show signs during this period. It can only be detected by a longitudinal section of the root. In the spring, especially with sudden changes in air temperature, as well as the influence

of unfavorable wintering conditions, the affected roots of rapeseed become slimy, soften, and the rosette of leaves is easily separated from the root. Plants wither and dry up [306]. Sometimes affected plants begin to form new leaves at the expense of root nutrients, and over time they droop and die [110; 307]. Under favorable overwintering conditions, affected plants of cruciferous plant species with bacteriosis can have seeds, but with a reduced yield by 30–40% [308].

The formation of cavities in the roots occurs due to uneven water supply to the plant. The reason for this is a violation of the growth of parenchymal tissue under the influence of the pathogen. The same is observed in case of excessive nitrogen application for sowing winter cruciferous plant species [309]. The cavities contain pathogens – bacteria *Xanthomonas campestreis* (p.v. campestris) Dowson or Pseudomonas fluorescens p.v. napi Peresypkin. The source of bacteriosis infection can be affected root remains of winter cruciferous plant species and other winter cabbage crops. The carriers of the infection are pests (rapeseed borer, cabbage fly and others).

Viruses and bacteria, as well as some fungal pathogens, can be stored in root tissue. For example, bacteriosis pathogens settle in the roots of winter cruciferous plant species, in places of cavity formation [310]. Soil fungi are directly related to the root system. Some of them can transmit viral infection by mobile zoospores that parasitize the roots of cultivated and wild plants. Viral diseases include a mosaic of cruciferous plant species.

The root system of cruciferous plant species can be affected by blackleg pathogens – semi-saprophytic fungi from the genera Pythium, Pzingsh, Olpidium and others. Thus, when selecting breeding material, especially in selection for immunity, breeders and phytopathologists should pay attention to such a vegetative organ as the root [166].

White rust, white blister rust are common names for the disease caused by Albugo spp. on more than 400 plant species worldwide [311–313]. The name of the disease comes from the appearance of white pustules, resulting from the enzymatic breakdown of the epidermal cell wall, on the surface of leaves and other aerial parts of the host plant.

White pustules are a mass of dehydrated sporangiospores, which, when rehydrated in water droplets, lead to infection of stomata [315]. It is a representative of the eukaryotic oomycetes of the order Albuginales of the class oomycota, which are exclusively obligate biotrophic parasites with a

wide range of host plants [316–319]. *A. candida* exhibits obligate biotrophic feeding, completely dependent on host tissue. *A. candida* reproduces by asexual sporangia or zoospores and extremely resistant thick-walled sexual oospores. In all species of pathogens, oospores are the main source of inoculation [320]. Oospores are responsible for long-term survival in plant debris and are released when the host tissue decays [322; 336]. The presence of oospores in plant debris and perennial mycelium in the living tissue of the host (including weeds) allows the pathogen to survive between the host's growing seasons [321]. Moisture on the surface of the host plant is necessary for sporangia germination and infection by zoospores. The most likely sites of primary infection are the developing cotyledons of host plants. Albugo sp. enter through stomata, form intercellular hyphae, penetrate the plant cell wall, and invade the plant plasma membrane with the help of haustoria to take up plant nutrients and release effector proteins into host cells [322]. When the zoospores come into contact with the surface of the plant leaf, they settle in the stomata, incrustate and form a germ tube that extends into the substomatal chamber and penetrates the host cell. A primary vesicle is formed in the host cell, which ensures the further development of intercellular hyphae in a sensitive interaction [323]. When the infection matures, the zoosporangia forcefully rupture the plant's epidermis, and subsequent enzymatic digestion leads to the formation of characteristic blisters (‘white blister’). The disease is characterized by both local and systemic manifestations. Local infection is manifested in the form of white or creamy yellow pustules or "blisters" on the leaves and stems. Systemic infection leads to abnormal growth, inflorescence deformation and sterile flowers, commonly referred to as "deer head", which appears as a result of hypertrophy and hyperplasia. In addition to *A. candida*, which infects oilseeds and cruciferous plants, some other Albugo species are also known plant pathogens that cause huge yield losses in field crops, such as Albugo tragopogonis on sunflower, Albugo ipomoeaepandurate on sweet potato, and Albugo occidentalis on spinach. *A. candida* is an obligate biotrophic homothallic oomycete, the causative agent of white rust. According to molecular studies, the genus Albugo includes about 50 (usually) specialized pathogens, such as *A. laibachii* in *Arabidopsis thaliana* and *A. candida* in *B. juncea* [324–327]. The impact of the disease is very high in the Indian subcontinent, as

almost all released lines grown commercially in India are susceptible to the disease.

To date, *A. candida* forms 24 physiological races that infect more than 200 plant species in 63 genera from the families Brassicaceae, Cleomaceae and Capparaceae, each specializing in different host species, of which at least 10 specialize in different Brassicaceae species [328–339]. Among the identified races, race 2 (Ac2VRR) causes severe annual yield losses in oil mustard (*Brassica juncea* [L.] Czern. and Coss.) in Europe, India, Canada and Australia, and also infects some genotypes of other Brassica species, including oilseed rape (*Brassica rapa* L.) [340–342]. Race 1 (Ac1) affects Raphanus sativus, race 4 (Ac4) affects *Capsella bursa-pastoris*, race 5 (Ac5) affects *Sisymbrium officinale*, and race 6 (Ac6) affects *Rorippa islandica*. Race 7 (Ac7) is mainly restricted to B. rapa, but has also been reported to cause disease in some *B. napus* cultivars [343] and some genotypes of *B. juncea*. Race 9 (Ac9) infects *B. oleracea*.

In Ukraine, the main bacterial disease of cruciferous crops is root rot, which causes losses of up to 25% of the crop (in some years – up to 40-70%). Root bacteriosis is more common in winter rape. The development of the disease begins in late September or early October with the formation of rotting cavities inside the roots near the root collar and further browning of the core. In the fall, the disease hardly manifests itself externally, it can only be detected by a longitudinal section of the roots. In early spring, especially in snowless winters with sharp temperature fluctuations, most of the affected roots become slimy and soaked, which leads to plant death. The rosette of leaves is easily separated from the main root. Pathogens such as the bacteria *Xanthomonas campestris* and *Pseudomonas fluorescens* settle in the cavities. As pointed [166], in case of *X. campestris* infection, necrotic V-shaped spots surrounded by a chlorotic rim are observed on the leaf blades. The source of infection of winter rape roots with bacteriosis is plant residues, as well as cultivated and weedy cruciferous plants susceptible to this disease, especially rape.

Symptoms of bacteriosis varied in nature, but most often manifested as light brown spotting on the leaves, weak softening of the leaf petiole, ulcers on the stem, especially in the root part, and darkening of the vascular system. In the early stages of development, the affected tissue sometimes had a darker green color than the surrounding unaffected tissue. Sometimes

the spots looked as if they were soaked in water or oily, often with a light yellow halo resulting from the diffusion of bacterial toxins into the surrounding tissue. The spots that appeared on stems or leaf petioles were usually oblong in shape.

Most often, 2 types of pathogenic bacteria were isolated, one of which caused stem and vascular burns and belongs to the pathotype *Xanthomonas campestris* pv. campestris, the second one causing bacterial spotting was identified as *Pseudomonas syringae*. The pathogenicity of the above species was proven in greenhouse and chamber conditions. The bacteria caused a hypersensitivity reaction on tobacco, geranium and plenicranthus and infected rapeseed and sunflower. The yellow-pigmented isolates we isolated did not differ from the typical *X. campestris* pv. campestris strain in their phenotypic properties.

It has been established that the sources of infection of winter rape with these bacterioses are plant residues, as well as cultivated and weedy cruciferous plants, which are often affected by xanthomonads and are carriers of bacterial infection. In addition, as a carrier of vascular infection, bacteria enter the seeds, where they remain until the next year. According to some reports, different types of insects can be carriers of rapeseed bacteriosis. In this regard, the fight against bacterial diseases of rapeseed should be integrated (destruction of plant residues, weeds, seed treatment, insecticide treatment and the use of varieties that are least affected by these pathogens).

Seed mass of cruciferous plants, as a storage object, is characterized by increased activity of physiological and microbiological processes and is prone to rapid deterioration even when stored at humidity not only regulated by SSU, but also close to critical [344].

It is believed that the reduction of glucosinolates in the so-called new "00" rapeseed varieties, along with a positive impact on the quality of seed products, has negative consequences, reducing the resistance of plants and their seeds to pathogens [9].

The limits of active growth of mold fungi are the following combinations of seed moisture and temperature: 8 % and 25 °C, 10 % and 20 °C, 12 % and 39 less than 20 °C. At 14 and 16 % seed moisture, fungi multiply so that their number increases hundreds and thousands of times even at 10 °C. At low temperatures, Aspergillus spp. and Rhizobium spp. develop evenly, while

at high temperatures, the former develops more intensively. A significant increase in the content of A. flavus, which is capable of producing the most toxic metabolites, is noteworthy.

The development of mold microflora on the seeds of high-glucosinolate rape varieties is subject to the same laws. At high seed moisture, the expected increase in the number of microorganisms is not observed. Already at a moisture content of 18.6% and a temperature of 30 °C, there is almost complete inhibition of mold microflora. This is probably due to the fact that at high seed moisture content, an increase in temperature promotes the hydrolysis of glucosinolates. Under these conditions, it is possible to activate the enzyme myrosinase, which breaks down glucosinolates to form more toxic compounds.

Conflicts of microorganisms are more sensitive to the content of glucosinolates in seeds and their hydrolysis products, especially at the time of germination (in the lag phase), and less sensitive in the logarithmic phase of growth. This is confirmed by the rapid deterioration and intensive growth of microflora in seeds with low moisture content (8–13%), which is not enough for the release and hydrolysis of glucosinolates. In seeds with excess moisture, under favorable temperature conditions, glucosinolates are hydrolyzed to form toxic products that inhibit the growth of microbial spores, In seeds with a lack of moisture, microbial spores germinate without contact with glucosinolates.

The mycelium of microorganisms, possessing a powerful enzymatic system, is not inhibited even with a high content of glucosinolates. Numerous studies have established the possibility of accumulation of toxic compounds – aflatoxins produced by storage molds – in seeds, grains and their products.

High- and low-glucosinolate rapeseed seeds differ in the rate of accumulation of aflatoxins and their group composition: in high-glucosinolate rapeseed seeds, the accumulation of aflatoxins of groups B1 and G1 is more intense; in low-glucosinolate seeds, it is slower and they are represented by only one group B [345].

Localized aflatoxins are mainly in the seed coat. The seed kernel contains fewer aflatoxins, but their absolute amount is significant, so cake and meal have a high content of aflatoxins, and they are contained in rapeseed oil in the form of traces. Aflatoxins and glucosinolates (their

non-volatile components) reduce the biological value of meal proteins, which is determined by the test organism Tetrahymena pyriformis. The toxic effect of aflatoxins and glucosinolates in the meal is summed up, the minimum concentration of them that causes the death of the test organism is reduced [346].

The list of diseases of oil radish plants is similar to the cabbage group [347–353] (Figure 1.56–1.58, Table. 1.17). And according to I. Markov [4] cruciferous crops are characterized by high ecological plasticity in relation to emerging pathogens. However, the expansion of the area under oilseeds from the cabbage family and the increase in their yield in Ukraine is constrained, first of all, by the significant harmfulness of diseases inherent in oilseeds. The harmfulness of the diseases is manifested in a significant decrease in the quality of green mass, with their development reducing the content of vitamin C, protein, fat, and sugar. According to the author's research, the amount of amino acids in the affected leaves of rapeseed, rape, oil radish, depending on the intensity of the disease development, decreases by 1.4–2.7 times, the oil content in the affected seeds, depending on the pathogen, decreases by 1.3-3.4 times, the specific gravity of palmitic, stearic, erucic, eicosinic, linolenic acids increases significantly, while the specific gravity of oleic and linoleic acids in the composition of cruciferous oils decreases. The shortfall in seed yield from diseases, in particular in oil radish, depending on the variety and technology of its cultivation, ranges from 15 to 35% with a significant deterioration in its sowing qualities. According to the results of a comprehensive evaluation of the oilseed collection at NUBiP of Ukraine (Table 1.17), it was found that oil radish has the lowest resistance to Alternaria, downy mildew, gray and white rot, and phomosis. However, it is resistant to cylindrosporiosis and white rust and Fusarium wilt.

Alternaria ssp. The infection persists on the affected leaves of oil radish, plant residues of cruciferous crops and seeds. The disease begins to spread to young pods after flowering. Crops are particularly severely affected by high humidity and warm weather. It affects all organs of the rapeseed plant. During the germination period, it causes rotting of seedlings. On cotyledon leaves it appears in the form of dark brown spots that lead to decay and death of seedlings in the early stages of development. Light smoky spots with a light halo around the spot are formed on the leaves. Further, the

spots darken, acquiring a rounded shape up to 1 cm in diameter with a pronounced zonation from the center. Dark, rounded, depressed ulcers appear on the affected pods, deforming the pod. The stems are covered with oblong dark spots. The disease is most harmful during pod formation. The pods ripen prematurely and crack. In the years of epiphytic development of the disease, the length of the pod decreases by 8–26%, the number of seeds in the pod decreases by 12–59%, the weight of 1000 seeds – by 15–70%, the oil content in the seeds – by 11–27%.

Phoma lingam When infected seeds germinate, the disease manifests itself on the hypocotyl and cotyledons in the form of watery spots of various shapes, which, when dried, turn gray and pycnidia form on them. When seedlings are affected, dark spots appear in the root part of the stem and on the root. Subsequently, the affected areas dry up and brighten, which ultimately leads to the destruction of the root system and the death of the crop seedlings. During the growing season, the disease manifests itself on the stem in the root part in the form of dark ulcerative lesions that can spread to the root system, causing dry root rot. Oil radish plants with this type of lesion are stunted, have a chlorotic appearance, lie down and die. On leaves and pods, phomosis appears as gray dry spots with concentric zonation and dark pycnidia. The infection persists on plant residues and seeds. Phytopathological picture of the disease for oil radish in Ukraine: infection of seeds does not exceed 2%, damage to seedlings – 10–18%, stems – 30–46%, leaves and pods – 5.5–12.0% with the development of the disease 2–5%.

Peronospora brassicae. Causes premature death of leaves. In wet years, pods may be affected. The disease manifests itself on cotyledonous and true leaves. Yellow, blurry spots appear on the upper side of the affected leaf, and a gray-purple coating is visible on the lower side of the leaf, which is the conidial sporulation of the pathogen. Symptoms of the disease on the stems and pods are oblong gray-purple spots with sporulation of the pathogen. The pathogen infection is maintained by mycelium in the tissues of affected plants of oil radish and other cruciferous crops, as well as on plant residues. The source of infection can be infected seeds.

Gray rot (Botrytis cinerea). The source of infection is sclerotia and affected seeds. Affected stems are broken. The seeds are small with low sowing and technical qualities. Gray rot develops intensively in wet weather, affecting all plant organs.

Figure 1.56 – Rapeseed pod and stems affected by gray mold [69]

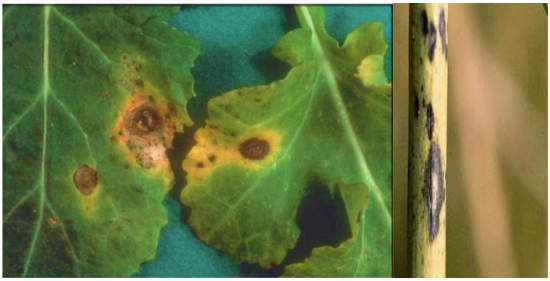

Figure 1.57 – Signs of Alternaria damage on the leaves of oilseed radish [56]

Figure 1.58 – Signs of phomosis damage to leaves and root system [56]

Figure 1.59 – Phomose dry rot of the root system of oil radish (magnification 400x) [56]

Figure 1.60 – White rot on oilseed radish pods [56]

Figure 1.61 – Leaves affected by downy mildew and signs of gray rot on oilseed radish [56]

Table 1.17

Oilseeds disease susceptibility in the conditions of the NUBiP of Ukraine, ASS [369]

Crop	Disease development, %									
	peronospo-rosis	alternaria	phomosis	cercospo-riasis	asco-chitosis	cylindrospo-rosis	white rot	gray rot	fusarium wilt	white rust
Winter rape	19.4	24.2	8.0	4.0	1.6	12.8	6.0	7.9	4.8	0.3
Spring rape	15.2	18.5	6.8	2.9	1.8	6.2	7.2	5.1	3.3	0.7
Common rape	10.3	5.5	3.5	2.2	6.5	2.7	2.2	3.2	2.0	0
White mustard	8.6	11.8	4.9	4.7	6.3	0	3.4	1.6	2.4	1.4
Gray mustard	11.4	17.2	1.4	0	6.0	0	1.0	3.1	1.8	0
Camelina	3.2	2.0	0	0	0	0	1.8	1.6	2.4	9.7
Oilseed radish	9.4	24.6	4.6	3.4	2.8	0	4.3	4.8	1.0	0
SSD_{05}	*2,4*	*2,7*	*1,3*	*1,1*	*1,1*	*1,6*	*1,1*	*1,3*	*1,0*	0,8

The affected areas look like brown, watery spots of arbitrary shape, covered with gray fluffy mycelium of the pathogen. In dry weather, the affected plant tissue dries and becomes light gray. On green pods, gray rot appears as a lightening of the pod. In wet weather, the affected pods become covered with a gray coating, and when dry, they crack. Black, small sclerotia form on the affected plant organs.

White rot (*Sclerotinia sclerotiorum*). The main source is sclerotia stored in the soil for more than 5 years. There are no resistant or slightly affected varieties. It affects stems, leaves, pods. The first signs of damage look like dark green spots with a characteristic shine, which increase very quickly in wet weather. After 3–5 days, the affected plant organs are covered with abundant, white, loose mycelium of the pathogen, from which black sclerotia of various sizes are formed. Sclerotia are formed both on the surface of the affected organs and inside the root, stem and pods. In dry weather, there is little sporulation on the surface of the affected organs, and the affected plant tissue looks discolored. Affected plants look prematurely ripe, the stems break. The disease is very harmful when the main stem is affected during the flowering period. When affected during this period, no seeds are formed. At later stages of the disease, small seeds with low sowing and technical qualities are formed: the weight of 1000 seeds is reduced by 20–60%, oil content – by more than 20%.

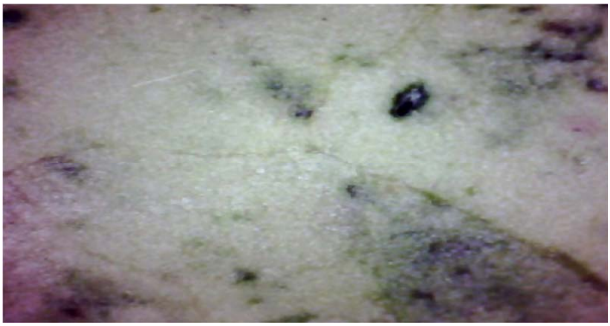

Figure 1.62 – White, felted mycelium of the white rot pathogen with the formation of black sclerotia on the surface of the oil radish leaf (magnification 200 x) [56]

Figure 1.63 – Pods of oil radish with signs of alternaria infection [56]

Cruciferous root rot has a certain pathological significance in the technology of cruciferous crops (Figure 1.64). For example, root rot of spring rape is characterized by widespread and high harmfulness in the Right-Bank Forest-Steppe of Ukraine. Under favorable conditions for pathogens, they cover up to 77% of plants, and their development reaches 64.1%. The disease is most harmful when plants are affected in the early stages of development (second pair of true leaves). The density of correlation between the decrease in seed weight per plant and the development of root rot is r = -0.63.

Investigated [354], that in the conditions of the Forest-Steppe of Ukraine in spring rape crops during the growing season, starting from the moment of seed germination, in addition to the known symptoms of the formation of bindings and drying of plants, the following signs of damage to the root system were differentiated by their nature of manifestation and development: thinning of the stem, peeling of the affected tissues, death of the main root and increased growth of lateral roots (Figure 1.64 A), formation of ulcers and their decay, ring rot (Figure 1.64 B), blackening of blood vessels (Figure 1.64 C).

Damage in the form of small ulcers with healthy edges is caused by nematodes, in particular the beet nematode (Figure 1.69 D), which later forms cysts on the root surface (Figure 1.69 E). They facilitate the penetration of fungi, resulting in very small spots in the affected areas, which later merge with each other, occupying a significant area of the root system.

A B C D E

Figure 1.64 – Diagnostic signs of damage to the root system of rapeseed: A – dying of the main root and growth of lateral roots; B – formation of cones due to the defeat of ring root rot; C – blackening of vessels with ring root rot; D – ulcers; E – cysts of beet nematode (Variety Maria, NUBiP of Ukraine "Agronomic Research Station", original) [369]

Figure 1.65 – Blackleg (pathogens – Pythium, Oomycota, Rhizoctonia, Deuteromycota, Olpidium, Chytridiomycota, etc. Occurs on mustard and rape [369]

Proved [369], that the symptoms of rapeseed root rot are not stable throughout the entire ontogeny of plants, they can change in different phases of plant vegetation. Two or more symptoms may appear on one plant and vice versa. Such a variety of symptoms may indicate the presence of a complex of root rot pathogens involved in the disease.

Root rot of spring rape has a high level of distribution and development, especially in the early stages of the crop's vegetation. Thus, in the conditions of the Agronomic Experimental Station of the Vasylkiv district of Kyiv region, during 2002–2005, the maximum prevalence of the disease reached 62.0%, the minimum – 13.8%, the maximum development – 31.0%, and the minimum – 9.4% in the varieties Kalynivskyi and Maria. A characteristic feature of rapeseed root rot is that some severely affected plants (up to the second pair of true leaves) dried up and collapsed. Therefore, they are not taken into account during subsequent surveys, resulting in an underestimation of the prevalence of root rot. A similar situation was noted in other areas of the study.

Indicators that equally reflect the harmfulness of root rot were the weight of seeds and the number of pods per plant. Thus, the decrease in these indicators due to root rot damage had an average correlation level from r = -0.56 to r = -0.63.

It is noted 370, that the mycobiota of the spring rape root system is represented by fungal species belonging to 22 genera, 3 divisions (Qomycota, Ascomycota, Vasidiomycota), two kingdoms (Chromista and Fungi). The main share of them is made up of fungi of the genus Fusarium (frequency of occurrence ranged from 56.9 to 64.2% over the years), Pythium (26.6–47.1%) and Rhizoctonia (15.4–22.9%). The greatest species diversity (19 species) was characterized by fungi of the genus Fusarium. The dominant among them were: *F. avenaceum, F. sambucinum* var. *minus, F. solani, F. oxysporum* (Table 1.18). The genus Pythium was represented by three species: *P. ultimum* var. *ultimum*, *P. hydnosporum*, and unidentified Pythium sp., and the genus Rhizoctonia was represented by R. solani and Rhizoctonia sp.

At the same time, it was determined [370], that low average daily temperature (+10 °C) and excessive precipitation per month, especially in the early stages of the crop's vegetation, contributed to an increase in the prevalence of spring rape root rot to 62% and development to 31%.

With more moderate levels of precipitation (no more than 20 mm per decade) and slightly higher average daily temperature (+18.6 °C), the prevalence of the disease during the growing season remained at the same level (33.9–39.3%). The development of certain pathogens was more dependent on temperature. Thus, in the studied years, with an increase in the average daily temperature during the growing season of spring rape, there was a tendency to a gradual decrease in the number of fungi of the genus Pythium (from 64.8 to 2.6%) and an increase in the number of representatives of the genus Rhizoctonia (from 6.9 to 20.4%).

Table 1.18

Species composition of micromycetes isolated from the affected root system of spring rape (Kalinovsky variety) [369]

Вид мікроміцетів	Frequency of occurrence, %			
	SE NUBIP of Ukraine "Agronomic Research Station"		"Velykosnitynske educational and research O.V. Muzychenko Educational and Research Farm	
	2002	2003	2007	2008
Pythium ultimum var. *ultimum*	32.2	15.6	27.4	22.4
P. hydnosporum	12.3	7.6	6.5	4.1
Pythium sp.	2.6	3.4	1.2	1.7
Fusarium avenaceum	11.9	10.1	11.9	6.4
F. oxysporum	2.3	6.8	8.4	7.1
F. sambucinum var. *minus*	9.1	12.4	10.3	6.4
F. solani	6.5	4.7	7.9	3.7
Інші види *Fusarium*	34.4	25.9	24.9	33.3
Rhizoctonia solani	12.2	16.4	20.3	14.8
Rhizoctonia sp.	3.2	6.4	2.6	4.1
Інші роди	5.9	17.8	11.0	19.6

At a uniform air temperature (+18.6 °C) in spring and summer, the frequency of isolation of fungi of the genus Pythium during the second survey corresponded to the level of the previous one (42.3–43.7%). At the same time, with an increase in the average daily temperature to +21.5 °C, intensive development of fungi of the genus Fusarium and

Rhizoctonia was observed. Meanwhile, precipitation was not a decisive factor. Thus, the root rot pathogens of rapeseed from the genus Pythium, in the initial phases of plant development, are able to develop at low temperatures and in a humid environment, while the development of Fusarium and Rhizoctonia species is more favorable with an increase in the average daily temperature.

Defined [369], that in vitro, the optimal growth and development of aerial mycelium of *P. ultimum* var. *ultimum* occurs on potato glucose and pea agar (Table 1.18).

Stable growth and development of the fungus with temperature changes was observed in starvation and corn medium. The linear growth of the fungal mycelium at a temperature of +10 °C on the vast majority of media ranged from 0.53 to 0.68 mm/h. At a temperature of +25 °C, the growth rate reached 1.03–1.11 mm/h in almost all variants. The appearance of the first oospores was noted after 48 hours, and after 120 hours their maximum number reached 255 pcs. in the field of view of the microscope (x100) on oatmeal agar. At +10 °C, no oospores were formed on potato glucose, pea agar and Chapek's medium (Table 1.19).

Table 1.19

Effect of temperature on the linear growth rate of mycelium and the size and number of oospores during the cultivation of *P. ultimum* var. ultimum on different media [369]

Growing medium	Growth rate, mm/h		Number of oospores on day 5, pcs.		Diameter of oospores, +/- µm	
	+10 °C	+25 °C	+10 °C	+25 °C	+10 °C	+25 °C
Potato glucose agar	0.68	1.1	0	140	none	23.7±0.1
Oat agar	0.53	1.03	16	255	none	21.0±0.1
Carrot agar	0.67	0.92	14	135	19.7±0.3	27.6±0.1
Corn agar	0.54	1.01	55	150	25.0±0.5	25.0±0.3
Starving agar	0.56	1.03	16	20	25.0±0.6	23.7±0.6
Pea agar	0.47	1.11	0	15	none	26.3±0.1
Rapeseed agar	0.43	0.85	1	30	21.0±0.1	27.6±0.3
Chapek's environment	0.67	1.01	0	0	none	none
SSD_{05}	0.09	0.1	9.4	47.3	–	–

Pathogenic isolates of Rhizoctonia spp. isolated from the root system of spring rape were identified as Rhizoctonia solani, which according to morphological characteristics and the nature of the anastomotic reaction was assigned to the group AG 2-1, and one unidentified species of Rhizoctonia sp. Defined [370], that the optimum temperature for the growth of R. solani (AG 2-1) is +20–25 °C, the linear growth rate was in the range of 0.92–0.95 mm/h, and intensive sclerotia formation was observed. For Rhizoctonia sp., a narrower temperature range of +25 °C is optimal; at the same time, the linear growth rate was within 0.87 mm/h, and at higher temperatures, slow mycelial growth, less bright color, and inhibition of sclerotia formation were observed.

The morphological characteristics of the identified 19 Fusarium species did not differ from those described in the literature. It is known that during the development cycle, fungi of the genus Fusarium form macro- and microconidia, forming sporodochia. The latter were observed in the pure culture of F. avenaceum, F. solani, *F. gibbosum* var. acuminatum. In addition, in the culture of F. solani, pionnots were formed on the studied parts of rapeseed plants. A rare phenomenon was recorded in the pure culture of F. oxysporum: germination of conidia into chlamydospores and formation of anastomosis between the two conidia. Defined [370] high pathogenicity of P. ultimum var. ultimum for *Brassica napus* L., which is manifested in the formation of a band on the root and root parts of the stem in 100% and the death of 95% of plants. The same symptoms were caused by soil infection with *Rhizoctonia solani* isolates (Figure 1.66).

P. ultimum var. *ultimum* and *Rhizoctonia solani* (AG 2-1) are characterized by high growth intensity. Their linear growth rate at the optimum temperature is 1.03–1.11 mm/h and 0.92–0.95 mm/h, respectively. The intensive growth of air mycelium of P. ultimum var. ultimum in vitro occurs at +25 °C on potato glucose and pea agar, and its oospores are better formed on oatmeal agar (255 units in the field of view of the microscope, x100). The first oospores appeared after 48 hours of incubation. The optimum temperature for the development of Rhizoctonia solani (AG 2-1) is +20–25 °C.

Isolates of the genus Fusarium Link were less pathogenic. Of the 52 studied strains isolated from the root system of spring rape, pathogenicity was confirmed for 13 strains of the following species: *F. avenaceum, F. avenaceum* var. *herbarum*, *F. moniliforme*, *F. moniliforme* var.

lactis, *F. oxysporum* var. *orthoceras*, *F. sambucinum* var. *trichoteciodes* (one strain each) and *F. oxysporum*, *F. sambucinum* var. *minus* (4 and 3 strains, respectively). They caused the formation of lighter and smaller bands. The plant severity ranged from 5.5–71.5%, and the disease development – from 2.8–53.6%. All studied strains (pathogenic and non-pathogenic) had a latent infection (latent phase).

Microscopic examination of the tissues of the affected root system revealed microscopic structures characteristic of individual pathogens: for P. ultimum – a significant number of oospores, for Fusarium spp. thin mycelium with chaotic branching, and for *R. solani* – wide, with direct branching (Figure 1.67).

Under the complex infection, an increase in the level of pathogenicity in the variant of P. ultimum var. ultimum and *R. solani* and a decrease in the level of pathogenicity under the condition of their interaction with F. avenaceum was noted (Table 1.20).

Figure 1.66 – Formation of lodging and desiccation of plants under the influence of *P. ultimum* var. *ultimum* (left) and *R. solani* (right, original) [369]

Figure 1.67 – Development of fungal structures in the affected tissues of spring rape root system (x200, original) [369]

Infection of soil with Rhizoctonia solani (AG 2-1) and P. ultimum var. ultimum leads to the death of 25 and 100% of plants, respectively. The fungi *F. avenaceum, F. avenaceum* var. *herbarum, F. moniliforme, F. moniliforme* var. *lactis*, *F. oxysporum* var. *orthoceras*, *F. sumbucinum* var. *trichoteciodes*, *F. oxysporum* and *F. sumbucinum* var. *minus* cause the appearance of a constriction on the root system and do not cause its drying out. In case of complex infection of plants with *P. ultimum* var. *ultimum* and *R. solani*, their pathogenicity increases.

Table 1.20

Pathogenicity of fungi against spring rape in soil co-infection in vitro [369]

Infestation of the soil with fungi	Gamination by 10 day, %.	Number of plants with signs of diseases, % on the day of accounting		
		15	20	
			of all	including deaths, %
Control – without infection	70.6	0.0	0.0	0.0
Pythium ultimum var. *ultimum*	0.0	not taken up		
Rhizoctonia solani	23.5	25.0	25.0	25.0
F. avenaceum	97.8	11.8	41.2	0.0
P. ultimum var. *ultimum* + *R. solani*	5.9	100.0	100.0	0.0
P. ultimum var. *ultimum* + *F. avenaceum*	64.7	0.0	18.2	18.2
R. solani + *F. avenaceum*	52.9	0.0	55.5	11.1
P. ultimum var. *ultimum* + *R. solani* + *F. avenaceum*	5.9	0.0	100.0	100.0

Investigated [369], that most isolates are in synergy with each other. Growth inhibition of *R. solani* and Fusarium species was detected when the colonies reached each other's boundaries, which is consistent with the manifestations of pathogenicity during artificial soil infection. However, this did not affect the formation of sporulation, and in the case of the *F. avenaceum* strain, it stimulated its growth. The obtained research results indicate the absence of a clearly expressed antagonism between the root rot pathogens of spring rape, which is the cause of the complex damage to plants of this crop by different pathogens simultaneously.

It has been established that the least development of the disease is achieved under the conditions of early sowing with a seeding depth of up to 2 cm and a seeding rate of up to 1.5 million units/ha. Sowing seeds with a row spacing of 45 cm and applying nitrogen fertilizers at a rate of 120 kg/ha (either once or separately) allows to restrain the spread and development of root rot in the initial stages of development. Later, this effect is not observed.

Many of the cruciferous vegetables we commonly consume belong to the cruciferous family, including broccoli, Brussels sprouts, cabbage, cauliflower, collard greens, kale, kohlrabi, mustard, rutabagas, turnips, and Chinese cabbage.

During the growing season, these crops are affected by many diseases that reduce yields and product quality. Among all the diseases, black rot, caused by the bacterium *Xanthomonas campestris* pv. *campestris* (Pam.) Dowson, is the most widespread and destructive disease of the cabbage family worldwide. Cruciferous cabbage is susceptible to the disease in cabbage, cauliflower, broccoli, kale, Brussels sprouts, Chinese cabbage, kohlrabi, turnips, mustard, radish, and rutabaga. It is one of the most destructive vascular diseases of cruciferous vegetables, which is found in all parts of the temperate and subtropical zones of the world, where there is heavy rain or heavy dew, and average temperatures range from 25 to 30 °C.

Pamela first reported the black rot [355] from Iowa, North America, on rutabagas. In 1898, Russell reported the disease on cabbage from Wisconsin. Since then, there has been a growing worldwide recognition of the seriousness of black rot in cruciferous crops. The disease was first reported on cauliflower in Norway [356]. It has since been reported to be widespread on cauliflower in all parts of the world [357].

The disease is very destructive and causes significant yield losses due to premature defoliation and reduced quality of cauliflower and cabbage heads and heads, respectively, during transportation, making them uncompetitive on the market. Yield losses of up to 50% of cabbage and 50 to 70% of cauliflower were recorded [133]. Significant crop losses due to the rapid spread of bacteria under favorable conditions, especially when growing seedlings, are also reported [358].

The pathogen systematically moves through the vascular bundles, turning them black, and causes the main symptoms on the leaves described

by different workers. The pathogen causes two types of symptoms. First, marginal chlorotic spots appear on the leaves, followed by darkening or blackening of the midrib and veins [359]. However, they report [360], that blackening of the veins is the first visible symptom associated with the accumulation of melanin in xylem cells. The pathogen colonizes the vascular system after entering the plant and produces a large amount of extracellular polysaccharide xanthan [361], which, together with the bacterial cells, clogs the xylem vessels, restricting water flow and leading to the characteristic V-shaped chlorotic lesions that begin at the leaf margins. As the bacterium moves through the plant, the vascular tissue darkens, leading to blackening of the veins. Systemic infection during storage often makes the product unmarketable. Infection with this pathogen can be accompanied by attacks by the soft rot bacterium Erwinia carotovora or the fungus *Sclerotinia sclerotiorum* [362].

Cruciferous black rot is caused by *X. campestirs* pv. *campestris* (Pam.) Dowson. It is a small, rod-shaped, aerobic, Gram-negative, non-spore-forming bacterium. The bacterium has a single polar flagellum, is positive for catalase, hydrogen sulfide, oxidase and does not produce nitrate and indole. On media containing glucose, it produces a yellowish extracellular polysaccharide called xanthan. *X. campestris* pv. *campestris* hydrolyzes starch, which is used to easily recognize the bacterium on Schaad's selective medium. Its growth is inhibited and retarded in the acidic pH range. The temperature range of survival is very wide (5–38 °C), with the optimum temperature being 30 oC and the lethal temperature around 50 °C. Described [363] bacterial colonies are yellow, shiny and mucoid, 1–2 mm in diameter, surrounded by a 2–4 mm wide zone of starch cycloheximide agar and nutrient starch cycloheximide agar and nutrient starch cycloheximide agar with antibiotics. It is known that there are six races of the pathogen in the world, of which races 1 and 4 predominate [364].

The bacterium infects all members of the cruciferous family, including rutabagas, cabbage, savoy cabbage, broccoli, turnips, radishes, kohlrabi, radishes, mustard species, and fodder cabbage [365].

The infection of cabbage with the black rot pathogen by hydatids was observed by previous researchers. Later, Clayton also observed the penetration of the pathogen through stomata on the lower surface of intact cauliflower and cabbage leaves. However, stomatal infections of

X. campestris pv. campestris have not been confirmed, and the bacterium usually enters through wounds or hydatids [366].

Typical V-shaped lesions developed when fully expanded and subordinate leaves of two-month-old seedlings sown in a greenhouse were inoculated by cutting them along the leaf margin with scissors or nail clippers dipped in a suspension of *X. campestris* pv. *Campestris* [367]. The bacterium caused black rot rapidly and in almost all inoculation sites when inoculated on hydatids or wounds of intact cruciferous plants [368]. Showed [369] a high correlation between juvenile inoculation, disease severity and resistance of mature plants, indicating that plants can be effectively evaluated at the juvenile stage to determine the resistance of mature plants to black mold. Different researchers have studied the development of black rot by artificially inoculating the pathogen using different methods. Bhide [370] compared the infection of 2-week-old, one-month-old and two-month-old cabbage seedlings with X. campestris pv. campestris by hydatids and stomata and found that hydatid infection was severe for plants of all ages, and lesions caused by the later methods did not increase, while lesions caused by the former covered most of the leaf surface and progressed down the petioles and stems. Initiation of disease by phytopathogenic bacteria depends on the concentration of the inoculum [371]. A minimum concentration of 106 cells/ml is required for the development of black rot symptoms [372]. They also observed slightly more infection of cabbage when the cell suspension was injected with a hypodermic syringe than when it was injected with a needle. They found [373] higher infection rates when seedlings were inoculated through damaged veins than through hydatids. Piercing the veins with a pin also caused more infection than spraying with a bacterial suspension. Cruciferous black rot occurs under warm and humid weather conditions. They found [374], that the disease occurs only under conditions of high atmospheric humidity. Large losses of cabbage and cauliflower have been reported due to severe outbreaks of black rot in conditions of heavy precipitation [375]. The disease was reported to be severe and very destructive in warm, humid weather conditions in various locations [376]. Reported [377], that warm summer weather is associated with the manifestation of black rot symptoms in cruciferous plants. The transfer of the pathogen with infected seeds of cauliflower and other cruciferous plants has been observed as a way of survival of *X. campestris* pv. *campestris* by

various researchers [378-381]. The bacterium also survived in the garden and on plants near the fields [382]. The bacterium can survive in naturally infected seeds for three years [383], in the remains of the diseased plant for at least one year [384–386], in host tissues for 615 days [387] and in cabbage stalk residues for 507 days [388]. The survival of the pathogen in naturally infected seeds for 18 and 28 months and in artificially inoculated seeds for 13 and 19 months when stored at room temperature and 10 °C, respectively, was reported. It was also found that the bacterium survives in infected stems and leaves in both dry and wet soil, but survival in wet soil was longer at later stages. It was also reported that the bacterium survives for 35 and 14 days in soils with a moisture content of 50 and 10–25%, respectively. The bacterium was isolated from seed washes and plant residues of cauliflower and cabbage, indicating that the pathogen survives in all of these sources, and suggested that survival on asymptomatic weed hosts may be problematic for understanding the epidemiology of the disease. Оцінювали [389] isolates of *X. campestris* pv. *campestris* collected in Japan from various diseased cruciferous plant species were tested for their virulence on cultivars with race-specific resistance to the pathogen. Only two races out of the 5 previously described were identified in Japan by differentiation. One hundred and sixty-four isolates of *X. campestris* pv. *campestris* and other *X. campestris* pathogens known to infect cruciferous plants (*X. campestris* pvs. *aberrans*, *raphani, armoraciae*, and *incanae*) were also evaluated by inoculation onto differential series of Brassica spp. to determine pathogenicity to cruciferous plants and race. Of these, 144 isolates were identified as *X. campestris* pv. *campestris* and grouped into six races, with races 1 (62%) and 4 (32%) predominating [166].

Developed [390] a sensitive and specific assay for detection of *X. campestris* pv. *campestris* by PCR using species-specific primers based on hrpF gene sequences. To evaluate the genetic diversity of pathogenic strains of *X. campestris* pv. *campestris*, the following were used [391] repeated DNA polymerase chain reaction (rep-PCR) using repeated extragenic palindromic, enterobacterial repeated intergenic consensus and BOX primers. З чорною гниллю хрестоцвітих можна боротися за допомогою культурних, хімічних, біологічних методів і методів стійкості хазяїна. З цією хворобою можна боротися шляхом обробки насіння гарячою водою впродовж 30 хвилин при температурі

50 °C. Однак це знижує життєздатність насіння і не знищує патоген повністю [392]. The location of the nursery should be changed frequently. To reduce the secondary spread of the pathogen, it is recommended to [393] use grass mulch, which reduces the degree of spraying of infected soil and, consequently, the secondary spread of the pathogen. Crop rotation with non-cruciferous crops should be maintained for 3–5 years. Assumed [394], that cultural practices can be conditioned to be used effectively for environmentally sound disease management in the field, either alone or as a component of integrated disease management. The strong antibacterial activity of Anacardium occidentale Linn. essential oil was reported against *X. campestris* pv. *Campestris* [395]. Some plant species have also been reported to have inhibitory activity against X. campestris pv. campestris. Reported [396], that extracts of twenty plant species exhibit antibacterial activity against *X. campestris* pv. *campestris* in the laboratory [397]. It is noted that biological control of this disease is still in its infancy. Endophytic bacterial strains isolated from cabbage leaves showed antagonistic activity both in greenhouse and field conditions [398]. The strains EN4 (*Kluyvera ascorbata*) and EN5 (*Alcabegenes piechaudii*) showed a decrease in disease incidence by 70.8% and 41.7%, respectively, while EN4 showed the greatest reduction in disease severity (77%) when the antagonist was applied 4 days before treatment and simultaneously, and antibiosis was considered as the mode of action of antagonists. The combined treatment of cauliflower seeds with SP009s (*Pseudomonas fluorescens*) at 1.5 units plus 4 times foliar spraying with SP007s (Bacillus sp.) at 0.1 units on days 14, 28, 32 and 46 after planting had the greatest potential to stimulate growth and reduce the intensity of black rot development, which led to a decrease in the incidence by 82.08% [399]. Various researchers around the world have used various fungicides and antibiotics in the form of foliar sprays to combat the disease. Recommended [400] 2–3 sprays with Cosid (0.5%), Cuprofix M (0.5%), copper oxychloride (0.5%) or dithane Cuprofix (0.5%) to control black rot of cabbage. Effective control of black rot has been reported with 3 foliar sprays of Kobox (containing 50% Cu) 4 g/l at 2-week intervals. Resistance to black rot caused by *Xanthomonas campestris* pv. *campestris* was studied on *Brassica oleracea*, *B. campestris* and *B. napus* [401] and suggested that the nonspecific stem resistance found in Chinese cabbage, broccoli, and kale may be an alternative means of

genetic protection against the pathogen. Resistance to the six known races of cruciferous black mold is absent or very rare in Brassica oleracea (genome C). However, race-specific broad-spectrum resistance (to typical strains of all six races) is often found in other Brassica genomes, including B. rapa (*Brassica campestris*) (genome A) [402]. As the pathogen is seed-borne and also survives in infected plant residues in the soil, success in disease control can only be achieved by applying an integrated approach to disease management. The use of *B. subtilis* for seed treatment, seed treatment + seedling treatment, seed treatment + seedling treatment + soil drenching, and seed treatment + soil drenching was effective in controlling *X. Campestris* [403]. Late infections can become a "wound" for the penetration of other putrefactive organisms and cause significant damage during storage. The bacterium survives in infected seeds for up to three years. Therefore, more attention should be paid to eliminating seed-borne infections. Controlling black mold begins with identifying potential sources of disease survival and using an integrated pest management strategy that includes host resistance, sowing disease-free seeds, avoiding disease spread, and proper sanitation. Sanitation is the primary method that reduces, eliminates, or removes the initial sources of disease. Common sanitation practices include crop rotation, seed disinfection, pruning of diseased plants, elimination of waste dumps, and destruction of alternative hosts. The development of crop varieties with disease resistance or tolerance to black mold is the focus of many breeding programs around the world. Today, many cruciferous crop hybrids with black mold tolerance are available for both fresh and processed commercial production.

1.2. Prevalence and damage of major diseases of cruciferous crops

Rapeseed diseases are less important than pests in terms of their economic value. Spring rapeseed suffers from the same diseases as winter rapeseed, but their spread and economic importance are usually less.

In continental regions, diseases cause less damage than in Western and Central Europe. If crop rotation rules are followed (returning rapeseed, including other cruciferous crops and beets, to the same place in three to four years), keeping the share of cruciferous crops, legumes and beets in the crop rotation no higher than 25%, and taking appropriate agronomic measures, fungicide use (which often does not pay off) is usually unnecessary.

But with the growing saturation of crop rotations with rapeseed and other host plants, typical crop rotation diseases are spreading more strongly. This is especially true for sclerotinia (*Sclerotinia sclerotiorum*), verticillium (*Verticillium longisporum*), cabbage clubroot (*Plasmodiophora brassicae*), root neck and stem necrosis (*Leptosphaeria maculans*, anamorph – *Phoma lingam*), gray spot (*Pyrenopeziza brassicae*, anamorph – *Cylindrosporium concentricum*) and white spot (*Mycosphaerella capsella*, anamorph – *Pseudocercosporella capsellae*), the causative agents of which accumulate in soils, as well as Alternaria spp.), whose pathogens live in terrestrial plant debris. While breeding for resistance to root collar necrosis, gray spot and cabbage clubroot has led to some success, control of verticillium and white rot has become a major problem in many growing regions.

Studies conducted in recent years have shown that the shortfall in the yield of spring rape seeds from diseases, depending on the variety and technology of its cultivation, ranges from 15 to 70% or more, with significant deterioration in its sowing and technological qualities [404–405]. In general, losses of field crops from pests have increased by 1.2–1.7 times compared to the losses of 1970–1980. The share of losses has changed significantly: from weeds it is 39.2%, diseases – 34.5%, pests – 26.3% [406–407].

It was found that when rapeseed pods are affected, the oil content in seeds, depending on the pathogen, decreases by 1.3–3.4 times, the specific gravity of palmitic, stearic, erucic, eicosic, linolenic acids increases significantly, while the specific gravity of oleic and linoleic acids decreases.

Crop losses in Germany as a result of severe alternaria damage can reach 50%, and even with moderate disease development, losses can reach 20% [408]. In Canada, losses reach up to 42% in some years [409].

When pods are affected by Alternaria, the photosynthetic surface of the valves and seeds decreases. This can cause premature "ripening" of plants, which is manifested in pods cracking and the formation of underdeveloped seeds. Affected seeds inside the burst pods shrivel up in dry weather and fall out unripe [410]. Sources of infection are infected seeds and post-harvest residues of plants, in which the pathogen is stored in the form of conidia and mycelium [411]. In this case, genotypes in which the accumulation of plastic substances depends more on plastids located in the seeds and pods are more affected. These are samples with a higher content of linolenic acid. It is possible that breeding for a lower content of linolenic acid leads to an increase in alternaria resistance. The opposite effect was not observed. Thus, when the surface of the pods was damaged by Alternaria with an intensity of more than 25%, the chemical composition of the seeds did not change [412–413]. At the same time, a high correlation was found between linolenic acid and the productivity of affected plants, and this relationship increases with the increase in the damage score. This is probably due to the fact that linolenic acid is involved in the photosynthesis of immature seeds and green pods [414–415].

Yield losses as a result of severe alternaria infection amounted to 50%, and with moderate disease development they reached 20%. In Canada, this figure reached 42%. In the UK, when about 10% of the surface area of the rapeseed pod was affected by the disease, the loss of seed yield was about 10%, and each additional percentage of damage led to a decrease in yield by 1% [416]. The weight of 1000 seeds depends on the degree of pods' damage by the disease. Thus, in spring rape of the Kovalevsky variety, it was 3.0 times lower when plants were affected by Alternaria, and in winter rape of the Tysmenytsia variety, it was 2.7 times lower compared to healthy plants. When rape plants are damaged by Alternaria, both seed weight and oil content are reduced. It was found that the oil content of winter and spring rape seeds affected by the black spot pathogen decreased by 23.2–27.5%, and the content of palmitic acid in rapeseed oil increased by 4.6–2.4%; stearic acid – by 3.2 and 2.3%; linoleic acid – by 9.1 and 5.1 %; erucic acid – by 3.6 and 3.9%; eicosene acid – by 3.3 and 2.8%, respectively.

The content of oleic acid, respectively, decreases by 19.2 and 10.9%; linoleic acid – by 4.6 and 5.6% [417–418].

In the UK, it has been found that when the surface of the pod is affected by more than 10% of the area, each additional percentage leads to a 1% reduction in yield. With a smaller pod area, yield losses vary. With 10% of the pod area affected, losses are approximately 10% [419]. The harmfulness of Alternaria is reduced in samples with rapid drying of pods, as this reduces the likelihood of damage.

Species of the genus Alternaria spp. in rapeseed agrocenosis do not have a narrow affiliation to certain organs and are able to affect all vegetative and generative organs of the plant, E. communis/brassicae – stems, leaves and pods. Species such as *P. brassicae* f. *brassicae* and *B. cinerea* affect only leaves. *F. oxysporum* and *V. dahliae* species, being the causative agents of tracheomycotic wilt, cause blockage or necrosis of the leading xylem vessels, which often leads to complete plant death. Root and stem rot pathogens are very harmful to rapeseed plants, caused by the fungi *S. sclerotiorum* and *S. bataticola*. The damage to such important plant organs as roots and stems leads to wilting or complete death of rapeseed. The fungus *Ph. lingam* is one of the most common and harmful species on winter rape and can also cause premature plant death.

The correlation between the severity of black spotting of pods on the main shoot and the yield was established ($r = -0.67$, $P < 0.02$) [420]. The weight of 1000 seeds under the influence of A. brassicae and A. brassicicola in spring rape of Kovalevsky variety is 3.0 times lower and in winter rape of Tysmenytsia variety 2.7 times lower compared to healthy [421] There is a discrepancy between the ranks of breeding samples in terms of damage and productivity reduction. Alternaria infection has a significant impact on laboratory germination of seeds and, especially, on germination energy, which varies from 62 to 90%.

Oil content of winter and spring rape seeds affected by Alternaria pathogens decreases by 23.2–27.5%. When winter rape seeds are affected by Alternaria pathogens, the content of palmitic acid in the oil increases by 4.6 and spring rape – by 2.4; stearic acid – by 3.2 and 2.3, respectively; linolenic acid – by 9.1 and 5.1; erucic acid – by 3.6 and 3.9; eicosene acid – by 3.3 and 2.8%. The content of oleic acid, respectively, decreases by 19.2 and 10.9; linoleic acid – by 4.6 and 5.6% [166].

It has been proven that seed yield losses due to downy mildew can be 10–30%. Under conditions favorable for the spread and development of Alternaria, seed yield losses can reach up to 30%, and in years of epiphytotic development of the disease – up to 50% or more, as in the case of phomosis. When rapeseed is affected by white mold, the yield loss is caused by the loss of young plants, premature seed maturation and pod cracking, a decrease in the weight of thousands of seeds and can reach 50%, and in years of epiphytic development of the disease – and more [422]. In view of the above, studies on the dependence of spring rape productivity on the disease complex are relevant in order to regulate the most effective control of plant damage by pathogens.

When pods are affected by *Ph. lingam* Desm, seed weight decreases in winter rape by 2.2 and in spring rape by 2.3 times, oil content – by 21.2–23.8%. The content of palmitic acid in the oil increases by 2.7 and 1.1; stearic acid – by 2.1 and 1.8; linolenic acid – by 5.2 and 3.0; erucic acid – by 3.8 and 2.6; eicosic acid – by 1.8 and 1.9%, respectively. The content of oleic acid decreases by 13.5 and 7.0; linoleic acid – by 2.1 and 3.4%, respectively [442].

In the course of the research, a close correlation was established (Table 1.21) between the severity of spring rape plants with diseases and the number of plants per square meter, as evidenced by the correlation coefficients obtained, the only exception was the damage by Alternaria, where the correlation coefficient was 0.51. In addition, a close correlation was found between the severity of spring rape crops with the studied diseases and the weight of seeds per plant and the number of seeds per pod. Regarding the number of pods per plant, the correlation is not close when spring rape is affected by phomosis, white rot, gray rot and a complex of the studied diseases (Table 1.21). In the study of the correlation between the weight of 1000 seeds and the severity of spring rape plants with diseases, it was found that the dependence is close in relation to the damage by all diseases, except for Alternaria.

The established close correlation between the elements of the yield structure and the severity of spring rape diseases is confirmed by the close correlation between the yield of spring rape and the severity of its diseases under study. Using the regression equations calculated on the basis of correlation and regression analysis between the values of disease severity (Y)

and seed yield (X) of spring rape, it is possible to quantitatively predict the change in yield using the values of disease severity of spring rape.

The linear regression equation of the form y = -6.4237x + 21.046 indicates that with a 1% increase in the incidence of Alternaria in spring rape, the yield of its seeds will decrease by 0.16 t/ha. Based on the coefficient of determination (R2 = (0.808)2 = 0.65), approximately 65% of changes in the yield of spring rape seeds are due to changes in the incidence of Alternaria, and 35% of changes are due to other factors.

The regression coefficient (b = -3.755) of the linear regression equation y = -3.755x + 11.945 indicates that with an increase in the amount of spring rape phomosis infection by 1%, the yield of its seeds will decrease by 0.27 t/ha. The coefficient of determination (R2 = (0.79)2 = 0.62) indicates that 62% of changes in the yield of spring rape seeds are due to changes in the amount of phomosis infestation, and 38% of changes are due to other factors.

Table 1.21

Correlation matrix between seed yield and disease incidence in spring rape [423]

Disease prevalence, %	Number of plants per 1 m², pcs.	Seed weight from 1 plant, g/plant	Structures per plant, pcs.	Seeds in a pod, pcs.	Weight of 1000 seeds, g	Yield, t/ha
Alternariosis	0.51	– 0.92	– 0.87	– 0.86	– 0.39	– 0.81*
Phomosis	0.75	– 0.98	– 0.69	– 0.93	– 0.71	– 0.79
White rot	0.84	– 0.94	– 0.52	– 0.92	– 0.83	– 0.78
Gray rot	0.93	– 0.70	– 0.07	– 0.75	– 0.96	– 0.72
Peronosporosis	0.70	– 0.93	– 0.96	– 0.94	– 0.88	– 0.90
The complex is above mentioned diseases	0.65	– 0.80	– 0.52	– 0.78	– 0.77	– 0.80

The regression coefficient (b = -5.4559) of the linear regression equation y = -5.4559x + 17.218 indicates that with an increase in the incidence of white rot in spring rape by 1%, the seed yield will decrease by 0.18 t/ha. The coefficient of determination (R2 = (0.784)2 = 0.61) indicates that 61% of changes in the yield of spring rape seeds are due to changes in the amount of white mold damage, and 39 % of changes are due to other factors.

The regression coefficient (b = -4.3224) of the linear regression equation of the form y = -4.3224x + 14.143 indicates that with an increase in the amount of gray mold infestation of spring rape by 1%, the yield of its seeds will decrease by 0.23 t/ha. The coefficient of determination (R2 = (0.715)2 = 0.51) indicates that 51% of changes in the yield of spring rape seeds are due to changes in the amount of gray mold damage, and 49% of changes are due to other factors that were not taken into account.

The regression coefficient (b = -6.0075) of the linear regression equation of the form y = -6.0075x + 18.477 indicates that with an increase in the amount of damage by peronospora of spring rape by 1%, the yield of its seeds decreases by an average of 0.17 t/ha within the considered row. The coefficient of determination (R2 = (0.899)2 = 0.8077) indicates that 81 % of changes in the yield of spring rape seeds are due to changes in the amount of damage by peronosporosis, and 29% of changes are due to other factors.

During the growing season, spring rape crops are affected by pathogens not only of one disease, but of the whole complex. Therefore, it was of interest to establish the relationship between its susceptibility to a complex of diseases (Alternaria, Phomosis, white rot, gray rot, peronosporosis) and seed yield. In the process of correlation analysis of the values of the above indicators, a close correlation coefficient of 0.80 was obtained (Table 1.22).

The regression coefficient (b = -5.3504) of the linear regression equation of the form y = -5.3504x + 16.832 indicates that with an increase in the severity of the spring rape disease complex by 1%, the yield of its seeds decreases by an average of 0.19 t/ha within the considered row. The coefficient of determination (R2 = 0.6424) indicates that 64 % of changes in the yield of spring rape seeds are due to changes in the severity of the disease complex, and 36 % of changes are due to other factors. The reliability of the presented equations is characterized by the following limits of experimental values: for yield – from 1.6-1.7 to 2.7-2.9 t/ha, Alternaria – from 1.9 to 11.0, Phomosis – from 0.7 to 6.1, white rot – from 0.9 to 8.0, gray rot – from 1.4 to 7.4 and downy mildew – from 2.4 to 9.1%. By studying the correlation-regression equation between the values of the disease complex (Y) and seed yield (X) of spring rape, it was found that the equation is valid within the experimental values from 1.6 to 3.0 t/ha for seed yield and from 0.9 to 8.5% for the disease complex.

The obtained data of correlation and regression dependence between the severity of spring rape by the studied diseases and seed yield made it possible to calculate the maximum permissible severity of plants by various diseases in order to obtain the theoretically possible calculated yield (Table 1.22), which is very important in regulating the degree of severity of spring rape by diseases. In the course of calculations, the need to reduce the severity of spring rape diseases with an increase in the planned seed yield was established.

It has been established that in order to obtain 1.5 t/ha of spring rape seeds, the damage by a complex of diseases should not exceed 11.04%, including Alternaria – 13.99, Phomosis – 8.03, gray rot – 12.47, white rot – 10.44 and peronosporosis – 11.11 %, and in order to to obtain a seed yield of 2.5 t/ha, the incidence of spring rape with a complex of diseases should not exceed 2.72 %, including Alternaria – 4.13, Phomosis – 1.99, white rot – 3.53, gray rot – 2.01 and downy mildew – 3.67 %.

A close correlation was found between the susceptibility of spring rape to a complex of diseases, including Alternaria, Phoma, white rot, gray rot and downy mildew, and such elements of the yield structure as the number of plants per square meter, seed weight per plant, number of pods per plant, number of seeds per pod and weight per thousand seeds. It was found that the correlation coefficient between seed yield and the susceptibility of spring rape to Alternaria was -0.81, Phomosis – -0.79, white rot – -0.78, gray rot – -0.72, peronospora – -0.90 and the above-mentioned disease complex – -0.80. In order to obtain the theoretically possible predicted yield of spring rape seeds of 2.5 t/ha, the damage to its crops by a complex of diseases should not exceed 2.72%, including Alternaria – 4.13, Phomosis – 1.99, white rot – 3.53, gray rot – 2.01 and peronospora – 3.67 % (Table 1.23).

Based on the research conducted [424] the study of the harmfulness of Fusarium depending on the time of appearance of external symptoms, data were obtained on the number of diseased branches on the plant, the number of diseased pods and the total number of pods formed on the plant. All these data formed the basis of an eleven-point scale developed by the authors to calculate the intensity of Fusarium wilt damage to rapeseed plants by the area of the affected part of the stem or individual branches of plants, similar to the scale proposed for calculating the development of white rot in rapeseed [381]. The scoring scale is as follows:

– 0 points – no damage;

– 1 point – one branch with up to 10% of pods of the total number of pods on the plant is affected;
– 2 points – one branch with up to 20% of pods formed;
– 3 points – one or two branches – up to 30%;
– 4 points – two to 40%;
– 5 points – three or four – up to 50%;
– 6 points – three to five – up to 60%;
– 7 points – four to five – up to 70%;
– 8 points – five to six – up to 80%;
– 9 points – six to seven – up to 90%;
– 10 points – all branches are affected – 100% of pods.

Table 1.22

Forecast of spring oilseed rape seed yield depending on its disease severity [443]

Theoretically possible estimated yield, t/ha	Affected, %					
	disease complex	including				
		alternariosis	phomosis	white rot	gray rot	peronosporosis
0,1	22,70	27.78	16.50	25.00	22.26	20.78
0,5	19,37	23.84	14.08	21.42	18.88	18.55
1,0	15,21	18.91	11.06	16.95	14.66	14.09
1,5	11,04	13.99	8.03	12.47	10.44	11.11
2,0	6,88	9.06	5.01	8.00	6.23	6.65
2,5	2,72	4.13	1.99	3.53	2.01	3.67

Table 1.23

Fusarium damage on spring rape and mustard, 2018–2021 [443]

Crops	Disease severity, % by lesion score				
	1 point	2 point	3 point	4 point	on average
Spring rape	12.6	43.2	60.4	71.2	46.8
Brown mustard	16.6	50.1	70.1	82.4	54.8
White mustard	22.7	44.8	64.1	87.2	54.7

It was also noted that disease damage to winter rape and winter mustard led to lower yield losses compared to spring crops. The highest yield losses were noted when symptoms of Fusarium wilt appeared in the flowering

phase – 100%. With a strong degree of damage to the seed filling phase (green pod), the yield per plant decreased by 8.5%, medium – by 7.4 and weak – by 3.8% compared to the control, i.e. yield losses amounted to 94.4%, 82.2% and 42.2%, respectively. Yield losses are expressed as a percentage per plant compared to the control (healthy plant). A similar pattern of yield decline was observed at a later stage of the disease: with a mild degree of Fusarium infection in the yellow-green pod phase, yield losses amounted to 3.3%, with an average – 31.1, and with a strong one reached 76.7%.

The weight of 1000 seeds of rapeseed plants affected by Fusarium wilt in the green and yellow-green pod phase was 1.4 and 1.6 g, respectively, and in healthy plants – 2.5 g. The study of some biochemical characteristics of rapeseed seeds from healthy and Fusarium-affected plants showed that with severe damage in the yellow-green pod phase, seed oil content decreased by 3.7%, and in the green pod phase – by 14.0% compared to the control (seeds from unaffected plants). As for the content of glucosinolates in the seeds, an inverse relationship is observed. The level of glucosinolates decreases from a mild to a severe degree of damage and from the later phase of plant death to the earlier one.

On the other hand, the defeat of winter rape and mustard plants by phomosis reduced their productivity by an average of 36.1–37.1%. The lowest harmfulness of the disease on both crops was observed at a degree of plant damage of 1 point, i.e. 13.2–14.1%. Differences were noted at 2 points of plant damage: the damage was moderately high (26.5%) on rapeseed crops and high (32.5%) on mustard. The infestation of rapeseed and mustard plants with 3–4 points of damage led to a significant decrease in yield (by 48.1–56.7% and 45.1–56.6%, respectively).

Thus, with a severe degree of damage in the yellow-green pod phase, the amount of glucosinolates was 8.5 μmol/g, and in the green pod phase – only 6.8 μmol/g.

Observations showed that necrosis of various sizes caused by *A. brassicae* was present only on the lower and middle leaves, not spreading to the stem of plants in all studied cultures. The mycelium of E. communis in the form of a white web covered all plants, but did not penetrate into organ tissues. The infectious material of fungi of the genus Alternaria nees was isolated on all studied crops only from the

shells of pods. In addition, single plants of rapeseed (spring and winter) and winter mustard affected by phytoplasma (pathogens – Aster yellows phytoplasma) were observed.

Thus, the damage to plants of these crops by downy mildew, powdery mildew, Alternaria and phytoplasma during the years of research at the experimental plots did not lead to a decrease in the quality and quantity of seed yield. Fusarium was the most harmful on spring rape, black mustard and white mustard; phomosis in the form of stem cancer and stem form of sclerotinia were the most harmful on winter rape and black and brown mustard. As a result of the research, it was found that Fusarium damage to plants caused an average significant decrease in the productivity of spring crops: spring rape – by 46.8%, white mustard and black and brown mustard – by 54.7–54.8%. Fusarium damage on rapeseed ranged from low (12.6%), when plants had 1 point of damage, to high (43–2-71.2%), when plants had 2–4 points of damage. Infestation of black mustard and white mustard plants with 1 point led to a decrease in yield by 16.6–22.7% (average degree of damage), and 2–4 points led to a significant decrease in yield: 50.1–82.4% on brown mustard and 44.8–87.2% on white mustard (Table 1.24).

Table 1.24

Harmfulness of phomose rot on winter rape and mustard, 2018–2021 [353]

Crop	Disease severity, % by lesion score				
	1 point	2 point	3 point	4 point	on average
Winter rape	13.2	26.5	48.1	56.7	36.1
Winter mustard	14.1	32.5	45.1	56.6	37.1

It has also been established [97], that phomosis causes a significant decrease in both the number of leaves per plant and its leaf surface in rapeseed. In healthy plants in the flowering phase, the number of leaves was 36 pcs. and in phomosis-infected plants – 30 pcs. The leaf surface area of the affected plants was 1.5 times less than that of healthy plants (Tables 1.25–1.26).

Table 1.25

Influence of the pathogen *Phoma lingam* D. on the physical and chemical properties of spring rape plant tissue (Kalinovsky variety)

Plant condition	Dry matter content, %	Osmotic pressure of cell sap, atm	Transpiration intensity mg, water per 1 cm^2 per hour
Healthy	15.21	17.31	77.51
Affected	18.10	23.31	21.23

Table 1.26

Effect of phomosis on photosynthesis intensity and photosynthetic potential of spring rape plants (Kalinovsky variety)

Plant condition	Photosynthesis intensity, mg/CO_2 per square meter per hour	Number of leaves per plant, pcs.	Leaf area of one plant, sq. cm
Healthy	3.51	36.0	601.4
Affected	1.27	30.0	400.3

The intensity of photosynthesis in healthy rapeseed leaves was 3.51 mg/CO_2 per square meter per hour, and in the affected ones – 1.27.

Along with the disruption of photosynthesis, the decrease in yield in plant disease is associated with increased respiration. The reason for the intensification of the process of respiration of the diseased plant is a response to physiological irritation caused by the penetration of pathogens.

The protective role of respiration is expressed in:

1) inhibition of the activity of hydrolytic enzymes of microorganisms;

2) decontamination of toxic compounds by oxidation to final physiolo-gically neutral decomposition products;

3) participation of oxidative enzymes in the synthesis of cell wall substances, which is associated with the restoration of the affected surface, as well as the formation of mechanical barriers to the penetration of infection and its further spread in the tissues of the host plant.

The increase in respiration rate in the tissues of the affected plant depends on its resistance to the disease. In susceptible varieties, the respiration process is weakened and even stops after a while. This is due to

the full utilization of the plastic substances of the affected tissue. In resistant varieties, however, the intensity of respiration in tissue damage remains elevated even after the infection is suppressed [425].

In addition, it is reported [445] about a 1.16-fold increase in peroxidase activity in leaves of the spring rape variety Kalynivskyi affected by downy mildew compared to the variety Valero. A similar increase in activity (1.17 times) was recorded in phomosis lesions. The analysis of the data in Table 1.27 confirms that the resistance of the spring rape variety Kalinovsky is manifested in the ability of affected plant cells to induce an increase in the amount of peroxidase. In addition, our studies also revealed [445] an increase in lignin biosynthesis in the affected tissues of spring rape.

The analysis of the data shows that in the leaves affected by downy mildew in the resistant variety Kalinovsky the lignin content was 1.3 times higher than in the relatively susceptible variety Valero. A similar increase was recorded in the case of phomosis. The increase in lignin content in plant tissues and its interaction with cell membrane components, in our opinion, contributes to the activation of the protective function in the resistant variety of spring rape Kalinovsky (Table 1.28).

In the process of research [445] the content of nitrogen (protein, non-protein, total) in rape varieties with different disease resistance was also determined.

Table 1.27

Peroxidase activity in varieties of spring rape with different disease resistance

Variety	Disease	Leaves	Peroxidase activity ml of 0.1 normative iodine per 1 g of crude substance
Kalinovsky	Downy mildew	Healthy	8.9
		Affected	12.6
Kalinovsky	Phomosis	Affected	13.3
Valero	Downy mildew	Healthy	8.5
		Affected	10.8
Valero	Phomosis	Affected	11.3

Table 1.28

Lignin content of spring rape varieties with different disease resistance

Variety	Disease	Leaves	Lignin content, %.
Kalinovsky	Downy mildew	Healthy	0.38
		Affected	0.65
Kalinovsky	Phomosis	Affected	0.60
Valero	Phomosis	Affected	0.51
	Phomosis	Affected	0.47

The table shows that in the affected plants of spring rape of the resistant variety Kalinovsky the content of protein nitrogen is 0.3% higher than in the susceptible variety Valero, non-protein nitrogen – by 0.1%, and total nitrogen, on the contrary, is lower by 0.17% (Table 1.29).

Table 1.29

Nitrogen content in varieties of spring rape with different disease resistance (in mg per 100 g of crude matter)

Variety	Disease	Leaves	Protein nitrogen	Non-protein nitrogen	Total nitrogen
Kalinovsky	Downy mildew	Healthy	2.41	0.58	2.88
		Affected	1.62	0.81	2.22
Kalinovsky	Phomosis	Affected	1.80	0.65	2.51
Valero	Downy mildew	Healthy	2.05	0.68	2.48
		Affected	1.31	0.70	2.39
Valero	Phomosis	Affected	1.36	0.59	2.17

Thus, the studies found that the loss of protein nitrogen in diseased plants of the resistant spring rape variety was less than in a similar disease of a relatively susceptible variety, and the loss of total nitrogen, on the contrary, was greater.

Thus, the defeat of *Phoma lingam* D. in plants of spring rape variety Kalynivsky is accompanied by a violation of metabolic processes in plant cells. Under the influence of extracellular enzymes of the pathogen in the affected tissues of rapeseed plants, the content of dry matter and osmotic pressure of cell sap increases, and the assimilation process is delayed, which leads to a violation of the water regime. The end result of the disturbed metabolic process in the cell is the rapid drying and death of leaves and even rapeseed plants.

Along with impaired photosynthesis, the intensity of respiration increases in diseased rapeseed cells, in which oxidizing enzymes such as peroxidase, catalase, polyphenol oxidase, etc. take an active part. Redox processes occurring in diseased plant cells under the influence of enzymes contribute to the biosynthesis of lignin in cell walls, the accumulation of ascorbic acid, etc.

The protective role of respiration is expressed in the inhibition of the activity of hydrolytic enzymes of the pathogen, oxidation and decontamination of its toxic compounds, as well as the formation of mechanical barriers to the penetration and spread of infection in host plant tissues, etc.

It has also been proven [445], that in the resistant variety Kalinovsky, the difference in ascorbic acid content in healthy and downy mildew-affected leaves was 2.7 mg%, and in phomosis – 3.4 mg%. At the same time, in the relatively susceptible variety Valero, the difference was 12.6 mg% in the first case and 13.9 mg% in the second (Table 1.30). In the Kalinovsky variety, the amount of ascorbic acid exceeded the Valero variety by 15.8 mg%, affected by downy mildew, and by phomosis – by 16.4 mg%.

Table 1.30

Ascorbic acid content in leaves of different resistance to diseases of spring rape varieties [445]

Variety	Disease	Leaves	Ascorbic acid content mg 100 g.s.p.
Kalinovsky	Downy mildew	Healthy	40.3
		Affected	37.6
Kalinovsky	Phomosis	Affected	36.9
Valero	Downy mildew	Healthy	34.4
		Affected	21.8
Valero	Phomosis	Affected	20.5

Similar studies have also shown the role of ascorbic acid in the identification of spring rape downy mildew. As a result of biochemical studies, it was found that on average over three years of research, the content of ascorbic acid in the affected leaves of susceptible plants of the Furrat variety decreased by 22.6 and 28.6% compared to healthy ones, while in

resistant varieties Vasylkivskyi – by 16.4 and 21.6% and Kovalevskyi – by 14.2 and 2.7%, respectively (Table 1.31).

Thus, the decrease in ascorbic acid content in the susceptible variety is more pronounced than in the resistant varieties. The rapid decrease in the content of ascorbic acid under the influence of the pathogen reduces the resistance of plants to the pathogen and contributes to the successful course of the pathological process.

Additionally, it is noted that when rapeseed plants are affected by the pathogen downy mildew, the activity of peroxidase increases in different resistance varieties of rapeseed Yarogoak, In resistant varieties Vasylkivskyi and Kovalevskyi, the activity of peroxidase in moderately affected leaves was on average 3 and 0.7 times higher than in the susceptible variety Furrat, and in heavily affected leaves the activity of peroxidase was 4.4 and 1.1 times higher, respectively. It should be noted that the difference in the content of peroxidase between diseased and healthy plants in all studied varieties was approximately the same. Thus, the peroxidase enzyme plays an important role in the plant's defense functions against the pathogen. In more resistant varieties, the activity of peroxidase increases and depends on the degree of disease development.

It is noted that the harmfulness of sclerotinia on winter rape and mustard also depended on the degree of plant damage, increasing from low at 1 point (9.7% and 14.8%, respectively) to high at 4 points (66.7% and 14.8%, respectively). damage (66.7% and 70.7%, respectively).

On average, the yield losses of rape due to the disease were lower compared to mustard – 35.3% and 43.9%, respectively (Table 1.31). The results of the same studies indicate (Table 1.32) that the content of the main ash elements in mg/kg of green mass varies in different resistance varieties of winter rape.

Thus, in the variety Tysmenytsia, which is the standard, the content of ash elements in healthy plants was significantly lower than in the affected ones, potassium was 20 mg/kg less, sodium – 0.8 mg/kg, manganese – 28.7 mg/kg, calcium – 9.7 mg/kg, copper – 0.8 mg/kg. The same pattern is observed for the Fedorivsky Improved and Xaverivsky varieties, although the difference is much smaller. As for iron, on the contrary, it accumulates much more in healthy plants by 39.0–43.0 mg/kg of green mass. Such data suggest that metabolic processes in affected plants are much slower and

the plants themselves begin to age earlier, and therefore more ash elements accumulate in affected plants (Table 1.32).

Table 1.31

Ascorbic acid content (leaves) in spring rape varieties with different resistance to downy mildew, mg% per 100 g of dry matter [426]

Variety	Plant condition	Ascorbic acid content in the budding phase			
		1981	1982	1984	Average
Furrat	Healthy	48.7	45.6	48.1	47.5
	Moderately injured	23.6	24.9	26.1	24.9
	Severely injured	16.5	20.1	20.0	24.9
	SSD_{05}	0.3	10.2	0.4	–
Vasilkovsky	Healthy	40.3	41.4	58.3	46.7
	Moderately injured	35.5	28.7	26.6	30.3
	Severely injured	26.4	25.4	23.4	25.1
	SSD_{05}	0.8	0.3	0.4	–
Kovalevsky	Healthy	46.4	47.3	57.7	50.5
	Moderately injured	36.0	38.0	34.9	36.3
	Severely injured	28.6	32.1	19.5	26.8
	SSD_{05}	0.2	2.2	1.9	–

Analysis of the quality indicators of rapeseed green mass showed that their content in affected plants was significantly lower than in healthy plants, and the ash content was 0.5–0.7% higher. In the winter rape variety Fedorivsky, the improved dry matter content was 0.2–0.9% higher, and protein, respectively, by 0.5–2.5%. All other parameters were equivalent (Tables 1.33–1.35).

Visual assessment of spring rape, black and white mustard, and winter rape and mustard crops during the years of research showed that the plants were affected by harmful diseases: Fusarium, Phomosis and Sclerotinia with varying degrees of damage, from 0 (healthy plant) to 4 (completely affected plant) points.

The greatest decrease in plant productivity among all studied crops was observed in [353] of the studied crops at a damage level of 4 points. However, the harmfulness of Fusarium on spring rape, black and brown and white mustard, sclerotinia and phomosis of winter mustard at plant severity of 2 and 3 points was also high, indicating a significant negative impact of these diseases on plant productivity of the studied crops. Damage to

winter rape and mustard resulted in a smaller decrease in plant productivity compared to spring crops. Fusarium infection significantly reduced the productivity of plants of spring rape, black and brown mustard and white mustard. The maximum damage of the disease reached 71.2, 82.4 and 87.2%, respectively, and the degree of plant damage was 4 points. The productivity of winter rape and brown mustard plants was significantly reduced by phomosis in the form of stem cancer and stem sclerotinia, reaching 56.7 and 66.7 %, respectively, in rape and 56.6 and 70.7% in mustard.

Table 1.32

Peroxidase activity (leaves) in spring rape varieties with different resistance to peronosporosis, ml of 0.1 N iodine per 1 g of crude matter [445]

Variety	Plant condition	Peroxidase activity during the budding phase			
		1981	1982	1984	Average
Furrat	Healthy	6.5	6.9	2.4	5.3
	Moderately injured	9.7	10.2	2.8	6.6
	Severely injured	12.6	13.1	3.2	9.7
	SSD_{05}	0.7	0.5	0.2	–
Vasilkovsky	Healthy	8.2	9.5	6.4	8.0
	Moderately injured	11.6	11.4	8.8	10.6
	Severely injured	14.6	16.7	11.0	14.1
	SSD_{05}	0.5	0.8	0.8	–
Kovalevsky	Healthy	7.9	8.8	1.6	6.1
	Moderately injured	10.8	12.2	2.0	8.3
	Severely injured	14.5	15.1	2.7	10.8
	SSD_{05}	1.4	0.6	0.6	–

Table 1.33

Content of main ash elements in mg/kg of green mass of winter rape varieties with different resistance [445]

Variety	Plant condition	K	Na	Mn	Ca	Mg	Cu	Fe
Tysmenytsia (standard)	Good Doer	28.1	1.2	60.0	34.5	2.7	5.5	136.1
	Affected	30.1	2.0	90.3	44.2	3.3	6.3	97.0
Fedorovsky improved	Good Doer	27.0	1.1	61.0	35.0	2.81	5.7	137.0
	Affected	27.5	1.62	81.1	40.1	3.16	6.1	94.0
Xavierivsciy	Good Doer	27.9	1.15	61.4	35.8	2.9	5.6	138.1
	Affected	27.7	1.53	77.5	42.2	3.06	6.0	98.5

Table 1.34

Chemical composition and nutritional value of green mass of winter rape varieties with different disease resistance [445]

Variety	Plant condition	Dry matter %	Content in dry matter, %				
			Protein	Fat	Fibre	NEF	Ash
Tysmenytsia (standard)	Healthy	13.1	18.5	4.9	26.6	40.7	9.3
	Diseased	14.3	16.7	3.1	22.2	40.1	9.8
Fedorovsky improved	Healthy	14.0	19.0	4.8	26.1	40.9	9.2
	Diseased	14.5	18.2	4.5	27.0	40.6	9.7
Xavierivsciy	Healthy	13.9	18.8	4.9	25.8	40.5	9.4
	Diseased	14.4	18.5	4.7	24.4	41.0	9.9

Table 1.35

Harmfulness of sclerotinia in winter rape and mustard, 2018–2021 [353]

Crop	Disease severity, % by lesion score				
	1 point	2 point	3 point	4 point	on average
Winter rape	9.7	26.5	38.3	66.7	35.3
Winter mustard	14.8	34.7	55.4	70.7	43.9

Additionally, it is noted that plant damage during the growing season by a complex of different diseases is a problem for cruciferous crops in all countries of cultivation. The species composition of pathogens and the harmfulness of diseases on rapeseed and mustard may differ depending on the agroecological zone of cultivation. However, some diseases significantly reduce the quality and quantity of the crop in all growing regions. These diseases include Fusarium in the form of tracheomycotic wilt, Phomosis in the form of stem cancer and stem sclerotinia. Fusarium pathogens penetrate through the root system into the stems, where mycelium develops and blocks the conducting vessels, which leads to premature drying of plants, sometimes without seed formation [446]. The stem cancer form of phomose rot on rapeseed and mustard plants leads to the formation of deep ulcers (necrosis) of various diameters on the stem. The stem tissue in this area, as well as above and below the necrosis, rots, the stem breaks in this place and the plant lodges. And even if seeds are formed, they will fall out of the pods or rot inside them [429–430]. When the infectious agent of sclerotinia gets on rapeseed and mustard plants, the surface of the stem is covered with ulcers, the ulcer quickly increases in depth and width, all affected tissue discolors and becomes fibrous over time, the stems break in the affected areas, and the

seeds ripen prematurely and fall out. On the surface and inside the affected discolored stem, sclerotia are formed in large quantities [431–432].

Weather conditions during the growing season of spring and winter rapeseed and mustard have a favorable effect on the development of many pathogenic fungi: the average daily air temperature from May to July exceeded the average annual temperature by 0.5–4.0 ^{0}C, the amount of precipitation during this period was 40–110 mm, the average relative humidity for the entire growing season of crops exceeded 58%.

Research conducted [353] indicate that yield reduction from Fusarium wilt in rapeseed depends on the condition of the plants, the timing of the onset of disease symptoms and the degree of damage. Strong, moderate and weak degrees of Fusarium damage were assessed by determining:

– the percentage of dried branches on the plant out of the total number (central and lateral branches of the first order) to healthy branches;

– the number of diseased pods (partially fulfilled and completely sterile) to healthy pods (fulfilled);

– weight of seeds from diseased pods to weight of seeds from healthy pods and other quantitative indicators.

The direction of use of rapeseed oil primarily depends on the composition of fatty acids in it, the ratio between saturated, simple unsaturated and polyunsaturated fatty acids.

The following qualitative characteristics are important for the use of rapeseed oil for food purposes:

– low content of saturated fatty acids, especially palmitic acid;

– adequate content of polyunsaturated acids;

– predominance of simple unsaturated fatty acids, especially oleic acid.

Especially valuable is the content of simple unsaturated oleic acid (C 18:1). It lowers blood cholesterol level, protects human vascular system from atherosclerotic changes, regulates blood pressure level, reduces the degree of hypertension and has positive effect on diabetics.

Fusarium wilt of yellow-seeded rape significantly worsens the biochemical parameters of seeds (Tables 1.36–1.37). Thus, with a strong development of the disease in the phase of yellow-green pod, the content of oleic acid decreases by 2.5%, and in the phase of green pod – by 6.8%. At the same time, the total content of saturated fatty acids – palmitic and stearic acids – increases in seeds collected from diseased plants up to

8% with a severe degree of damage in the green pod phase and up to 6.5% in the yellow-green pod phase, compared to 5.5% in seeds from healthy plants. Apparently, this is due to the phenomenon of senescence (acceleration of the aging process) under the influence of the pathogen, which increases the outflow of plastic substances from the pod and stem valves into the seeds. The increase in the content of polyunsaturated fatty acid linolenic acid against the background of a decrease in oleic acid from a mild to a severe degree of damage and from a late onset of disease symptoms to an earlier one makes the oil obtained from such seeds not meet the requirements for food quality, but is suitable for technical purposes.

Proved [448] a close dependence of the total yield per plant affected in the yellow-green pod phase by moderate and weak Fusarium on the weight of seeds from healthy pods and on the number of pods on the control plant, which is healthy, but to a lesser extent (Figure 1.73).

It can be concluded that Fusarium acts as a senescent agent that causes accelerated aging of pods that have completed production and leads to an increase in seed filling. With a severe degree of damage, the total number of pods and the number of healthy pods, height, weight of 1000 seeds and weight of seeds from healthy pods have the maximum impact.

When yellow-seeded spring rape plants were damaged to an average degree in the green pod phase, a high proportion of the impact on the yield of all these indicators was noted, except for the weight of seeds from healthy pods due to their small number. With a mild degree of damage in the same phase, their influence decreases, and the first and second places are occupied by the weight of seeds from healthy pods, as well as the total number of pods and the number of healthy pods per plant.

The greatest influence on the value of the weight of healthy pods per plant is exerted by such productive traits as the number of healthy branches and the number of healthy pods, as well as the weight of 1000 seeds in the case of Fusarium infection in the green pod phase to a lesser extent. By the stage of yellow-green pod, the average degree of damage, the share of participation of all the above traits drops sharply, and then slightly increases with a weak degree of damage. For healthy plants, the weight of seeds from healthy pods is strongly related to the number of branches. In the studies, the main influence on: seed weight: per plant Fusarium had

Table 1.36

Fusarium damage to yellow-seeded spring rape at the onset of symptoms of the disease at different stages of plant development [448]

Appearance of disease symptoms per phase	Degree of plant damage	Point defeat	The height of the plants, cm	Diseased branches on the plant, %	Number of pods per plant, %.		Weight of seeds per plant, г	Weight 1000 of seeds, г	Seed oil content, %.	Glucosinolates, µmol/g
					health	diseased plants				
Control (healthy plants)		–	137.0	0.0	100.0	0.0	9.0	2.5	48.7	11.0
Flowering	strong	10	91.0	100.0	0.0	100.0	0.0	–	–	–
Green pod	weak	6–7	126.0	56.7	18.0	82.0	5.2	1.6	42.5	7,9
	average	9	110.0	77.0	5.9	94.1	1.6	1.5	37.9	7,2
	strong	10	101.0	100.0	0.6	99.4	0.5	1.4	34.5	6,8
Yellow-green pod	weak	1–3	123.0	46.7	60.3	39.7	8.7	2.0	48.1	10,1
	average	4–5 –	122.0	49.3	51.4	48.6	6.2	1.9	47.1	9,9
	strong	8	112.0	75.4	28.7	71.3	2.1	1.6	45.0	8,5
SSD_{05}								0.1	0.8	0.8

Table 1.37

Effect of Fusarium on fatty acid composition of oil in spring rape [448]

Appearance of disease symptoms per phase	Degree of plant damage	Reduction of of oil content compared to the control, %	Fatty acid content in the oil, %					
			saturated		simple unsaturated		polyunsaturated	
			palmitic	stearic	oleic	erucic	linoleic	a-linolenic
Control (healthy plants)		48.7**	3.7	1.8	64.2	0.0	22.9	7.4
Green pod	weak	12.8	4.1*	2.2*	58.8*	0.0	26.2*	8,7*
	average	22.2	4.4*	2.7*	57.7*	0.0	26.5*	8,8*
	strong	29.1	4.4*	2.7*	57.5*	0.0	26.8*	8,9*
Yellow-green pod	weak	1.0	3.7	1.8	63.6	0.0	22.8	8,1*
	average	3.4	3.9	1.8	62.4*	0.0	23.8*	8,1*
	strong	7.6	4.1*	2.1*	61.7*	0.0	23.9*	8,5*
SSD_{05}			0.2	0.3	0.7	–	0.7	0.4

Note: * – significantly at the 0.05 level of significance; * * * – in control – oil content of absolutely dry seeds, %

by means of seed weight from diseased pods. The number of diseased branches, diseased pods and seed weight from diseased pods had the closest positive relationship with the yield per plant at strong and weak degrees of plant damage in the green pod phase, and had a slightly lesser effect at a strong degree of damage in the yellow-green pod phase.

Indicators – the number of diseased pods and the number of diseased branches per plant separately largely determine the yield: the first – with a strong degree of damage in the green pod phase, the second – with an average degree in the same phase.

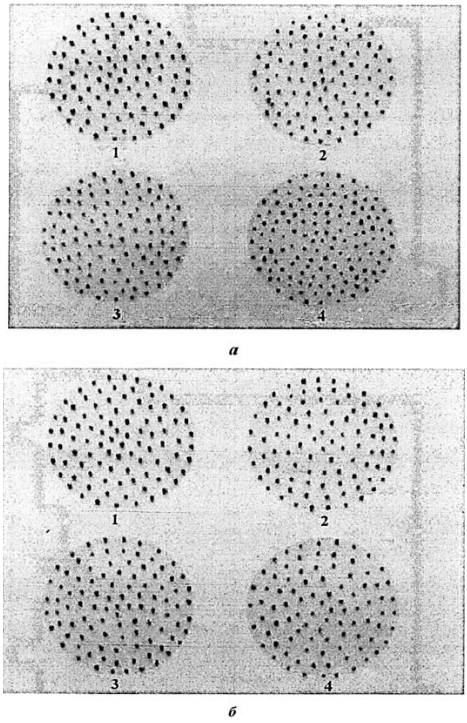

Figure 1.68 – Seeds of spring rape type "000" from plants affected by Fusarium wilt in the green pod phase (a) and in the yellow-green pod phase (b) to varying degrees: 1 – control (healthy plant), 2 – weak, 3 – medium, 4 – strong [448]

The height of diseased plants has a medium effect on the weight of seeds from diseased pods in the wilting stages of green and yellow-green pods, but these traits are not related to the severe damage of plants in the green pod stage.

Pairwise direct close relationships of seed weight from diseased pods with the number of diseased pods and the number of diseased branches with plant height were found in both phases. Moreover, with the appearance of disease symptoms on more developed rapeseed plants in the yellow-green pod phase and with a severe degree of damage, the yield from diseased pods increases in direct proportion to their number, which is the reason for the high interdependence of the traits under consideration. In turn, the number of diseased pods is determined by the number of diseased branches and height, which are private determinations of the first and second groups of traits. The determination due to their interaction, i.e., the increase in determination from the joint influence of these two groups of factors, tends to increase from a weak degree in the green pod phase to a weak degree of damage in the yellow-green pod phase.

When symptoms of Fusarium wilt appeared in the flowering phase, the combined trait of plant height and the number of diseased branches had a stronger effect on the number of formed but undeveloped fruits on the plant.

In addition to the negative impact of Fusarium on the yield structure of yellow-seeded spring rape, deterioration of seed quality was also found (Table 1.38). The germination energy of seeds obtained from affected plants in the green pod phase decreased by 15–39%, and by 6–8% in the yellow-green pod phase, and laboratory germination by 6–9 and 4–5%, respectively.

Thus, the greatest yield losses of yellow-seeded spring rape were observed when symptoms of Fusarium wilt appeared in the flowering phase – 100%. With a strong degree of damage in the green pod phase (10th damage point on an 11-point scale), yield losses amounted to 94.4, with an average (9th damage point) – 82.2 and weak (6th–7th damage points) – 42.2%. A similar pattern of yield decline was observed with later manifestation of the disease: with a weak degree of Fusarium infection in the yellow-green pod phase (1st – 3rd damage points), yield losses were 3.3%, with an average (4th-5th damage points) – 31.1, and with a strong (8th damage point) reached 76.7%. The weight of 1000 seeds of rapeseed plants affected by Fusarium wilt to a high degree in the phases of green and yellow-green pods was 1.4 and 1.6 g, respectively, which is 44.0 and 36.0% less than the weight of 1000 seeds of healthy plants.

Table 1.38

Effect of Fusarium on the sowing quality of spring rape seeds of type '000' [448]

Appearance of disease symptoms per phase	Degree of plant damage	Seed germination energy, %	Laboratory germination rate of seeds, %
Control	–	89.0	99.0
The green pod	weak	74.0*	93.0*
	average	60.0*	92.0*
	strong	50.0*	90.0*
Yellow-green pod	weak	83.0	95.0*
	average	83.0	94.0*
	strong	81.0	94.0*
SSD_{05}		9.3	3.4

Note: * – significant at the 0.05 level of significance

Under severe Fusarium wilt damage of spring rape type "000" in the yellow-green pod phase, the oil content of mature seeds decreased by 3.7%, and in the green pod phase – by 14.0% compared to seeds from healthy plants. With a severe degree of damage in the yellow-green pod phase, the amount of glucosinolates was 8.5 μmol/g, and in the green pod phase – only 6.8 μmol/g.

With a strong development of the disease in the yellow-green pod phase, the content of oleic acid in mature seeds decreases by 2.5%, and in the green pod phase – by 6.8%. The increase in the content of polyunsaturated fatty acid linolenic acid against the background of a decrease in oleic acid from a mild to a severe degree of damage and from a late onset of disease symptoms to an earlier one reduces the economically valuable characteristics of the oil and makes it suitable only for technical purposes. Fusarium infection reduces the germination energy of spring rape seeds by 15–39% when symptoms of the disease appear in the green pod phase and by 6–8% in the yellow-green pod phase, and laboratory germination of seeds by 6–9% and 4–5%, respectively.

It was noted [452], that the isolation of pathogens causing root rot of seedlings and tracheomycotic wilt of plants showed that the main cause of the disease is fungi of the genus Fusarium. The species of this genus were identified by phytopathologists. In the culture of fungi, *F. oxysporum* was found in 97.1% of cases, *F. solani* Arr. et. Wr. in 2.2%

of cases and F. buharicum (Jacz) Raillo in 0.7% of cases. The study of their morphological characteristics revealed that Fusarium oxysporum var. orthoceras prevails among them. It is characterized by filmy-webbed, felt-like or fluffy mycelium, with no color or colored in raspberry-purple tones on the Gram stain. Macroconidia are sickle-curved, often with three septa with a large number of microconidia. Several isolates isolated from rapeseed plants were represented by F. gibbosum. The main features of this species are fluffy, felt mycelium, yellowish-red in color on the Gram stain (Bondartsev scale). The macroconidia are curved, with 3–5 septa and a distinct pedicel. A large number of chlamydospores. All isolates were tested for aggressiveness before the start of the main work, which allowed us to divide them into 3 groups according to this criterion: highly aggressive, moderately aggressive and non-aggressive.

Observations [97] showed that the temperature optimum for infection of yellow-seeded spring rape with F. oxysporum is in the range of 14–16 °C, which is 6–10 °C lower than for infection of blue-seeded rape. Thus, at early terms of spring sowing of "000" type rapeseed, conditions are created that are more favorable for infection, i.e. the infectious background provides a higher susceptibility of breeding samples, and, conversely, later sowing terms are characterized by a weakened infectious background. Late sowing dates are more favorable for infection of "00" type spring rape.

The main sources of spread of rapeseed diseases are the remains of diseased plants, contaminated soil and seeds. Seed material that has not been treated is a source of diseases such as Alternaria, Fusarium, Phomosis, gray rot, downy mildew, and a number of others. Seed infection directly leads to a decrease in germination energy and a drop in germination rate. Sowing with infected seeds causes the pathogen to be transmitted to plants during the growing season, thus creating foci of infection that cause infection of the new crop. With contaminated seed, pathogens of certain diseases of spring rape can be introduced into the soil from year to year and accumulate there. The infectious germ can be located on the surface of the outer shell of healthy seeds. Such an infection does not directly affect the seed, and only during germination does it infect the seedlings. Spreading in an adult plant, it contributes to the outbreak of the disease on crops.

In addition to parasitic microorganisms, saprotrophic microorganisms, such as bacteria and fungi, grow and develop on seeds under certain

conditions. Their intensive development is accompanied by mold or rotting of seeds and leads to complete seed death if no preventive measures or measures to improve the seeds are taken in time.

Since seeds obtained from Fusarium-affected plants are characterized by low germination energy and germination rate, and the pathogen can be transmitted with seed material due to damping-off during contact with infected stems, for example, during threshing, our task was to identify the most effective fungicides to suppress the infectious origin of Fusarium on seeds and protect weakened seeds and seedlings from mold in soil conditions. For this purpose, a number of experiments were conducted in the laboratory and in the field.

The harmfulness of the above diseases of cruciferous plants is confirmed by the results of the scale assessment of the degree of plant damage in Tables 1.39–1.46. In this regard, personalized scales for some types of cruciferous crops, for example, varieties of spring and winter rape, will also be useful [97].

Table 1.39

Scale of alternariosis and sclerotiniasis lesions

Score of damage	Degree of damage	Characteristic features	Area of the affected plant surface, %
0	None	Healthy plants	0
0-1	Minor	Single spots on individual leaves	<1
1	Initial	Up to 10 spots on the plant	1–5
2	Weak	Up to 1/10 of the entire plant surface is affected	6–10
3	Average	The lesion covers 1/4 of the entire plant surface	11–25
4	Strong	The lesion covers 1/2 of the entire surface of the plant. Individual spots on the pods	26–50
5	Very strong	Most leaves have dried up, stems and pods are affected	51–75
6	Catastrophic	Most of the leaves are dead, the pods are cracking. The plants are dying	>75

Table 1.40

Scale of rapeseed damage by peronospora and phomosis

Score of damage	Degree of damage	Characteristic features	Area of the affected plant surface, %
0	None	Healthy plants	0
0-1	Minor	Single spots on individual leaves	<1
1	Weak	A lot of spots	1–10
2	Average	Affected up to U of the leaf surface, conidial sporulation of the fungus on the lower side. Individual spots on pods	11–25
3	Strong	Up to 50% of the leaf surface is affected, yellowing of the leaf blade begins, stems and pods are affected	26–50
4	Very strong	Affected leaves turn yellow and die. The pods crack	>50

Table 1.41

Rapeseed powdery mildew damage scale

Score of damage	Degree of damage	Characteristic features	Area of the affected plant surface, %
0	None	Healthy plants	0
0-1	Minor	Single pads of fungal mycelium on individual leaves	<1
1	Weak	Many pads of mushroom mycelium	1–10
2	Average	Up to 30% of the leaf surface is affected, conidial sporulation of the fungus. Individual pads of fungal mycelium on pods	11–25
3	Strong	Up to 50% of the leaf surface is affected, strong conidial sporulation of the fungus, leaf blade death begins, stems and pods are affected	26–50
4	Very strong	The affected leaves die off. The pods crack	>50

Table 1.42

Accounting for disease damage to rapeseed crops [445]

Disease	The vegetation phase	Inspected part of the plant
Blackleg, bacteriosis, fusarium	One to three true leaves	Root collar, root *
Peronospora, phomosis, fusarium, bacteriosis, snow mold. Rosette. All rosette leaves, root collar *	Rosette	All rosette leaves, root collar *
Peronosporosis, cylindrosporium, white spot, Alternaria, phomosis, white rust	Full flowering	Leaves of lower and middle tiers, stem, central and lateral cauline
Powdery mildew, fusarium, white and gray rot, Alternaria, cylindrosporium, phomosis, white rust	The green pod	Leaves of lower and middle tiers, stem, central and lateral cymes, all pods
White and gray rot, alternaria, cylindrosporium, phomosis, verticillium, fusarium	Yellow-green pod	Stem, all pods

Note: * – winter rape is inspected before the plants go into winter (in the phases of one to three true leaves and rosettes) and in spring (when the vegetation is restored).

Table 1.43

Scale for evaluation of resistance of rape varieties to downy mildew [445]

Score of damage	Characteristics of the disease manifestation	Degree of resistance
9	There are no typical signs of damage. Individual chlorotic and necrotic spots occasionally appear on the lower stem leaves	Highly resistant
7	Yellowish spots appear on the upper side of some lower leaves. 5 to 10% of such leaves are affected. The damage to the lower leaves is from 10 to 20%.	Resistant
5	There are some spots on the upper leaves.	Medium resistant
3	The damage to the upper leaves is from 5 to 20%, the lower leaves – 20–50%. Spots merge, part of the leaf dies.	Receptive
1	The whole plant is affected, the leaves gradually die off. The plant dies.	Very susceptible

Table 1.44

Scale for evaluating resistance of rapeseed varieties to phomosis [445]

Score of damage	Characteristics of the disease manifestation	Degree of resistance
9	There are no typical signs of damage. On the lower stem leaves, individual chlorotic and necrotic spots are occasionally found.	Highly resistant
7	On the lower leaves there are individual rounded spots of ash-grayish color with a brown border, yellowing of the tissue is detected around them. The damage to the lower leaves is up to 5%.	Resistant
5	On the lower leaves, grayish spots with a brown border with pycnidia in the center in the form of dots are well defined. The damage to the lower leaves is from 5 to 10%. Some spots are found on the upper leaves.	Medium resistant
3	Oval spots are well defined on the lower leaves. From 10 to 50% of the surface of the lower leaves is affected, and from 5 to 10% of the upper leaves. When such plants are ripe, the leaves are also covered with spots.	Receptive
1	On the seedlings of young plants, the stem tissue is discolored with the formation of a strip of dead tissue, the plant dies. In adult plants, the spots on the lower leaves merge, and the leaves die. The tissue of the pod valves is severely affected.	Very susceptible

Table 1.45

Scale for evaluating resistance of rape varieties to Alternaria [445]

Score of damage	Characteristics of the disease manifestation	Degree of resistance
9	There are no typical signs of damage. On some lower leaves, barely noticeable small dots are occasionally found, around which a light green color is formed.	Highly resistant
7	On some lower leaves and stem there are several dark dots around which yellowing of the tissue is observed. The damage is up to 5%.	Resistant
5	Small dots appear on the leaves and pods. Lower pods are affected up to 5%, upper pods – up to 10%.	Medium resistant
3	The lower pods are affected with deep depressed spots from 5 to 10%. The upper pods are covered with small dots from 10 to 25% of the surface and above.	Receptive
1	The lower pods curl and die. The upper ones are covered with deep depressed spots up to 5%. The pods shorten and crack. The number of seeds decreases to 20%. Seeds are small and underdeveloped.	Very susceptible

Table 1.46

Scale for evaluating the resistance of rape varieties to powdery mildew [445]

Score of damage	Characteristics of the disease manifestation	Degree of resistance
9	There are no typical signs of damage. Chlorotic and necrotic spots and a weak coating are occasionally found on individual lower leaves.	Highly resistant
7	Small pads are found on the lower leaves and stem, around which chlorotic or necrotic spots form. A white spider web coating is noticeable on the lower third of the stem and leaves. The damage is from 5 to 10%.	Resistant
5	The affected plant is up to half covered with a white spider web. The lower leaves are more severely affected with a gradual transition to moderate and weak. The damage is from 10 to 20%.	Medium resistant
3	One third of the stem and leaves are severely affected. The lower leaves curl and dry out. A white spider web coating appears on the upper leaves and stem in some places. In some places, the coating is also found on young pods. The damage is from 20 to 50%.	Receptive
1	The whole plant is affected. The leaves curl and dry out. Severely affected pods turn yellow. The seeds are small. The plant gradually dries up.	Very susceptible

Non-infectious symptoms on cruciferous crops (Figs. 1.69–1.72) caused by low temperatures, soil compaction, and lack of nutrients should not be forgotten and should be clearly separated from infectious pathogenesis.

Timely assessment of the pathogenesis of cruciferous crop agrocenoses based on typical signs of the development of such diseases is important in terms of monitoring the prevalence and harmfulness of cruciferous crops. For example, here is a typological system for evaluating rapeseed recommended by the phytosanitary services of Europe and Canada [437].

Sclerotinosis. Look for areas with dead or prematurely mature plants. Brown or discolored plants scattered throughout the green crop may indicate a low level of infection. Stem sclerotinia rot is most dangerous when stem infection occurs at an early stage, and is so severe that entire plants die before the seeds are ripe. Inspect the lower and middle sections of the stem for large discolored or yellowish-brown lesions. In some cases, even green stems can develop white fungal growths. You can find the infection very low on the stem, often where infected leaves have fallen on the stems at

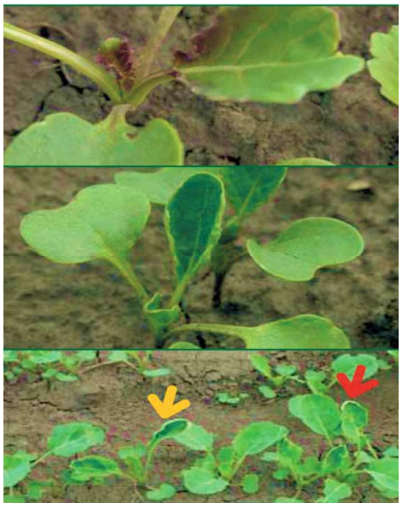

Figure 1.69 – Effect of low temperatures on rapeseed plants [433]

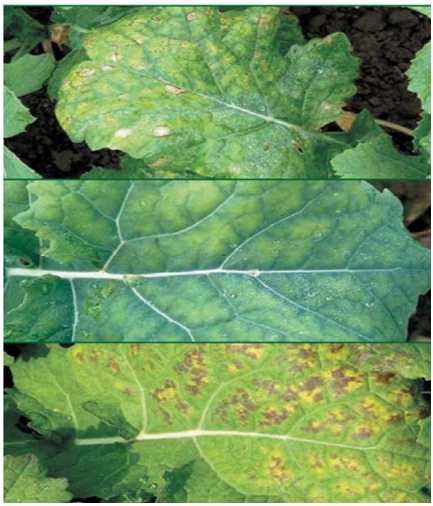

Figure 1.70 – Magnesium deficiency in cruciferous plants [434]

Figure 1.71 – Sulphur deficiency in cruciferous vegetables [435]

Figure 1.72 – Results of soil recompaction [436]

ground level. As it dries, the infected stem becomes discolored or brown like bone and may begin to crack or split. The infected stem tissue is often hollow and hard, and black sclerotia bodies that look like mouse droppings can be found inside infected stems. Sclerotinia can be found higher in the crown on lateral branches and pods, but yield losses at these infection sites are usually minimal compared to lower stem infections. Typically, yield losses due to sclerotinia stem rot account for approximately 50% of the incidence. For example, if 10% of the stems are infected, the yield loss will be approximately half of this amount, or 5%. Wet conditions right up to harvest can cause further germination of sclerotia and the appearance of

Figure 1.73 – Sclerotinia in a rapeseed field [438]

apothecia. If this late-season spore release does cause lesions on decaying leaves, these lesions form too late to cause additional yield loss, but yield loss for these infection areas is usually minimal compared to lower stem infections.

Phomosis. Look for areas with dead or prematurely mature plants. Inspect the lower and middle sections of the stem for damage. Black pepper-like dots (pycnidia) may appear in the lesions. When blackleg is severe enough to cause yield loss, the plant develops irregular, knotted, woody sores at the base of the stem. This infection will eventually grow through the stem, cutting off the flow of nutrients. If you see the plants drying up, pull them out and use garden shears to cut off the top of the root, about half an inch below the base of the stem. If more than half of the stem area is blackened, blackleg has probably reduced the yield of that plant. How to evaluate blackleg yield: If blackleg levels are higher than expected, even with a fungicide application, check the notes to see when the fungicide was applied. To be effective, the fungicide selected for blackleg control should be applied at the 2–4 leaf stage of the crop with the appropriate rate and volume of water.

A few weeks before harvesting, you may also find late-developing blackleg lesions higher up on the cruciferous stems. Look for pycnidia in the lesions on the top of the stem as a sign of blackleg. This can be caused by the less virulent blackleg pathogen L. biglobosa. Cut the stems at ground level to check for blackleg (Figures 1.74–1.75).

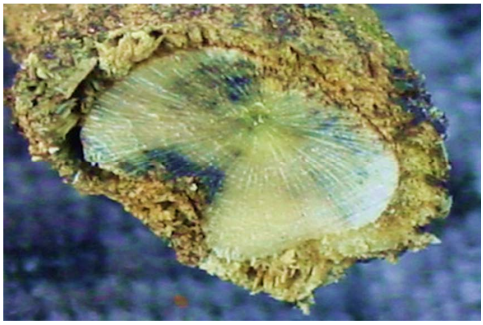

Figure 1.74 – Rapeseed stem affected by blackleg [452]

	No diseased tissue is visible on the transverse section
	Diseased tissue occupies 25% or less of the cross section
	Diseased tissue occupies 26-50% of the cross section
	Diseased tissue occupies 51-75% of the cross-section
	Diseased tissue occupies 75% or more of the cross-section
	Diseased tissue covers 100% of the cross-section, with significant narrowing of the affected tissue; tissue is dry and brittle; the plant has died

Figure 1.75 – Scale for assessing blackleg infestation in rapeseed [455]

Clubroot. Above-ground symptoms, including wilting and premature maturation, should be evident in heavily infested plants. Plants can be infected with clubroot even if no above-ground symptoms are present. It is important to pull or dig up the plants to examine the roots for clubroot. When looking for clubroot, it is important to inspect the roots of plants at

the entrance to the field, depressions, or areas with premature maturation. A mild or severe infection has almost the same risk of spreading the disease through equipment and tillage practices. If galls are present, mark the spot and pull plants around the infected plants to determine the full area of infection Keep in mind that the formation of pathogen spores on each plant is incredibly high, so you should take seriously the formation of quarantine measures to prevent the spread of the disease in this particular field as a way to slow the spread of this disease.

Alternaria. In crops, small black spots as signs of the disease gradually move up the plant, eventually reaching the pods. The maximum severity of the signs of the disease is most noticeable during the ripening phase of plants, especially after the physiological destruction of the wax coating. UV radiation, temperature fluctuations and intense precipitation destroy this wax barrier. Cool, damp weather can also exacerbate Alternaria infection, and rain splashes can spread the disease to other plants. In cases of severe Alternaria infestation, early swathing of rapeseed can have an overall economic benefit compared to later separate harvesting.

This measure prevents Alternaria from spreading to the plant pods. When infected areas account for 50% or more of the crop, early separate harvesting may be the best way to preserve the yield on these infected

Figure 1.76 – Different degrees of clubroot damage in rapeseed (this tiny clubroot gall (right position) will not affect this year's yield, but will release spores for future infestations) [456]

plants. The disease can continue to spread through the vegetative parts of the plant, and windrowing accelerates the drying of the crop.

Table 1.47

Comparison of the main diseases of rape and other cruciferous plants [455-456]

Disease	**Sclerotoniosis**	**Phomosis (pathogen *L. maculans*)**	**Phomosis (caused by *L. biglobosa*)**	**Verticillium**	**Gray stem rot**	**Fusarium wilt**
Signs on the stem	Bleached or white. The stems break easily. Dark sclerotia form inside the stems. There may be signs of white mold growth	Stem lesions with pycnidia (black spots) forming inside the lesion. The base of the stem becomes woody. Blackening is visible on the cross section	Shallow stem damage with pycnidia	Shredding of the stem tissue. Tiny black micro-sclerotia are formed under the outer peeling layer	Large stem with purple or gray specks. Pod damage is also possible	Disco-loration of the stems; yellow or reddish-brown stripes on the stems
Signs on the pod	Dried pods due to damage to the base of the inflorescence. Sometimes white mold	None	None	None	Gray spots	None
Signs at the base of the stem (on the outside)	None	Cankers	None	None	None	None
Cross section of the stem base	Clean, dry	Black areas. With severe damage, the surface is completely black	Usually the disease does not reach the base of the stem	Grayish tint along the entire section. Darkens as microsclerotia accumulate. May have an intense extension to the top of the stem	None	None

Figure 1.77 – Alternaria disease can cause pods to dry out prematurely [455]

Gray stem rot. The disease is caused by Pseudocercosporella capsellae and occurs in most rapeseed fields during the maturation of the crop, but usually develops too late in the growing season to significantly affect crop yields. Silver to purple spots appear on the stem. They can cover entire stems and continue to spread through the stubble as the plants decompose. Gray stem rot can be confused with other diseases that cause stem damage and discoloration, such as blackleg, sclerotinia stem rot, and verticillium rot. How to distinguish gray stem rot from sclerotinia (black leg): at the end of the season, cut off the top of the root at the base of the stem and look for dead blackened tissue in the bark of the stem part – this is a sign of sclerotinia (black leg) and not gray stem rot. Black spots will be visible on the black stem. With gray stem rot, the stem remains strong at the site of the lesion. Sclerotinia stem rot causes the formation of a fleshy stem, which is easily crushed after drying. Sclerotinia stem rot stems are also lighter, although it can be difficult to tell the difference if you don't have samples of both infections to compare.

Verticillium blight is a pinkish streaky and belt-like lesion with depressions and a gray discoloration at the maturity stages of rapeseed plants. The stems are crushed, revealing tiny and uniform microsclerotia under the infected layer of the stem epidermis (skin). The gray spots on the stem, if present, will be on the surface, in small numbers in a manner.

Thus, it is easier to detect verticillium directly during or after harvest. Symptoms of Verticillium are not always visible during pre-harvest diagnostics. Symptoms may only appear as a whitening of the stem on one side, which can be easily confused with sclerotinia stem rot. Transverse sections of the roots may have a grayish tint, which can be confused with black leg or gray stem rot. The best time to evaluate verticillium is after harvest, when the microsclerotia in the stem are fully developed. When the plant is fully mature, the stem peels off, revealing tiny black microsclerotia that look like ground pepper. These microsclerotia remain on the stem of the plant or fall into the soil. Although it may seem similar to the blackleg symptom, these specks are under the stem wall in verticillium and always on the surface in blackleg. The table provides more tips on how to distinguish between the main diseases of rapeseed during the period of their monitoring in the crop's agrocenoses.

Stem rot and brown girdling root rot. Rapeseed plants with brown surface symptoms at soil level are likely to be suffering from Fusarium root rot, which causes brown lesions with concentric markings. Another possibility for adult rapeseed roots is brown girdle root rot, which is a bigger problem in classic rapeseed. Symptoms of the disease are orange-brown lesions on the taproot of rapeseed, which, if severe, can encircle the root and split it off. These diseases can be much more common in short rotation rapeseed crop rotations.

Figure 1.78 – Rapeseed stem gray rot [455–456]

Figure 1.79 – Verticillium wilt in rape (peeling shows darkening / under the epidermis and outer bark of the stem) [455–456]

Figure 1.80 – Brown girdle root rot in severe damage causes complete severance of the root part from the stem (left position of the figure), which leads to lodging and death of plants [447; 484–486]

Fusarium wilt. It can lead to discoloration of the stems with a slight pinkish tint, characteristic of the fungus Fusarium. Discoloration can occur only on one side of the stem, which is a typical sign of Fusarium wilt. This disease has been virtually eliminated in modern rapeseed varieties due to genetic resistance.

Table 1.48

Comparison of the pathogenesis of blackleg, clubroot and sclerotinia in rapeseed [446–483]

Ratio indicators	Black leg	Clubroot	Sclerotoniosis
1	2	3	4
Pathogen reservoir plants	Crucifers, including some common weeds	Crucifers, including some common weeds	Broadleaf crops, including rapeseed, soybeans, sunflower, pulses
Main distinguishing features	Lesions with specks of pycnidia inside are formed on the leaves. The infection spreads to the base of the stem, where ulcers form. When you cut open stems, you will find blackened tissue inside. Moderate cases will lead to yield loss, even if the plant does not die	Galls form on the roots. In serious cases, large tuberous galls will restrict the flow of nutrients and water up and down the plant, killing the plant	Lesions form on the leaves and stems. Over time, the stems rot, then become white and brittle. Plants die prematurely, and seed set is significantly reduced. Black sclerotia form inside (and sometimes outside) the damaged stems
The stage of infection persistence	Plant residues	When each gaul collapses, it releases billions of spores into the soil	In the form of sclerotic bodies in the soil
Ways of distribution	Pseudothecia and pycnidia on infected canola residues release spores that continue the infection cycle. Pycnidiospora from pycnidia travel only a few meters. Smaller ascospores released by pseudothecia into the air can travel further	The spores move with the soil. As the soil moves, the clubroot spreads. Soil moved across fields and from field to field by machinery is the most common vector of the disease. The spores infect the roots of the host, continuing the cycle	Sclerotia form apothecia, from which spores are released. The spores can be carried by the wind for kilometers, but most of them come from fields or from fields that are connected. When release coincides with canola flowering and wet conditions, infestation can occur

(End of Table 1.48)

1	2	3	4
Crop rotation factor	2-3 year interval of cruciferous return to this field	A 2- or 3-year break between canola crops can reduce the number of viable spores by 90%, but this may still be sufficient to cause intense damage if the number of spores 1 000 000 / g of soil	The benefits of crop rotation for sclerotinia are less than for blackleg and clubroot because many crops are susceptible, sclerotia are widespread, and released spores are carried to adjacent fields. However, higher severity will be observed with shorter crop rotations
Resistant varieties	Yes	Yes	Increased resistance in selected varieties
Genetic resistance	Yes	No	No
Availability of effective fungicides	For example, in case of early damage	No	Thus, when used during the budding-flowering period

It is important to remember that monitoring and forecasting the spread and development of diseases in cruciferous crops is an integral part of integrated plant protection. Lack of forecasting makes it impossible to control and predict the phytosanitary situation of crops, timely and effective use of plant protection products. Without a forecast, epiphytoties of many dangerous diseases, significant crop losses, and cost overruns of inputs are inevitable. The forecast makes it possible to rationally organize and timely carry out preventive and eradication measures, optimize crop cultivation technologies in accordance with the actual and predicted degrees of disease development and their economic importance; plan production volumes, procurement of fungicides, improve their range, technologies and regulations for their use; inform breeding centers about the emergence of new aggressive races of pathogens in field populations.

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CHAPTER 2. VIRAL DISEASES OF CRUCIFEROUS PLANTS: PREVALENCE, BIOLOGY AND DEVELOPMENT CYCLE, EFFECTIVE CONTROL TACTICS

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DOI: https://doi.org/10.30525/978-9934-26-358-3-2

2.1. Prevalence and species specificity of cruciferous viral diseases

Viral diseases in cruciferous plants are an important factor in reducing the yield of modern adapted varieties. The virological pathogenesis of cruciferous plants has a long history. Thus, the cruciferous mosaic virus was found on radish [1] in 1925. It was observed that both wild and cultivated radish (*Raphanus raphanistrum* L. and *R. sativus*) were affected by mosaic disease, which caused distortion and often blistered areas on the leaves (Figure 2.1).

In 1933 it was reported [2] on mosaic radish disease on the cultivated Daikon variety in Japan.

Additional reports of viral diseases occurring in other closely related species have been found, and their mention may be of interest. In 1924, it was described [3] mosaic disease of snake radish (*Raphanus sativus* L. var. *caudatus* Alef.), known in India as Mogri. This disease caused spotting on leaves, stems and pods in the early stages of infection. Later symptoms included pallor, swelling and deformation of leaves and pods, abnormal flower and fruit shape, and stunted plant growth.

In 1932, it was described [4] mosaic disease *Raphanus macropoda* Lév.

Viral disease of wild radish (*Raphanus raphanistrum* L.) from South Africa in 1931 was reported in other studies [5]. The virus known as ramen has also infected turnips and daikon [6].

The symptoms caused by radish mosaic virus were identical in the field and in the greenhouse. In greenhouse conditions, at temperatures between 13 °C and 19 °C, the first symptoms consist of small, roughly circular or

irregular chlorotic lesions that appear randomly between and adjacent to the veins. Some of these lesions often merge. Over the course of several days, the chlorotic lesions become more numerous and soon replace the normal dark green tissue, giving it a distinctly chlorotic color and rough spotting, in contrast to the normal, healthy state.

After 10 days to 2 weeks, the normal dark green tissue appears as irregularly shaped, non-rising islands against a prominent yellowish-green chlorotic background (Figure 2.1). There is little or no leaf distortion, although sometimes raised dark green islands were observed on radish plants in the greenhouse for up to a month after inoculation. Necrotic lesions and stunting of infected plants were not observed in the field or in the greenhouse.

Symptoms caused by radish mosaic virus after mechanical inoculation in a greenhouse at 13 to 19°C – normal dark green tissue appears as irregularly shaped, non-raised islets on a prominent, yellowish-green, chlorotic background.

Viral diseases of other cruciferous crops have also been studied. Thus, viral diseases of rapeseed [8] (Table 2.1) are of particular importance in the epidemiology of viral infections, as rapeseed is an ideal host for overwintering viruses that infect other plants of the cabbage family. More than 12 viruses from different viral groups are known to infect rapeseed, among which the most common and harmful are: Turnip yellows virus (TuYV), Cauliflower mosaic virus (CaMV) and Turnip mosaic virus (TuMV).

A detailed list of viruses from different virus groups that infect and cause varying degrees of losses in rapeseed cultivation [9] is represented by such viruses as Beet western yellow virus (BWYV), Cauliflower mosaic virus (CaMV), Turnip mosaic virus (TuMV), Cucumber mosaic virus (CMV), Tomato spotted wilt virus (TSWV), Tobacco mosaic virus (TMV), turnip yellow mosaic virus (TYMV), broccoli necrotic yellow (BNYV), turnip rosette virus (TRoV), turnip wrinkle virus (TCV) and radish mosaic virus (RMV) have been reported to infect canola from various growing areas around the world. Yield reductions due to BWYV, CaMV and TuMV, which exhibit severe viral symptoms, are estimated to be between 70 and 79%. In China, viruses that cause rapeseed mosaic caused 30% of the yield loss, which is estimated to be 50–80% of the yield loss (Figure 2.2) [10].

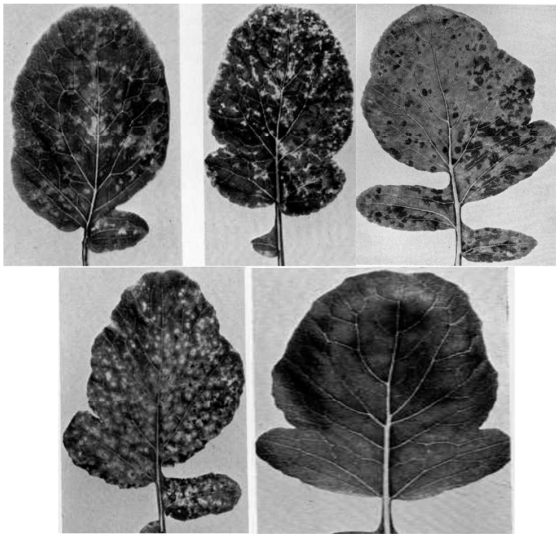

Figure 2.1 – Symptoms caused by mosaic virus on white radish leaves after mechanical inoculation in a greenhouse at 13° to 19°C: The leftmost position is symptoms consisting of small, round to irregularly shaped spots, chlorotic lesions (lesions scattered indiscriminately). The following positions are symptoms of interinfectious lesions consisting of irregularly shaped light and dark green areas that together form spotting. Lower rightmost position – control without inoculation [7]

Figure 2.2 – Massive infection of winter oilseed rape plants in the fall with a virus infection [11]

Turnip yellows virus (TuYV) is one of the most harmful and misunderstood viral diseases of the crop. It is believed that TuYV is one of the main reasons why commercial oilseed rape crops do not reach their genetically "programmed" yield potential. Viral symptoms can be difficult to recognize and can be easily confused with other diseases or nutrient deficiencies (Figures 2.3–2.5).

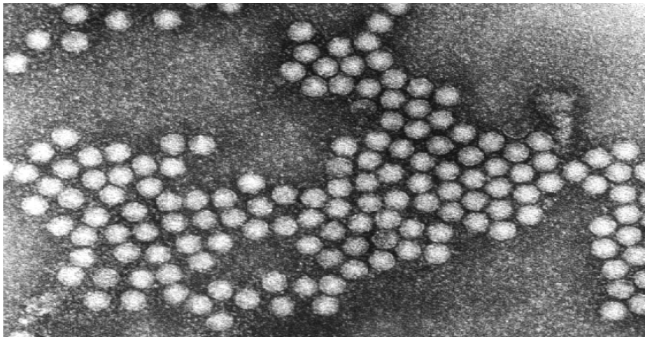

Figure 2.3 – Electron micrograph of TuYV virus particles [12]

Figure 2.4 – Spectrum of symptoms caused by natural infection of TuYV on rapeseed leaves collected from commercial crops during May [13]

Figure 2.5 – Foliar symptoms of TuYV virus in rapeseed [14]

Until recently, Turnip yellows virus, like Brassica yellows virus and Brassica yellowing virus, was considered to be an isolate of a single virus, Beet western yellows virus (BWYV). However, in 2002, the International Committee on Classification and Taxonomy of Viruses recognized *Turnip yellows virus* as an independent virus. How to recognize this viral disease? Typically, the leaf margins of affected plants turn red or purple, while yellow mosaic patterns develop on the entire leaf blade (Figures 2.6–2.7).

In rapeseed, infection with the virus can cause partial dwarfing of plants and reddening of the lower leaves, but infected plants usually do not show obvious symptoms. Symptoms of BWYV are often confused with symptoms of nutritional and physiological disorders. In Europe, BWYV infection leads to a 10–34% reduction in rapeseed yield, a decrease in seed oil content and an increase in glucosinolate content [18]. Viral symptoms were most noticeable in late winter and early spring before stem elongation and flowering of winter cruciferous crops.

Table 2.1

Rapeseed viruses [15–17]

Virus		The total number of reservoir plants	Method of transportation				
			mechanical	aphids		fleas	other insects
				persistent	non-persistent		
Cauliflower mosaic virus *cauliflower mosaic Caulimovirus*	CaMV	<100	+		–(–15)		
Cucumber mosaic virus *cucumis mosaic Cucumovirus*	CMV	>700	+		+(>80)		
Turnip mosaic virus *turnip mosaic Potyvirus*	TuMV	<100				+	
Turnip jaundice virus *turnip yellow* Luteovirus	TuYV	<50		+ (–17)			
Turnip yellow mosaic virus *turnip yellow mosaic* Tymovirus	TuYMV	>50	+			4–	+
Turnip wrinkle virus *turnip crincle* Carnnovirus	TuCV	<100	+		+	+	
Turnip rosette virus *turnip rosette* Sobemovirus	TuRV	<50	+			+	
Radish mosaic virus *radiscfi mosaic* Comovirus	RaMV	<50	4–			+	+

Figure 2.6 – Symptoms of rapeseed virus disease [19]

The discoloration is first seen on older leaves, but by early summer the symptoms can spread to all leaves. Often, the disease is asymptomatic in plants (both rapeseed and many weed species), so infected plants become a source of viral infection and contribute to the spread of the virus. Symptoms typical of TuYV can be easily confused with nutrient deficiencies and water shortages, frost damage, or even natural aging. For example, in England in 1968–1970, the discoloration of lettuce caused by a viral infection was mistakenly attributed to magnesium deficiency. Therefore, it is important to distinguish between a real virus infection and a nutrient deficiency by the symptoms on the same winter oilseed rape (Figs. 2.8–2.18).

Naturally, the main danger of the disease is not discoloration of the plants, but a significant reduction in crop yields (up to 30%). Subsequently, as a result of infection, plants become stunted, the leaf area is significantly reduced, the number of seeds per pod and oil content decrease, and, conversely, the glucosinolate content increases.

The virus is circulating in all key regions of global rapeseed production, including across Europe. In 2015–2016, heavy infestations were observed in Germany, France, Poland and the Czech Republic, and the average level of infection was observed in the UK.

Figure 2.7 – Typical symptoms on Capsella bursa-pastoris 10 weeks after inoculation with Turnip yellow yellow Luteovirus (TuYV)

Researchers identify three main reasons for the rapid spread of TuYV

1. Global warming (longer periods of aphid activity and, accordingly, an increase in the population of this pest).

2. Landscaping (more host plants for viruses and their vectors).

3. Prohibition of seed treatment with neonicotinoid insecticides (reduced protection of sown seeds).

Seed treatment with neonicotinoid insecticides allows its producers to reduce the aphid population by 85% and significantly reduce

Figure 2.8 – Manifestation of sulfur deficiency in rapeseed [20]

Figure 2.9 – Manifestation of boron deficiency in rapeseed [20]

the spread of the virus during the period when the crop is at its most vulnerable stage. Since 2013, the two main neonicotinoids – clothianidin and imidacloprid – have been banned in the European Union for use in open spaces, so only contact-acting insecticides are used. Among the pyrethroid insecticides against aphids, pimethroxine or thiacloprid-based products are effectively used.

Figure 2.10 – Manifestation of magnesium deficiency in rapeseed [21]

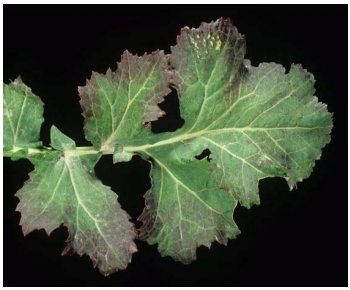

Figure 2.11 – Typical signs of phosphorus deficiency in rapeseed [22]

Figure 2.12 – Typical signs of potassium deficiency in rapeseed [23]

Figure 2.13 – Typical signs of nitrogen deficiency in rapeseed [24]

Figure 2.14 – Typical signs of iron deficiency in rapeseed [23]

Milder weather conditions in the fall and winter favor the reproduction of the main vector of the virus, the peach aphid Myzus persicae, and thus the rapid spread of the virus. Climate change may significantly worsen the situation, as warmer conditions will favor the survival and reproduction of M. persicae throughout the winter.

More than 150 species of cultivated plants and weeds from 20 families are susceptible to TuYV. The host range is very wide, including most types of cabbage (canola, kale, Brussels sprouts, broccoli, cauliflower, kale, rutabaga, turnip, Chinese cabbage), radish, lettuce, spinach, peas and beans. It has also been reported to attack a wide range of common weeds, including wild brassica, wild radish, shepherd's purse, shepherd's purse, shepherd's purse, tenacious marigold, dandelion, deaf nettle, tenacious marigold, and nettle. In addition to rapeseed, these weeds are a significant reservoir for

Figure 2.15 – Signs of molybdenum deficiency in rapeseed [25]

Figure 2.16 – Signs of manganese deficiency in rapeseed [23]

overwintering clubrooted moths, which threaten vegetable crops. They can be reservoirs of the virus in natural conditions and a source of possible viral epidemics.

Among the Iranian isolates, turnip mosaic virus (TuMV; family potyviridae, genus potyvirus) causes important diseases of crops worldwide,

Figure 2.17 – Signs of calcium deficiency in rapeseed [26]

Figure 2.18 – Signs of zinc deficiency in rapeseed [27]

including: vegetables, e.g., Brassica oleracea ssp. botrytis (cauliflower), *B. napus, B. rapa, B. junce* (mustard), *Raphanus sativus* (radish), *Rheum rhabarbarum* (rhubarb), and ornamental plants such as *Matthiola incana* (rosemary) and *Limonium vulgare* (statice). It also infects a wide range of naturally occurring weed species, including Raphanus raphanistrum (wild radish). This virus is transmitted intermittently by several different aphid species. It is considered one of the most important viruses infecting field cruciferous vegetables [28]. It also damages field crops of *B. napus* in many European countries, where TuMV infection was recorded on 14% of crops and 5% of plants in general, with yield losses in infected crops reaching 70% [29] (Figs. 2.19–2.24).

Figure 2.19 – Signs of TuYV virus on rapeseed [30]

Figure 2.20 – Symptoms of TuYV on rapeseed leaves [31]

Figure 2.21 – Symptoms of TuYV virus on rapeseed leaves (symptoms on the top and bottom of the leaf may differ) [32–33]

Figure 2.22 – Uninfected Brussels sprouts (left) and plants infected with TuYV (right). Note the difference in color between infected and uninfected plants, as well as the size of the plants [34]

Figure 2.23 – Symptoms of cabbage tip scorch caused by TuYV virus [35]

Figure 2.24 – Difference in leaf discoloration (autumn) in resistant and susceptible plants: left – TuYV resistant hybrid, right – susceptible hybrid [36]

Cauliflower mosaic virus (CaMV) causes canola mosaic, which is characterized by yellow ring spotting on the leaves (Figure 2.25) [37]. The veins on the infected leaves become noticeably lighter, and over time, necrotic spots appear on them. CaMV causes stunted growth of infected plants, young leaves are usually underdeveloped and deformed over time [38]. Plants infected with the virus at a young age become weak and develop fewer flowers. Rapeseed mosaic can cause underdevelopment of seeds:

the weight of 1000 seeds from infected plants is 40% less than that of healthy seeds, and their germination rate is reduced by 20% [39–40].

CaMV affects only cabbage crops – rapeseed, mustard, cauliflower, broccoli [41–42] The virus persists on plants of wild weeds or self-sowing rapeseed plants. CaMV is transmitted non-permanently by many aphid species, including green peach and cabbage aphids [43–44]. The virus remains in the insect's mouth for a short period of time and dies when the infected aphids feed on healthy plants. The virus is not transmitted by seeds [45–46].

Additionally, it is also noted that in many regions CaMV virus is the main viral disease infecting cruciferous crops, including: *Brassica oleracea* var. *capitata*, *B. oleracea* var. *italica*, *B. oleracea* var. *botrytis*, *B. oleracea* var. *acephala* and *B. oleracea* var. *rapa*, *B. napus, B. pekinensis* and *Raphanus sativus*, The virus causes mosaic and bright vein chlorosis in most hosts. In chronically infected plants, symptoms may be masked, especially on tall *Brassica oleracea* var. *capitata*, *B. oleracea* var. *italica*, *B. oleracea* var. *botrytis*, *B. oleracea* var. *acephala* and *B. oleracea* var. *rapa*, *B. napus, B. pekinensis* and *Raphanus sativus*. The virus causes mosaic and bright vein chlorosis in most hosts. In chronically infected plants, symptoms may be masked, especially at high temperatures.

Infected plants of turnip, Chinese cabbage and other species tend to flower prematurely. CaMV is widespread in temperate regions, and pulses are usually infected wherever they are grown [47]. Biodiversity of 21 CaMV isolates [48] from different regions and with different symptom severity were evaluated on turnip (*Brassica rapa*), clinging marigold (*Datura stramonium*) and kohlrabi (*B. oleracea* var. *gongylodes*). These isolates caused a variety of symptoms on turnip. Kohlrabi plants infected with all tested isolates eventually recovered and became symptom-free. All isolates were transmitted by the green peach aphid (*Myzus persicae*). The ORF VI gene of nine selected CaMVs was amplified using specific primers. Comparison of the sequences of the amplified fragments showed high identity (96.9–100%) of the studied isolates [49].

Autumn is considered to be the most critical period for growing rapeseed. It is during this period that early crops are most often infected. Infection of plants after the formation of the rosette has a slight effect on yield.

The main way to combat the virus is to take preventive measures to destroy the source of viral infection – cruciferous weeds and self-seeding

Figure 2.25 – CaMV symptoms on rape leaves [50]

of rapeseed (especially in summer). To prevent aphids from invading young rapeseed plants, the density of crops must be high enough. It is very important to control the time of sowing seeds so that the peak of aphid migration does not coincide with the period of development of young rapeseed plants.

In mustard, the viruses BMYV, TuMV and CaMV are widespread and very common (Figs. 2.26–2.27).

Turnip mosaic virus (TuMV) is found everywhere in temperate and tropical regions. It is the second most common pathogen in terms of

Figure 2.26 – TuMV virus on mustard [51]

Figure 2.27 – TuMV virus on mustard [52]

prevalence and harmfulness, second only to cucumber mosaic virus. It infects more than 300 plant species from 43 families, including all cultivated, ornamental, wild and weeds of the Cabbage family. Due to the deformation of the leaves caused by the virus, the marketability of the product decreases, and more severe damage causes the plant to die. Affected plants experience stunted growth, early defoliation, which leads to a significant reduction in yield (up to 100% depending on the crop) and significant economic losses. The harmfulness of TuMV is sharply increased when plants are co-infected with other viruses (Figure 2.28–2.29) [53–54].

The first signs of virus infection are pale chlorotic or necrotic localized lesions on the leaves. Over time, the veins lighten, and systemic necrosis appears, turning into a continuous mosaic (Figure 2.30). Severely affected plants become stunted and deformed. Fewer pods are formed on diseased plants, they become twisted and have fewer seeds.

Viruses are usually transmitted over short distances (up to several hundred meters). The main vectors of TuMV spread are green peach (*Myzus pericae*) and cabbage (*Brevicoryne brassicae*) aphids, and the infection is easily transmitted mechanically. Weather conditions and air temperature significantly affect the activity and migration processes of insects, which, in turn, affects the spread of TuMV.

Dry and warm weather favors the reproduction and spread of aphids, and thus the early and intense spread of the virus. In the event of a primary focus of infection in the field, insecticides should be applied immediately, otherwise (if the number of aphids is not controlled) the virus can spread from plant to plant quite quickly (Figs. 2.32–2.34). Seed transmission of the virus has not been observed.

Figure 2.28 – Mosaic symptoms on rapeseed plants induced by turnip mosaic virus [55]

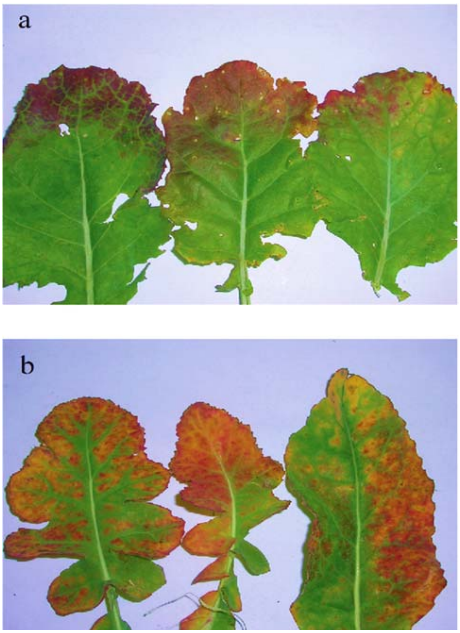

Figure 2.29 – Signs of turnip mosaic virus in rapeseed (A – onset, B – development of infection) [56]

Figure 2.30 – Turnip mosaic virus TuMV site in a rutabaga field showing premature yellowing of older leaves [57]

Figure 2.31 – A rutabaga plant infected a few weeks earlier with the Turnip mosaic virus TuMV. Note the old yellow leaves and young deformed leaves with a mosaic pattern of yellow and green areas [58]

Rapeseed mosaic, wrinkle mosaic and greening of rapeseed flowers are found on rapeseed. Rapeseed mosaic is characterized by light green spots on the leaves. The new leaves are underdeveloped and bent. The causative agent of the mosaic is the common cucumber mosaic virus *Cucumber mosaic virus*. It is spread by aphids and remains in overwintering plants. Cucumber mosaic can cause seed underdevelopment – the weight of 1000 seeds from affected plants is 40% or more less, and their germination rate is reduced to 20%. *Cucumber mosaic virus* affects a wide range of plants: 775 species belonging to 365 genera and 85 families. The largest number of species is represented by the following families: pumpkin, cabbage, nightshade, and Asteraceae [59].

Wrinkle mosaic causes lightening and fringing of the veins, mottling, and the formation of dark green spots with alternating yellow spots that are arranged in circles. Affected plants are stunted, have a depressed appearance, and the leaves often become wrinkled.

The causative agents of wrinkled mosaic are a mixture of cauliflower viruses *Cauliflower mosaic virus* and bean wilt virus [64]. Cauliflower mosaic virus is represented by a single DNA molecule, can be diluted at 10-3-10-4, and is inactivated at a temperature of 72–78 °C. The diameter

Figure 2.32 – The TuMV-infected turnip plant on the right has fewer leaves and a smaller root compared to the healthy plant on the left [60]

Figure 2.33 – Winter rapeseed carrion infected with TuMV [61]

of the virus particles is 50 nm. The viruses are spread by aphids, especially peach aphids, and remain in overwintering plants. Affected plants produce 2 times less seed yield and 1.5 times less green mass. Viruses that cause wrinkle mosaic affect cabbage and legumes.

Figure 2.34 – Green peach aphid on the undersurface of a rutabaga leaf. This common aphid is one of many species that can spread the disease. The virus is spread only by aphids [62]

Figure 2.35 – TuMV mosaic virus in rapeseed [63]

Black ring spot. Small black necrotic ring-shaped spots appear on the leaves. Later, the leaf blade turns yellow and dies. With a strong manifestation of the disease, the plants form a small number of flower-bearing branches. Seeds in the pods are underdeveloped or not formed at all. The causative agent of the disease is *Turnip mosaic virus*, a mosaic virus of black ring spot of cabbage. It is transmitted by contact, as well as by various types of aphids. It is not transmitted by seeds. In addition to rapeseed, it affects plants from the cabbage family. It hibernates in the tissues of living plants.

Greening of flowers is caused by underdevelopment of internodes and leaves, lightening of their veins [65]. The leaves become dense in texture. The flowers turn green and often proliferate. Affected plants usually do not form pods. Greening of flowers is a mycoplasma disease. The causative agent of the disease is the clover dwarf mycoplasma. It is spread by the cicadas *Euscelis plebejus* Fall and *Macrosteles laevis*. In addition to rapeseed, it affects cabbage, dope, chrysanthemum, terry, clover, etc. The pathogen does not spread with seeds. Mycoplasma bodies are stored in overwintering plants.

To combat viral and mycoplasma diseases, it is necessary to systematically control weeds, insect vectors, and to maintain spatial isolation of rapeseed crops from cabbage, clover and other crops of at least 1000 meters.

Since 1991 and 1996, symptoms have been observed in winter and spring rapeseed crops in England, France, Germany, the Czech Republic, and the United States, and research has shown that they are caused by a viral disease [66]. The first authors believed that the disease was caused by the beet western yellows virus (*Beet western yellows* Luteovirus). In Europe, the most common strain of this virus is the beet mild yellowing Luteovirus (BMYV), which in some years causes great damage to beet production, especially in Western and Central Europe [67]. However, analyzes have shown that rapeseed is infected by a separate virus from the Luteovirus group, which can be distinguished from unnamed viruses by monoclonal antibodies in an ELISA test and by the range of host plants. By its properties, the virus is identical to the virus, which was described by a number of authors in the 50s and 60s under the name turnip yellows virus (*turnip yellows Luteovirus* TYV) [68–71]. Later it was described under the name tunip mild yellowing virus (TuMYV). We refer to this virus as turnip yellows virus (TYV) after its first description. Although it belongs to the Luteovirus group, which includes such important pathogens of crops as beet

mild yellowing virus (BMYV) and potato leafroll virus (PLRV), the host range of crops is very different, as shown by our analyses (Table 2.2).

According to our studies, the following crop plants are not infected by any of the above viruses: barley (*Hordeum vulgare*), sunflower (*Helianthus annuus*), cucumber (*Cucumis sativus*), alfalfa (*Medicago sativa*), meadow clover (*Trifolium pratense*), carrot (*Daucus carota*) and parsley (*Petroselium crispum*).

The range of host plants for turnip yellows virus is much larger (>50) than for beet mild yellow virus (<30) and potato leaf curl virus (<40). Of the weeds and wild plants that may play an important role in the epidemiology of this disease as reservoir plants and sources of infection, all important cruciferous weeds are affected by turnip yellow virus: field bindweed (*Lepidium camprestre*), weed bindweed (*Lepidium ruderale*), common bursage (*Capsella bursa-pastoris*), field mustard (*Sinapis arvensis*), field thistle (*Thlaspi arvense*), wild radish (*Raphanus raphanistrum*), as well as medium stellaria (*Stellaria media*), common buttercup (*Senecio vulgaris*), dandelion (*Taraxacum officinale*), medicinal arugula (*Fumaria officinalis*), stinging nettle (*Lamium amplexicaule*), self-sown poppy (*Papaver rhoeas*) and Veronica ssp. Among them, the host plants for turnip yellow virus and mild beet yellow virus are *Capsella bursa-pastoris*, common buttercup (*Senecio vulgaris*), common arugula (*Fumaria officinalis*), stem-med stinging nettle (*Lamium amplexicaule*) and self-sown poppy (*Papaver rhoeas*).

Figure 2.36 – Head of white cabbage (Brassica oleracea) infected with turnip mosaic virus [72]

The following weeds are not affected by turnip yellow virus: white quinoa (*Chenopodium album*), blue cornflower (*Centaurea cyanus*), soft-flowered galinsoga (*Galinsoga parviflora*), common mustard (*Polygonum lapathifolium*), common dope (*Datura stramonium*), stinging nettle (*Urtica urens*), dioecious nettle (*Urtica dioica*), clinging feverfew (*Galium aparine*), black nightshade (*Solanum nigrum*), chicken millet (*Echnicochloa crus-*

galli), fragrant chamomile (*Matricaria chamomilla*), white stinging nettle (*Lamium album*), pink thistle (*Cirsium arvense*), field thistle (*Sonchus arvensis*), garden thistle (*Sonchus arvensis*), vegetable thistle (*Sonchus oleracea*), plantain lanceolata, plantain major, annual meadowfoam (*Mercurialis annua*), yarrow (*Achillea millefolium*), and blunt sorrel (*Rumex obtusifolius*). These plants are also not affected by the mild beet yellow virus.

Table 2.2

Host plants of selected viral infections [73; 77]

Type of cultivated plant	Viruses		
	Beet mild yellowing virus (BMYV)	Turnip yellow virus (TuYV)	Potato leaf curl virus (PLRV)
Brassica napus var. *napus*	–	+	–
Brassica rapa var. *silvestric*	–	+	–
Sinapis alba	+	+	–
Raphanus sativus var. *oleiformis*	–	+	–
Camelina sativa	+	+	–
Brassica mapa var. *rapifera*	–	+	–
Brassica napus var. *napobrassica*	–	+	–
Brassica olecea	–	+	–
Raphanus sativus var. *niger*	–	+	–
Raphanus sativus var. *sativus*	–	+	–
Solarium tuberosum ssp. *tuberosum*	–	–	+
Beta vulgaris var. *altissima*	+	–	–
Beta vulgaris var. *crassa*	+	–	–
Beta vulgaris var. *conditiva*	+	–	–
Beta vulgaris var. *vulgaris*	+	–	–
Spinacia oleracea	+	+	–
Lactuca sativa	–	+	–
Capsicum annuum	–	–	+
Lycopersicon esculentum	–	–	+
Nicotiana tabacum	–	–	+
Phacelia tanacetifolia	+	+	–
Lupinus luteus	+	–	–
Lupinus albus	+	–	–
Pisum sativum	+	–	–
Vicia fabae	+	–	–
Cicer arietinum	+	–	–
Ornithopus sativus	+	–	–

In Western and Central Europe, as well as in the United States, the turnip jaundice virus is widespread. In commercial crops, 40 to 100% of plants are affected. Depending on the time of infection, virus isolate, susceptibility of the variety and degree of damage, the virus can cause yield losses of up to 50% and a reduction in oil yield of up to 15%. Experiments conducted in Aschersleben (Germany) over three years (1993-1995) with two virus isolates and two varieties of winter rape yielded the following results. Yield losses ranged from 12.1–34.3%, with an average of 20.4%, or 8 centner/ha. Symptoms of the virus on winter rape appear in the fall in the form of a purple-red color of the leaf margin. Later, whole leaf blades acquire this color. The symptoms are very similar to those caused by a lack of various nutrients, moisture and stagnant waterlogging of the soil of common sorrel (*Achillea millefolium*), blunt sorrel (*Rumex obtusifolius*). These plants are also not affected by the mild beet yellow virus [74]. Accurate diagnosis is possible only by means of virological analysis (ELISA). After mild winters, these symptoms are observed in the spring. Affected plants are stunted, branch less and form inferior pods. Similar symptoms are observed in spring rape and other susceptible crops.

Aphids play an important role in plant epidemiology. The virus is transmitted in a persistent manner with varying efficiency by at least 17 aphid species [75–77]. The main vectors are the following aphids: green peach, green-striped potato, currant, lupine, mealybug, cabbage, asparagus, large potato and corn aphids [78]. In addition to green peach and large potato aphids, none of the 17 aphids that transmit the turnip jaundice virus transmit the beet mild yellow virus [79]. Cauliflower mosaic virus (*Cauliflower mosaic Caulimovirus* CaMV) is one of the most dangerous pathogens for plants of the Brassicaceae family. In Southeast Asia, this virus infects various types of cabbage, daikon, seed radish, turnip, rapeseed, white mustard, sarepta mustard, and black mustard. Reservoirs of the virus in nature are weeds from the Brassicaceae family: watercress or common rape (*Barbarea vulgaris*), capsella bursa-pastoris, Sophia's descurainia (*Descurainia sophia*), field thistle (*Thlaspi arvense*), field mustard (*Sinapis arvensis*), and medicinal walker (*Sisymbrium officinale*). The virus persists in infected plants and in cabbage heads left unharvested in the field. The main symptoms of infection are lightening of all leaf veins

(Figure 2.37), dark green border of the main and middle veins, interveinal chlorosis, leaf disfigurement and stunted growth. Seed transmission was not observed. However, the virus infection affects seed germination, often reducing it by up to 100%, possibly due to damage to the embryo. At the same time, diseased plants produce small, dissimilar seeds with a thin, wrinkled shell.

The pathogen is effectively transmitted by aphids. Peach and mustard aphids are able to transmit cauliflower mosaic virus even after a single test puncture of a leaf. For cabbage aphids, the period of perception of infection is about 6 hours, while the ability to infect individuals of this species remains for more than 24 hours. Pea aphids, which are not specific for cruciferous plants, are also able to carry this virus, but after a longer perception of it (about a day).

In a number of countries, *Western yellow beet luteovirus* (BWYV) is introduced into rapeseed crops by aphid vectors that previously fed on infected host weeds such as wild radish and volunteer canola. BWYV can reach high levels in rapeseed crops if vector aphids emerge early in the growing season.

Figure 2.37 – Cauliflower mosaic virus: A – infected cauliflower (*Brassica oleracea*); B – leaves of infected (left) and uninfected (right) daikon (*Raphanus sativus* subsp. *acanthiformis*); C – leaf of infected (left) and uninfected (right) seed radish (*Raphanus sativus* var. *radicula*) [75]

2.2. Integrated systems and methods for controlling viral diseases in cruciferous crop agrocenoses

What are the main methods of controlling viral diseases of rapeseed?

First of all, weeds and insect vectors should be systematically controlled, and spatial isolation of rapeseed crops from cabbage, clover and other crops (at least 1000 m) should be maintained. The natural resistance of plants is the only possible, effective and environmentally friendly way to fight viruses.

In fact, the following recommendations can be formulated for virus control in cruciferous crops based on a number of studies [76–77]:

– Where practicable, preserve stubble and use direct seeding. Stubble helps to keep aphids away from a number of crop species. Sow with equipment that minimizes stubble damage. Do not leave stubble directly over the seeds as this prevents germination.

– Control broadleaf weeds in crops, around the perimeter of crops and on fallow land. This is especially true for cruciferous weeds, which can serve as reservoirs and centers of virus infection. Broadleaf weeds of other families can be reservoirs of BWYV.

– Sowing at the recommended time. A 1–2 week delay can reduce virus infection in some seasons if aphid flight ends before emergence. Sowing should always be the first priority to optimize yields regardless of disease. However, early maturing rapeseed varieties and all mustard varieties produce optimal yields at later sowing dates. These varieties sown at the end of the optimal time may have an advantage in areas and seasons where the virus limits yields.

– For rapeseed, seeds treated with the active ingredient imidacloprid should be used. Aphid resistance to imidacloprid has not been reported.

– The prevalence of aphids should be monitored in rapeseed crops. Periodically check the plants, including the underside of the leaves, for aphids. A large number of aphids, especially green peach aphids, indicates the possibility of a virus infection. It is important to check the plants frequently between the stages of emergence and leaf formation. Spray and observe the destruction of aphids. If there are a lot of aphids between emergence and leaf formation, choose a registered afficide (recommended with the active ingredient pyrimicarb).

– Test for viruses. If virus-like symptoms are observed, organize laboratory testing. Tests should include BWYV for rapeseed and BWYV and TuMV for mustard. At least 5 plants with symptoms and 5 plants with relatively asymptomatic disease should be tested. This can establish which types of viruses occur in the agrocenosis.

It is also emphasized that [78], that due to the limited host range for CaMV, cruciferous growers should pay special attention to the control of cruciferous weeds around seed plots and production fields. This should be combined with early aphid control in crops and adjacent areas. BWYV, CaMV and TuMV have been detected on wild radish weeds. In general, cases of BWYV were recorded more on wild radish than on rapeseed.

Control of rapeseed virus diseases [75; 79] is based on the development of new varieties with natural or genetically engineered resistance to the viruses, early insecticide applications on BWYV-infected crops, removal of host weed reservoirs, and possibly cultural control measures that limit the spread of the virus, such as those used against non-host viruses. BWYV is not seed-borne and must survive the summer in living host plants. It is not known whether CaMV and TuMV can be seed-borne.

To reduce the impact of TuYV on rapeseed yields, a system of preventive measures should be applied, including the cultivation of virus-resistant varieties, pre-sowing seed treatment and the use of insecticides.

Identifying and introducing resistance genes into the crop is an alternative strategy to combat this viral disease. In 2014–2018, breeders introduced a new rapeseed variety, Amalie (Limagrain), the first commercial variety with TuYV resistance, to the market. The use of this variety on an industrial scale should provide a 30% increase in yields compared to non-tuYV resistant species. Many researchers consider the TuYV-resistant Architect (Limagrain) hybrid to be the most promising for the European market. At the same time, farmers should keep in mind that TuYV-resistant hybrids are not resistant to aphid damage, so insecticides should be used in case of mass migration.

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CHAPTER 3. GENERALIZED SET OF MEASURES TO PROTECT AGROCENOSES OF CRUCIFEROUS CROPS FROM DISEASES

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DOI: https://doi.org/10.30525/978-9934-26-358-3-3

Important in terms of disease control in cruciferous crops is, first of all, timely monitoring of their agrocenoses, which is recommended to be carried out in accordance with certain terms and phenophases.

Rapeseed requires skillful protection against pests and diseases, and the focus of the entire cultivation technology on loss prevention. This is achieved by following the principles of adaptive or integrated farming [1].

The cultivation of resistant crop varieties is one of the central aspects of integrated crop protection. It is also possible to use varieties that are not fully resistant. The cultivation of relatively non-susceptible varieties in combination with agronomic, sanitary and preventive measures allows to minimize the use of chemicals. Using varieties with different resistance bases and maintaining them is an important element of integrated protection. For the effective use of the resistance factor, information on the composition and dynamics of the pathogen population is required. The results of virulence analysis should be reflected in breeding for resistance and in variety change [2].

The large number of harmful diseases affecting rapeseed plants, the relatively narrow gene pool of the species, the genetic homogeneity of modern "00" type varieties and the rapid increase in sown areas pose a serious threat of epiphytoties. In this regard, in all breeding programs, special attention is paid to the creation of rapeseed varieties resistant to various diseases (phomosis, Alternaria, peronosporosis, sclerotinia, verticillium, fusarium, etc.).

With the emergence of the first low-erucic rapeseed varieties, the problem of resistance to phomosis attracted the most attention from breeders.

The French single-zero winter rape variety Jet Neuf is one of the first sources of resistance to this disease that was widely used. In the case of France, high resistance to phomosis is characterized by winter rape varieties Darmor, Tandem [3] i Ramses [4]. Field resistance found in Rafal, Bienvenu, Sarepta and Quinta varieties [5].

In the UK, varieties with field resistance to phomosis SarNsogpe and Corniche have been identified [6], which, however, are not popular with farmers due to low yields. In Germany, Lirajet, Liberator, and other varieties have field resistance to the disease [7]. and Maxol. According to the results of the immunological evaluation conducted in Poland, the following winter rape varieties were classified as resistant: Libravo, Liradette, LAH 390, MAN 1390 [8]. Breeders have created a large number of spring rape varieties resistant to phomosis: in Australia – Mashka [9], Barossa [10], Yikadee, Eureka і Shiralee [11]; у Канаді – Stellar, Profit [12], Cresor, Legend та Innovator [13], in Poland – Bronowski and Mar; in Ukraine – Kovalevsky.

There is not always a correlation between the resistance of rapeseed to phomosis in the seedling and adult phases [14–15].

In Australia, the main component of field resistance to phomosis is adult plant resistance. The field resistance of adult rapeseed plants to phomosis is polygenic in nature, it is associated with the rate of formation of strong cortical tissue and lignin formation.

In the study of digaploid lines from anthers of F_1 hybrids obtained from crossing varieties Cresor (resistant) and Westar (susceptible), genotypes moderately affected by phomosis in the seedling stage and resistant to this disease in the adult state were identified. High resistance to phomosis was found in field conditions in plants of monosomal rapeseed lines with the added fourth chromosome of *Brassica nigra*. It has been shown that the genes of resistance to phomosis in B. juncea plants are localized in the genome [16]. And when hybridized, they can be easily transferred to the genome of *B. napus* plants [17]. The control of full resistance of *B. juncea* seedlings is carried out by the genome and is determined by one dominant gene. In order to transfer resistance to phomosis to rapeseed plants, somatic hybridization with *Sinapis alba* is being carried out [18]. When transgenic plants were created by integrating a chitinase-producing gene, resistance to phomosis increased slightly, except for one genotype [19].

Under the conditions of Ukraine, increased resistance to phomosis was noted in winter rape varieties Fedorovsky, Fedorovsky improved, Garant, Ivanna, BNV 63, Quinta, Ustinovsky, VRG 109, VDH9002, Galitsky, Horizon, NPP 041, Xaverovsky [20]; in France – in the varieties Jet Neuf, Lembke, Bienvenu. Quite high resistance to Alternaria was found in the Japanese variety Norin44 [21]. Among the spring rape varieties with high field resistance to Alternaria are the following: in Ukraine – Kovalevsky. Yumba, Salut, Ergl, Klytinnyi 8, Nikitinetskyi, Kalynovskyi, Iris, Orion [22].

Various studies have shown that S. alba can be a source of resistance to Alternaria in interspecific crosses. The wild species *Eruca sativa*, *Camelina sativa* and *Capsella bursa-pastoris* are even more interesting in this regard.

In experiments with the introduction of several foreign cytoplasms into the genome of *B. juncea* plants, it was shown that the cytoplasms of *B. campestris* > *B. chinensis*, *B. japonica* species reduce, and *B. napus* and *B. carinata* – increase resistance to Alternaria; the cytoplasm of black mustard does not affect this trait. Resistance to Alternaria leaf spot in Sarepta mustard is caused by one dominant gene. All resistant plants have purple leaves, thick, lobed with protruding veins. All of these traits can be used as gene markers for preliminary evaluation of genotypes for disease resistance in large plant populations [23]. During the selection of embryos from plants of the winter rape variety Primor (susceptible to A. brassicicola) in a selective medium with a filtrate of the pathogen culture, it was possible to isolate resistant samples [24].

As a result of determining the resistance of rapeseed varieties and samples to downy mildew, the spring variety Cresor was isolated, which has race-specific resistance [25], line RES 26 (obtained in Poland by selection from the winter rape variety Janetzkis), which has a dominant monoline (selected from the variety Komet) with resistance due to two independent genes [26].

When evaluating resistance to sporulation on individual cotyledon leaves of winter rape in the laboratory, the following varieties were highly resistant to downy mildew: Cobra, Liporta and Lirabon; medium resistant – Liborius and Arabella; moderately resistant in the field – Envoi and Samourai [22].

The following varieties and cultivars were weakly susceptible to downy mildew: in the UK – winter rape varieties Venvenu, Fiona, Korina and Darmor; in Ukraine – spring rape varieties: Kovalevsky, Vasylkivsky, Maryanivsky and Ukrainsky.

In France, transgenic rapeseed plants based on the Westar variety were developed that produce the enzyme oxalate oxidase, which leads to the degradation of oxalic acid. Some of the resulting plants had increased resistance to sclerotinia. Transgenic plants producing chitinase were also less affected by *S. sclerotiorum*.

In Germany, three lenticular mutants of rapeseed were obtained, whose susceptibility to *S. sclerotiorum*, *L. maculans* and *B. longisporum* fungi according to ELISA test corresponded to 0.21, 0.59 and 1.62 FPE (fungal protein equivalent) against 0.69, 3.98 and 5.54 FPE in conventional varieties, indicating a reduced susceptibility of *Lenticular mutants* [27]. In China, the sterile line 90A was isolated, which is much more resistant to the disease than the fixer with the same genotype; the difference between them is that in the sterile line, the pistils emerge before the flower blooms and the petals fall off later. Plants of six other lines with cytoplasmic male sterility (41A-46A) were less affected than the fixers due to the smaller size of the petals and their later falling off [28].

In France, germplasm with increased resistance to sclerotinia was isolated from the gene pool of rapeseed of Asian origin: Norin9, Norm 16, Genkai, Isuzu, Kogane, Miyuki [29].

In Germany, relatively high resistance was observed in winter rape varieties Doral, Librador, Liroma; in Sweden and Ireland, in spring rape variety Brio. After ethyl methyl sulfonate treatment of spring rape plants of Linetta M2 variety, one highly resistant line was isolated [30]. Winter rape varieties Lirajet, Liberator are relatively resistant to sclerotinia in Poland [31], Vog, VON 1592, VON 1693, MAN 1391, MAN 1592.

A number of cultivars have been selected in the UK for breeding for resistance to light leaf spot: Rochet, Express, Falcon, Libravo, Nickel, Inca, Tomahawk [27]. Dominant genes determining resistance to clubrooted pigeonpea identified in *B. oleracea* representatives polygenic recessive resistance to clubroot pigeonpea was found [32]. Genotypes resistant to this disease were also selected in the *S. nigra* population [33]. Oilseed radish

samples, as well as Evvin, Lergo, Salyut and Karat rape varieties, are the most resistant to clubroot [34].

In the experiments to evaluate the source material for resistance to verticillium, it was not possible to identify fully resistant rapeseed genotypes, but there was considerable variability among the samples in the degree of damage to mature plants. Separate cultivars were found to be resistant to this disease: in Poland – VON 1582, in Germany – Korina and Jet Neuf [35].

In most regions of the world, rapeseed is resistant to Albugo sandida (Pers. Et Lev.) Kuntze (white rust), but many varieties in central and eastern China are susceptible to the disease.

Rapeseed is heavily affected by white rust. Therefore, breeders should be careful not to introduce susceptibility with oriental varieties or interspecific crosses with rape.

Absolutely non-susceptible samples of rape to Fusarium wilt have not been found, but as sources of resistance to Fusarium, we can recommend the variety samples of Japanese origin Isuzu, Murasaki, Chisaya. For the purposes of heterotic breeding, it is desirable to use at least one resistant parental form, preferably the maternal one. No resistant samples of white rape and white mustard were found, cabbage samples vary considerably in resistance, and a fairly high level of resistance is observed in samples of oil radish, black radish and mustard, Abyssinian, and Sareptian. Some species can be used to isolate donors of Fusarium resistance and then be included in interspecific crosses with rapeseed.

There are reports that transgenic plants with increased resistance to Fusarium in winter rape have been obtained on the basis of radish defensin RsAfp.

Thus, for such harmful diseases of rapeseed as Alternaria, sclerotinia and verticillium, no sources of resistance within the species have been identified, although differentiation of genotypes by the degree of damage by this disease has been noted. The greatest attention of breeders is attracted to selection for resistance to phomosis. A large number of winter rape varieties resistant to this disease have been developed in France, and spring rape varieties in Australia and Canada. Sources of resistance to cylinderspore are mostly found in the UK. The most significant successes in breeding disease-resistant rape varieties and in creating sources and donors of

resistance are currently associated with the transfer of resistance factors by remote hybridization and transgenesis; selection on selective media in tissue culture is promising.

Sprouted seeds and seedlings of rapeseed can be affected by pathogens of various diseases. Therefore, seed treatment is a crucial measure in the fight against diseases. The right place in the crop rotation, spatial separation from areas where rapeseed was grown in the previous year, careful stubble cultivation, optimal nutrient supply, especially boron, and the creation of viable crops are the most important preventive measures to reduce the likelihood of disease infection. Since breeding for resistance has led to positive results in recent years, the selection of resistant, suitable varieties for a particular area of rapeseed cultivation is an important indirect control factor.

Early sowing, high sowing density, wet and mild autumn, as well as damage to plants by rapeseed flea beetle, cryptic borer, cylindersporium and frosts have a stimulating effect on the development of the disease. The use of fungicides does not always pay off. Numerous experiments with fungicides have shown that their effectiveness is higher in the fall than in the spring. By combining both methods, it is possible to increase the effectiveness of the fight against necrosis of the root collar and stems.

Growing healthy rapeseed seed material limits the spread of the most harmful diseases in each zone of the country.

To prevent the accumulation of infection in the soil and dramatically reduce plant disease damage, it is necessary, first of all, to strictly observe crop rotation in crop rotations. Rapeseed should not be returned to its original place until 3–4 years later [36].

In permanent culture, the incidence of *Ph. lingam, S. sclerotiorum, V. longisporium*, and to a lesser extent Alternaria spp. increased.

In Poland, the damage of winter rape by verticillium in permanent sowing was studied (from 1968 to 1994). In monoculture, 8.5% of plants had microsclerotia, and in crop rotation, 2.2%.

A significant increase in the incidence of winter rape with clubroot was observed with an increase in the share of the crop in the crop rotation (when cultivating about 10-12% of the sown area with clubroot, up to 46% of the plantations were affected) and, conversely, in some regions of France, where the crop rotation was grown every other year or in one

of three years for 30-40 years, clubroot has never been economically important.

To prevent epiphytosis of Alternaria and Phomosis, it is not recommended to plant rapeseed in low areas with excessive soil moisture [37]. Fields separated from last year's rapeseed crops, and even from this year's cabbage crops, by at least 1 km are optimal. Seed rapeseed should be planted after perennial and annual grasses, and cash crops should be planted after grain crops. This improves the activity of soil microorganisms – antagonists of pathogens of most diseases, which is especially important against clubroot, wilt and phomosis. In addition, the cultivation of garden savory and thyme as an intermediate crop for three years also contributes to the formation of a crop rotation [38] and peppermint [39]. A 60–95% reduction in moth infestation of Chinese cabbage (*Brassicae rapa* ssp. *pekinensis*) and *Brassicae deracea* var. *italika* plants (depending on the inoculum density) was obtained during a four-week period of growing *B. napus* as a bait.

According to V.H. Paul (1992), the main measures to combat downy mildew are the cultivation of disease-resistant varieties and the mandatory observance of crop rotation.

But not only the cultivation of resistant rape varieties, but also the agrotechnical method of plant protection has a fundamental impact on the state of its agroecosystem [40].

According to [41] The choice of a predecessor is primarily determined by the time of harvest. Spring rapeseed can be grown after any grain crop and even potatoes. Since manure is often applied to potatoes in Eastern Europe, spring rape, as the next crop, is always a good utilizer of the remaining nutrients. The accumulation of infection and the harmfulness of diseases increases dramatically if crop rotation is not followed. Thus, when sowing rapeseed after rapeseed, the incidence of Fusarium in the first year after sowing rapeseed was 21.2%; in the second year – 18.5% [42].

A long-term experiment conducted in Germany [43] convincingly proves that long-term cultivation of rapeseed in the same place, with a share of 33% in the crop rotation, has a favorable effect on the development of diseases and a decrease in yields. The more diverse the crop rotation and the smaller the share of rapeseed in the region, the lower the risk of mass reproduction of many pathogens of this crop. Studies have shown that the most favorable conditions for high yields of rapeseed exist in fields that

have been vacated after early potatoes, legumes, clover, alfalfa and annual fodder crops. Recommended [44] sowing rapeseed after peas and vetch-oat mixture grown for green fodder.

In addition, it is known that microelements also affect the resistance of rapeseed plants. With a seed yield of 30 centner/ha, rapeseed removes about 200-400 g of boron, 5-16 g of molybdenum, and 300-1800 g of manganese from the soil. Boron plays an important role in increasing the elasticity of tissues, which reduces the cracking of stems and roots during strong growth, and thus reduces the damage to plants by diseases. If the soil lacks boron, rapeseed plants are late to emerge from the rosette phase ("rapeseed sitting"), their growth is slowed down, young leaves are lighter in color, and the edges of the leaf blades are curled. Older leaves show spots of red to red-purple color. Boron deficiency is observed primarily in very light and calcareous soils, and even in drought. Since boron is difficult to move in the plant, small doses of boron in the form of fertilization will have the best effect.

It is necessary to carefully follow the rapeseed cultivation technology developed for each zone of the country. Much attention should be paid to preserving soil moisture, accumulating nutrients, and controlling weeds, especially cruciferous weeds, and pests that are reservoirs and carriers of many diseases. For these purposes, the fields freed from grasses are cultivated using the semi-pair system, and after grain crops, stubble is immediately peeled with disk stubble harrows to a depth of 6–8 cm in a unit with harrows, and after 10–12 days, the field is cultivated using the technology adopted for each zone. The infectious background of sclerotinia can be reduced by a complex of surface tillage with incorporation of plant residues into the lower horizons.

It is necessary to maintain a sufficient amount of humus to increase the biological activity of the soil and the associated antipathogenic potential of the soil. Fertilizers focused on the removal of nutrients based on soil and plant analysis, it is undesirable to apply timely increased doses of potassium fertilizers do not affect the degree of development of downy mildew, however, the introduction of nitrogen in high doses leads to increased damage to rape downy mildew [45].

Increasing the seeding rate of winter rape from 5 to 8 kg/ha leads to a significant increase in the number of affected plants with stem phomosis.

Thus, the rate of disease development with an increase in the seeding rate increased by 1.84 times, and the prevalence of the disease increased by 1.10 times.

In winter rape, increased doses of nitrogen did not have a significant effect on *Ph. lingam*, *B. concentricum*, Alternaria spp. and *S. sclerotiorum*, but with increasing doses of nitrogen, the incidence of *B. cinerea* and Ersyphe spp. increased.

With the increase of sulfur, zinc and boron content in the soil, the resistance of rapeseed to diseases increases [46].

The use of zinc and boron can lead to a reduction or prevention of canola clubroot disease [20].

The optimal soil reaction (pH 6.5–7.5) must be maintained. With an increase in pH from 43 to 54, the severity of winter rape plants increases from 54.1 to 73.9%; at pH 64 it decreases to 50.0%; and at pH 7.3–8.0 it increases again to 72.7%. The author explains these established peculiarities of plant response to *P. brassicae* infection by the specific requirements of winter rape to soil conditions [47].

In soils containing more organic carbon, a decrease in carpogenic germination was observed, while pH did not affect the germination of S. scierotiniorum sclerotia. The percentage of lesions increased with increasing sand content in soil samples, but decreased with increasing silt and clay content [48].

Preparing seeds for sowing is of great importance. After they are brought to a moisture content of 10–12%, they are thoroughly cleaned of weeds, and small, lightweight and defective seeds are removed. After cleaning and drying, the seeds are treated 2–3 days before sowing with 80% of the SP TMTD (5–6 kg/t of seeds) against bacteriosis, phomosis, ascochitosis, blackleg, downy mildew, olive spot? seed mold, black mold or 50% SP Derosal (2–2.5 kg/t of seeds) against root rot, or 70% SP Vitavax 200 (2–3 kg/t of seeds) against seed mold, black spot, downy mildew, helminthosporium root rot.

Applying a thin (several mm) film of biocompatible polymers, including active substances, to the seed surface is a new technique that allows better fixation and distribution of pesticides around the grain, as well as better environmental protection. Coating rapeseed seeds with SEPIRER film treated with the insecticide/fungicide oftanol T. ensured greater

efficiency of pesticide treatment at early stages of development (seed or germinating sprout).

The seedbed for rapeseed should have a finely lumpy structure, which is important not only for obtaining friendly germination with a minimum number of seeds, but also for enhancing the effect of herbicides if the rates of their use are reduced for environmental and economic reasons.

Excessive soil crumbling should also be avoided, because with heavy rainfall there is a risk of flooding and crusting, which will negatively affect the field germination of seeds and contribute to the defeat of seedlings by root rot and black leg [49].

Positive results of early sowing to protect winter rape from phomosis were noted: at the time of the onset of climatic conditions favorable for the development of the pathogen (temperature less than 15 °C), the crop is already at the stage of growth, immune to the pathogen [50].

With an increase in plant density from 80 to 240 per 1 m^2, the incidence of B. cinerea, *S. concentricum* and *P. parasitica* increases.

When rapeseed emergence occurs, shallow loosening of row spacings in wide-row crops is recommended to limit blackleg and phomosis, as well as to control weeds, and harrowing across rows in continuous crops when four leaves are formed.

A balanced fertilization system has a positive impact on controlling the prevalence of cruciferous crops. Mineral fertilizers increase the plant's resistance to environmental stressors, increase disease resistance, and accelerate seed development and maturation.

For example, here are the results of studying the effectiveness of microfertilizers on the development of Fusarium and Alternaria in spring rape (Table 3.1).

On average, over 3 years, a decrease in the development of diseases was observed with the use of foliar fertilizers. The lowest damage by Fusarium was noted in the variant with the introduction of Intermag Profi Oilseeds (1 l/ha) + Ultramag Boron (1 l/ha) + Biostim Oilseeds (in 2 phases) (0.5 l/ha), the development of the disease was 10.7% (9.2% lower than in the control). The effect of fertilizers on the development of late blight was not significant, depending on the variant, the reduction of the disease varied from 3.2% (Biostim Oilseed (1 l/ha) + Ultramag Boron (1 l/ha), Intermag Professional Oilseeds (1 l/ha) + Ultramag Boron (1 l/ha) + Biostim Oilseeds

(2 phases) (0.5 l/ha)) to 2.0% (Intermag Professional Oleaginous (1 l/ha) + Ultramag Boron (1 l/ha)).

Table 3.1

Impact of liquid mineral fertilizer treatment on the disease incidence of spring rape, 2015–2017, % [53; 56]

Variant	Fusarium				Pod alternaria			
	2015	2016	2017	Average	2015	2016	2017	Average
Control (without processing)	18.1	19.1	21.7	19.6	19.3	26.3	23.1	22.9
Intermag Profi Oil (1 l/ha) + Ultramag Boron (1 l/ha)	36.0	10.5	19.2	21.9	13.0	26.0	23.8	20.9
Biostim Oil (1 l/ha) + Ultramag Boron (1 l/ha)	20.9	15.7	10.6	15.7	10.8	25.8	22.4	19.7
Intermag Profi Oil (1 l/ha) + Ultramag Boron (1 l/ha) + Biostim Oil (1 liter/ha)	15.3	14.6	17.3	15.7	14.8	25.4	21.9	20.7
Intermag Profi Oil (1 l/ha) + Ultramag Boron (1 l/ha) + Biostim Oil (2 phases) (0.5 l/ha)	8.7	12.2	11.2	10.7	11.8	25.3	22.1	19.7
SSD_{05}	8.1	2.1	4.1		1.8	0.7	0.9	

Similar studies were conducted by Y. Savchuk [52]. The winter rape varieties used in the research were Snow Queen, Andromeda, and Vesuvius, which are undergoing state testing. Sowing dates were studied: early (August 11); optimal (August 21); late (August 31). Before sowing, the seeds were treated with microfertilizers such as Vuxal microplant, Terios and Askofol. Vuxal microplant is a highly concentrated suspension of micronutrients intended for late fertilization of intensive crops. Vuxal Terris is a public fertilizer for seed treatment with nitrogen, phosphorus, copper, manganese, molybdenum and zinc. Vuxal ascophol is a highly concentrated suspension extracted from the brown water of Ascophyllum nodosum. The research was conducted at the Agronomic Experimental Station of the National University of Life Sciences of Ukraine in 2014–2017.

It was found that microfertilizers had no significant effect on the development of diseases. The disease susceptibility of winter rape varieties overwhelmingly depended on the sowing time and the properties of the variety. According to the tables, the winter rape variety Vesuvius was relatively resistant to downy mildew, the damage of which in the early and optimal sowing dates was 0%; late – 3.1% (control). The damage to the variety Snow Queen by this disease at the optimal sowing date was 0%, in the early and late sowing dates the damage by downy mildew was 3.5 and 2.1%, respectively. The winter rape variety Andromeda proved to be resistant to downy mildew. In the early sowing period, the damage to the varieties by phomosis amounted to 18.6 – 22.5% (Tables 3.2–3.3).

Table 3.2

Disease incidence in winter rape varieties (early sowing) [53; 56]

Variety	Microfertilizer	Disease, %		
		downy mildew	phomosis	alternariosis
Snow Queen	Control	3.5	20.8	5.8
Andromeda		0.5	18.6	25.0
Vesuvius		0.0	22.5	20.4
Snow Queen	Microplants	1.5	10.2	6.6
Andromeda		0.1	10.0	16.6
Vesuvius		0.0	8.0	10.0
Snow Queen	Ascophol	2.0	15.1	5.8
Andromeda		0.0	5.6	10.0
Vesuvius		0.0	10.0	12.0
Snow Queen	Therios	2.8	10.0	6.5
Andromeda		0.0	10.0	15.0
Vesuvius		0.0	20.0	15.4

In the optimal and late sowing periods, the damage was 45 times less, which is associated with the biological properties of the pathogen and the developmental stage of the variety (Table 3.4).

The damage to the winter rape variety Snow Queen by phomosis at all sowing dates was stable. In the early sowing period, the maximum damage by Alternaria in Vesuvius and Andromeda varieties was 20.4 and 25.0%, respectively (control variant) (Table 3.4).

Table 3.3

Disease incidence in winter rape varieties (optimal sowing time) [53; 56]

Variety	Microfertilizer	Disease, %		
		downy mildew	phomosis	alternariosis
Snow Queen	Microplants	0.5	2.4	3.1
Andromeda		0.1	0.8	1.1
Vesuvius		2.2	3.1	2.8
Snow Queen	Control	0.0	5.2	6.4
Andromeda		0.0	2.0	3.6
Vesuvius		0.0	0.8	3.0
Snow Queen	Therios	1.2	1.2	1.2
Andromeda		0.5	2.2	4.1
Vesuvius		0.0	0.4	1.0
Snow Queen	Ascophol	1.2	0.8	0.8
Andromeda		0.8	1.3	2.8
Vesuvius		2.1	3.3	3.8

Table 3.4

Disease incidence in winter rape varieties (late sowing) [53; 56]

Variety	Microfertilizer	Disease, %		
		downy mildew	phomosis	alternariosis
Snow Queen	Ascophol	1.0	0.3	2.2
Andromeda		0.6	0.5	1.1
Vesuvius		1.1	0.9	0.6
Snow Queen	Therios	0.0	0.3	0.5
Andromeda		0.0	0.3	1.3
Vesuvius		0.1	0.5	0.5
Snow Queen	Control	1.2	5.1	3.3
Andromeda		0.5	1.1	2.3
Vesuvius		3.1	2.2	3.0
Snow Queen	Microplants	0.8	0.0	1.2
Andromeda		0.0	0.3	0.1
Vesuvius		2.0	1.8	2.6

The use of micronutrient fertilizers depending on the sowing time limits the development of diseases in winter rape varieties. Thus, with the use of Vuxal Microplant, Ascophol and Terios in the optimal and late

sowing periods, the damage to varieties by phomosis and alternaria was 1.5–2 times lower compared to the control. In the early sowing period, the use of micronutrient fertilizers reduced the damage by downy mildew by 1.0–1.5 times.

Microfertilizers Vuksal Microplant were highly effective against diseases of winter rape in the early sowing period, and Terios and Askofol in the optimal and late periods.

To reduce seed losses due to black spotting, rapeseed is harvested in a short time. In the case of separate harvesting, mowing into swaths begins when the seeds are brown on the central stem. Swaths are threshed at a seed moisture content of no more than 12%. For direct harvesting, seed moisture content is allowed up to 10% [53].

It is noted that a rational fertilizer system can regulate the prevalence of diseases of winter rape [53–54]. The system of mineral nutrition of plants is of particular importance in the fight against rapeseed diseases. Thus, the introduction of nitrogen in the form of ammonium nitrate (N_{60}), without phosphorus and potassium, into the main fertilizer contributed to better seed germination compared to the control (by 2.9%), reduced the number of affected plants by blackleg by 25%, but increased the disease of alternaria and root bacteriosis by 16.6% and 27.3%, respectively. The introduction of phosphorus-potassium fertilizers ($P_{90}K_{150}$) into the main fertilizer had a more positive effect on all processes of growth and development of winter rape, in particular, seed germination was higher by 5.9% and 2.8% compared to the control than in the variant with nitrogen (N_{60}). In the autumn period, rapeseed plants on the background of phosphorus-potassium fertilizers developed a better root system and better tolerated frosts, respectively, by 83.3% and 22.2%, 36.1% and 28.9%. Phosphorus-potassium fertilizers increased the resistance of winter rape plants to blackleg, alternaria and root bacteriosis by 2.7, 1.5 and 1.8 times compared to the control, respectively, and by 2.0, 1.8 and 2.3 times compared to the variant where N_{60} was used. The application of the main mineral fertilizer at a dose of $N_{15}P_{35}K_{90}$ increased the density of seedlings by 5.9% compared to the control, the length of lateral branches of the main root by 18 cm or 2.5 times, the number of leaves of the autumn rosette and better wintering of plants. Symptoms of mineral nutrition deficiency were detected in 15% of plants, which is 4.5 times less than in the control. This dose of fertilizer

contributed to a sharp decrease in the number of plants affected by diseases compared to the control: black leg by 4 times, Alternaria by 10 times, and root bacteriosis by 1.8 times. The main fertilizer $N_{30}P_{70}K_{120}$ had a positive effect on all processes of winter rape development in the autumn, in particular, field germination of seeds was higher by 14.7% compared to the control and by 8,3% compared to the variant with $N_{15}P_{35}K_{90}$. Increasing the dose of phosphorus and potassium fertilizers contributed to better root system formation. The length of lateral branches of the main root exceeded the control variant by 3 times, and by 1.5 times – the variant with the introduction of $N_{15}P_{35}K_{90}$. The structure of the rosette of rapeseed leaves in the autumn period of rapeseed vegetation corresponded to the optimal amount, which contributed to an increase in the preservation of the number of plants after wintering, compared to other variants of the experiment. Increasing the dose of the main mineral fertilizer to $N_{60}P_{90}K_{150}$ had a positive effect on the growth and development of winter rape, the density of seedlings exceeded the previously indicated variants by 16.2, 9.7 and 1.3%, respectively; the length of lateral branches of the main root increased by 4 and 1.6 times, and by 6.7%, respectively. After the restoration of spring vegetation, the density of plants in the variant exceeded the previous variants by 1.9 times, 25.0 and 2.9 points, respectively. The development of diseases in the fall was observed on single plants. Mineral fertilizers applied during critical phases of rapeseed growth and development increase the resistance of winter rape plants to diseases. Thus, the introduction of nitrogen in the main fertilizer and feeding plants with it reduces the spread of phomosis and the intensity of the disease development, compared to the control, by 6,7 and 0,9 points, respectively; alternaria, by 2.8 and 8.1 points, respectively. The application of phosphorus-potassium fertilizers is more effective in increasing plant resistance to diseases. Compared to the control and nitrogen application, the introduction of $P_{90}K_{150}$ contributed to a decrease in the spread and intensity of phomosis development by 12.5 and 1.1, 5.8 and 0.2 points, respectively; Alternaria by 18.8 and 13.7, 16.0 and 5.6 points, respectively; Cylindrosporium by 8.0 and 5.1, 4.1 and 0.4 points, respectively. The application of balanced mineral fertilizers in low doses ($N_{100}P_{35}K_{90}$) dramatically reduces the spread and intensity of disease development compared to the control, one-sided nitrogen application and phosphorus-potassium fertilizers: Phomosis, respectively, by 16.6 and

1.7, 9.9 and 0.8, 4.1 and 0.6 points; Alternaria, respectively, by 28.5 and 18.0, 25.7 and 8.9, 9.7 and 3.3 points; Cylindrosporium, respectively, by 12.7 and 5.7, 8.6 and 0.6, 4.5 and 0.4 points. Further increase in balanced mineral fertilizers $N_{200}P_{70}K_{120}$ and $N_{230}P_{90}K_{150}$ does not significantly reduce the disease of winter rape with phomosis compared to the minimum dose of fertilizer $N_{100}P_{35}K_{90}$. The experiment showed a significant decrease in the spread and intensity of Alternaria and Cylindrosporium development.

The influence of soil cultivation systems on the development of some diseases of rapeseed was also investigated [55]. Thus, the experiment showed that the most common and harmful disease of winter rape is Alternaria brassicae. The development of the disease depends on weather conditions. In 2018, the air temperature was high for April (13,4°C), which was almost twice as high as the long-term average (7,7°C), and only 10.1 mm of rain fell (40 mm); such weather conditions did not favor the development of the disease and its first manifestations were recorded on June 20–22. In 2017, on the contrary, sufficient precipitation (III decade of April – 19.5 mm, I decade of May – 5.6 mm) and optimal air temperature in the first decade of May (13.8°C) were favorable for the development of Alternaria and the first signs of the disease were detected on May 13–15.

7 days after spraying the crops with Kolosal Pro fungicide (propiconazole + tebuconazole), the development of Alternaria varied within 1.0–1.2% with a spread of 10-15%, while in variants without fungicide protection, the development of the disease was 4.3–5.7% with a spread of 68% under different methods of soil cultivation (Table 3.5). It should be noted that the development of the disease under shelf tillage during the growing season was 1.5 times lower than under surface tillage. According to Table 5, 20 days after spraying, an increase in the development of the disease was observed. That is, the toxic effect of the preparation restrained the development of Alternaria for 18–20 days.

The technical effectiveness of the fungicide Kolosal Pro against Alternaria is the highest 14 days after spraying and is 84.0–88.0%.

The influence of soil cultivation system on the development of diseases of winter rape is also noted in another study [56] – under conditions of sufficient moisture of the Ivano-Frankivsk Institute of Agricultural Production, the use of plowing by 20–22 cm and shallow tillage by 5–6 cm allows to obtain friendly shoots of winter rape. Plowing the soil by 20–22 cm contributes

to better wintering of winter rape, which is 13.4% higher than the result obtained in the variant with shallow tillage by 5–6 cm. The damage to plants by downy mildew depends more on climatic conditions than on the tillage system.

The average long-term rate of winter rape damage by Alternaria and the intensity of the disease development in the variant with plowing at 20–22 cm was, respectively, 14.2 and 7.0%, which is lower than in the variant with shallow tillage at 5–6 cm, respectively, by 2.0 and 2.0 points.

On average, over 4 years of research, the number of winter rape plants affected by phomosis in the variant with shallow tillage by 5–6 cm was 3.2 points higher than in the variant with plowing by 20–22 cm.

An important part of the system of controlling the development of the cruciferous disease reserve is an established system of primary and secondary seed preparation and treatment. It has been established that rapeseed seeds with high moisture content are often subject to mold, which leads to loss of germination and deterioration of the quality of the oil and meal produced. To avoid this, immediately after threshing, the seeds are separated from the heap and spread out for drying with a layer of slightly more than 1 cm with frequent turning [55].

Table 3.5

Alternaria development on pods of winter rape (Institute of Agriculture of Western Polissya NAAS, 2017–2018) [55]

Experiment variant		Disease development (days) after spraying, %.			
		before spraying	after 7	after 14	after 20
Shelf by 20–22 cm (control)	Without pesticides (control)	1.0	4.3	7.5	17.0
	Integrated security system	1.0	1.0	1.2	3.8
Shallow by 10–12 cm	Without pesticides (control)	1.0	5.0	12.5	19.0
	Integrated security system	1.0	1.2	1.5	5.3
Superficial by 6–8 cm	Without pesticides (control)	1.0	5.7	11.7	20.0
	Integrated security system	1.0	1.2	1.5	5.0

Diseases, as noted in the previous sections, affect the quality and chemical composition of cruciferous seeds. Thus, in some studies it is noted [55] that according to I.L. Markov, the greatest changes in the fatty acid composition

of oil are observed when winter and spring rape seeds are damaged by pathogens of Alternaria, white and gray rot. At the same time, the proportion of saturated fatty acids, palmitic and stearic acids, monounsaturated fatty acids – erucic, eicosenic and polyunsaturated fatty acid – linoleic acid increases in the oil, but the proportion of monounsaturated fatty acid – oleic and polyunsaturated fatty acid – linoleic acid decreases. Many years of research have established [56] that abiotic factors are one of the main regulating factors of disease in rapeseed. Disease development intensifies when the optimal temperature and humidity coincide in certain periods of time. These optimal conditions are usually different for different pathogens or even for the same disease in regions with different climatic conditions and different agricultural practices. For example, under conditions of moderate temperatures and intense precipitation, the development of Alternaria in rapeseed is enhanced. Over the years of observation (1999–2006), in 6 cases out of 8, winter rape plants were affected by 45 to 100%, pods – 42%, with an average disease intensity of 18%. Spring rape was less affected by Alternaria than winter rape. Thus, in 2002, 46–90% of winter rape plants were affected, with a disease severity of 10–83%, and 26–42% and 3–13% of spring rape, respectively. In 2005, in the northwestern regions, 23–46%, or a maximum of 70%, of winter rape plants were affected, with a disease intensity of 2–10%, and spring rape, respectively, G1-26 and 0.1–5%, and 8–29% of winter rape pods, and 2–7% of spring rape pods. In 2006, 36–100% of winter rapeseed plants were affected in the northwestern regions, 18–56% in the central and southern regions, and 12–36% of spring rapeseed plants. In the northwestern and some central regions of Ukraine, winter rape root bacteriosis is annually observed on 12–64% of the surveyed areas, with 1 to 19% of diseased plants. The spread of rapeseed bacteriosis depends on the climatic conditions in September, when moisture deficit alternates with excessive precipitation, which can lead to the formation of a cavity (hollow) inside the roots, near the root collar, which is inhabited by bacteria. The second critical period for winter rape plants is snowless, frosty winters, as well as frequent thaws, when most of the affected roots become slimy and soaked, leading to plant death. One of the leading places in limiting the development of diseases belongs to the correct soil cultivation system that would meet the most optimal requirements of rapeseed for this agricultural measure.

Biological control of cruciferous crops is actively developing. Thus, against Fusarium and white rot of rapeseed, the staff of the Laboratory of Biological Plant Protection Products of the Oilseeds Research Institute tested the biological product Vermiculen – 0.2 kg/ha of paste based on a strain of fungus antagonist Penicilliitm vermiculatum. The biological effectiveness was 60-90%, and the biological product was not inferior to the effectiveness of foundationol [57]. The introduction of the bacterial strain MaBI Bacillus sp. into the soil as a suspension reduced the number of *S. sclerotiorum* apothecia to 18.8–36.5 % compared to the control, which resulted in a significant reduction in yield losses.

In the experiments, among 217 bacterial isolates isolated from rapeseed plants and related species, isolates inhibiting the growth of *P. sclerotiorum* were selected. Among them were *Pseudomonas fluorescens*, *P. chlororaphis*, *P. agglomerans*, *Stenotro-phomas*.Thirty isolates inhibited the growth of the pathogen due to volatile components, five isolates produced oxalate oxidase [58].

Inoculation of soils with the fungus *Coniotkyrium minitans* (IMI 134523), isolated from the sclerotia of *S. sclerotiorum* of rapeseed, led to a decrease in their survival and reduced the production of apothecia. The effectiveness was especially high when inoculating *S. minitans* in the fall (during sowing of winter rape). S. minitans survives for two years and was able to spread to neighboring areas and infect sclerotia there. However, *S. sclerotiorum* could not be completely eradicated [59].

The introduction of Trichoderma harzianum into the soil inhibited the mycelial stage of *S. sclerotiorum* by 94%, but did not affect the carpogenic germination. The latter was inhibited by 100% when flour from Dwarf, Essex rape seeds with a high glucosinolate content was added to the soil, with a 33% reduction in myceliogenic germination. Flour of the low-glucosinolate rapeseed variety Stonewall, introduced into the soil, reduced carpogenic germination by 44% and did not affect myceliogenic germination. Flour of both varieties inhibited colonization of T. harzianum sclerotia in the soil from 100% to 0 and 8%, respectively, which is why the biocontrol activity of *T. harzianum* decreased in the presence of rice flour [60].

A scheme has been developed to effectively protect winter rapeseed crops from weeds, pests and diseases under intensive cultivation technology. Thus, if 10–15% of leaf blades show symptoms of phomosis

or cylindrosporosis, the crops are immediately treated with fungicides. The most effective suppression of gray rot development on winter rape crops is achieved by treating with appropriate preparations at the optimum time – when 10–12% of affected plants appear. The minimum harmfulness of verticillium is observed when treating crops immediately after the first symptoms of plant wilting appear.

The high susceptibility of yellow-seeded samples of spring rape to Fusarium wilt, as well as the high harmfulness and widespread spread of this disease makes it necessary to use chemical control measures.

One of the most effective methods of chemical plant protection is seed treatment.

Seed treatment allows to:

– disinfect seeds from plant pathogens that are transmitted through seed material;

– protect seeds and seedlings from mold in soil conditions;

– to reduce damage to seedlings by root rot and soil-borne pests when treating seeds with combined preparations with the addition of insecticide;

– to reduce the negative impact of traumatic injuries on seed quality by activating its protective properties and preventing the development of microorganisms;

– to stimulate plant growth and development due to the effect of the products on some physiological processes in seeds and germinating plants;

The most effective way to disinfect seeds is to apply the pesticide in film-forming formulations, the so-called inlay and hydrophobization of seeds.

As film formers, you can use a 5% aqueous solution of polyvinyl alcohol, 2–2.5% aqueous solution of sodium salt of carboxymethyl cellulose (for encrustation) and a solution of polystyrene in chloroform (for hydrophobization).

An important advantage of inlaying is that the active substances on the seed surface are not fixed in a continuous film, but in discrete spots. Therefore, with the same protective effect, less active material is required than with classical methods of treatment.

Recommendations for the use of fungicides to prevent damage to spring rape plants by these diseases are ambiguous [61]. In the scientific literature, it is proposed to use the fungicide Forsazh, hp (0.6 l/ha) [62], Aliet, s.p. (1.2–1.8 kg/ha) and Rovral 50 VP, (1.5 kg/ha) [63], Caramba and

Folicur (0.3 l/ha) [64], Ridomil Gold (2.5 l/ha), Derosal 50 (10 kg/ha) and Sarfun 500 (0.6 l/ha) [65–66].

Chemical measures against diseases in rapeseed are also used only when absolutely necessary and reasonable. However, a mandatory measure against seed-borne diseases of rapeseed is disinfection of seeds against external and internal infection with fungicide-protectants approved for use in Ukraine. In order to detect the initial stage of disease development on rapeseed plants in a timely manner and to take effective protective measures to limit their harmfulness, it is necessary to systematically monitor diseases in rapeseed crops. Since most diseases develop simultaneously, rapeseed fields should be inspected at the appropriate time of the plant's growing season. Against the diseases that develop on rapeseed plants during the growing season, in each specific case, on each specific field, an informed decision should be made based on its phytosanitary condition, the expediency of preventive spraying of rapeseed crops with fungicides.

Table 3.6

In vitro evaluation of fungicide efficacy against *Fusarium wilt* pathogen of spring rape [67]

Варіант	**Overgrowth area of the Petri dish surface, cm^2 per day of accounting**			
	3th	**5th**	**10 th**	**20 th**
1	2	3	4	5
Control (without fungicide)	46.5***	63.6****	63.6****	63.6****
TMTD, SP (800 g/kg of thiram) etalon	0.0	2.5*	10.6*	63.6****
TMTD, VSK (400 g/l tyramine)	0.4*	3.1*	15.5*	63.6****
Maxim, CS (25 g/l fludioxonil)	1.2*	23.2**	31.2**	32.5**
Vincit, SC (25 g/l thiabendazole + 25 g/l flugriafol)	1.3*	3.3*	8.4*	45.1***
Corbel, KE (750 g/l phenropimorph)	1.1*	7.3*	11.7*	54.0****
Panoktin, BP (350 g/l guazatin)	0.1*	0.1*	0.8*	16.6**
Sportak, KE (450 g/l prochlorazole)	0.1*	0.1*	3.8*	17.9**
Raxil T, CS (500g/kg of thiram + 15g/kg of tebuconazole)	The mycelium grows upward only on agar cuttings without transferring to medium			
Raxil, CS (60 g/l tebuconazole)				

(End of Table 3.6)

1	2	3	4	5
Raxil T, CS (500g/kg of thiram + 15g/kg of tebuconazole)	The mycelium grows upward only on agar cuttings without transferring to medium			
Raxil, CS (60 g/l tebuconazole)				
Dividend, CS (30 g/l of difenoconazole)	Complete inhibition of *F. oxysporum* growth			
Premium, CS (25 g/l triticonazole)				
Folicur BT, CE; (125 g/l tebuconazole + 100 g/l bayleton)				

Note: * – very weak fungal growth (1-25 %); ** – weak growth (26-50 %); *** – medium growth (51-75 %); *** – strong growth (75-100 %).

Until now, the search for fungicides against any particular pathogen has been conducted empirically. To isolate one fungicide suitable for practical use, it is sometimes necessary to test up to 50 thousand chemical compounds [67], Therefore, for the initial selection of fungicidal compounds, methods that require a minimum amount of test substances and low labor costs are used.

For the primary screening of fungicides, a modification of the widely used diffusion method was used [67-68]. The essence of the test is that the test substance is applied to a sterile paper disk, placed in a Petri dish, poured with agar medium, and inoculated with a fungus. The sterile zone is used to judge the activity of the compounds. In laboratory conditions, the primary evaluation of the fungicidal activity of the drugs was carried out on a pure culture of Fusarium oxysporum: TMTD, TSK, maxim, vincit, corbel, panactin, sportak, raksil T, raksil, dividend, premis and follicle. TMTD, SP (800 g/kg of tyramine) was used as a standard (Table 3.7).

The studied fungicides Dividend, Premis, Raxyl and Folicur completely suppressed the development of pathogen mycelium within 20 days, which indicates their high efficiency. Subsequently, all the preparations were tested for disinfection of seeds from pathogens and molds.

Study [68] showed that rape seeds are a source of primary infection with Fusarium pathogens and molds.

The percentage of Fusarium spp. infection of seeds in the control (untreated) varied over the years and averaged 5% over 3 years, which is 2.2–10 times higher than in the inlaid variants. Throughout the entire

period, *F. oxysporum* did not develop on seeds treated with systemic preparations: Premis, Follicle, Raxyl T and Raxyl and contact panactin. In all other variants, with the exception of vincit, dividend and sportak, the beginning of the pathogen development coincided with the beginning of its development on untreated seeds (control). All the tested preparations also showed biological effectiveness, reducing the stock of infectious inoculum of such pathogens on seeds as Alternaria spp.

Table 3.7

Frequency of occurrence of Fusarium and mold pathogens on inlaid spring rape seeds [67]

Variant	Consumption rate, kg/t, l/t	Seeds with viable mycelium, % on the 10th day of recording		
		Fusarium spp	***Alternaria spp***	**others**
Control (without processing)	–	5.0	15.3	8.7
TMTD, SP (800 g/kg), benchmark	5.0	2.3	6.7	1.0
TMTD, VSC (400 g/l)	3.0	2.0 >	6.7	3.7
Maxim, CS (25 g/l)	2.0	2.3	2.7	2.0
Maxim, CS (25 g/l)	5.0	1.7	2.7	0.7
Vincite, SC (25+25 g/l)	2.0	1.3	8.3	1.7
Korbel, KE (750 g/l) + NaCMC	1.0	1.3	2.3	2.0
Sportac, KE (450g/l) + NaCMC:	2.0	0.7	0.7	0.3
Dividend, CS (30 g/l)	2.0	0.7	5.7	2.0
Panoktin, BP (350 g/l)	2.0	0.0	5.0	3.7
Premium, CS* (25 g/l)	2.0	0.0	11.5	2.0
Folicur BT, KE* (125+100 g/l) + NaCMC	1.0	0.0	7.0	0.0
Raxyl T, CS* (500+15 g/kg)	2.0	0.5	0.0	3.5
Raxyl, CS* (60 g/l)	0.5	0.0	1.0	1.0

Note: * – two-year data.

The inlay of spring rape seeds with all fungicides, in general, contributes to a decrease in germination energy and, in some variants, laboratory and field germination. These indicators varied over the years. The greatest negative impact of the preparations on the processes of seed germination is explained by the initial low quality of the seed material. Against the background of all

fungicides, the greatest phytotoxic effect on seedlings in the laboratory and young plants in the field was observed in Premis and Folicur BT, which on average over 2 years of testing reduced the energy of seed germination by 20.4–33.5%, laboratory germination by 9.2–18.4% and field germination by 7.4–11.3%. In seedlings under laboratory conditions in variants with Folicur, the root system was represented only by a central root with very weak pubescence, the length of which was 37.5–43.1% of the control, which had well-developed central and lateral roots with dense pubescence. As for Premium, with normal development of the root system of seedlings, their length was 53.1–58.5% of the length of seedlings from untreated seeds. Sportak significantly reduced the energy of seed germination in the first year of testing, but germination rates both in the laboratory and in the field were of the same order, from year 3 it was 5%, which is 2.2–10 times higher than in the variants with inlay. Throughout the entire period, the germination rate on seeds treated with systemic preparations: Premium, Folicur, Raxil T and Raxil and contact panactin, F. oxysporum did not develop. In all other variants, with the exception of Vincite, Dividend and Sportak, the beginning of pathogen development coincided with the beginning of its development on untreated seeds (control). All the tested preparations also showed biological effectiveness, reducing the stock of infectious inoculum of such pathogens on seeds as Alternaria spp.

During the three years of field experiments, the meteorological conditions for the growth and development of spring rape were not the same. However, the common factor is that during the flowering period of yellow-seeded rape, droughts were observed under the dominance of easterly winds. At high temperatures, yellow-seeded rape showed such phenomena as heterostylia, deformation of pistils, reduced pollen productivity, etc. This caused a low degree of realization of the potential productivity of yellow-seeded rape (Tables 3.8–3.9) and, apparently, low biological efficiency of seed treatment with fungicides. These results are consistent with the data obtained during the study of the influence of the level and mode of moisture supply to wheat plants on the effectiveness of pre-sowing seed treatment with contact and systemic fungicides. It has been shown that dry conditions at any stage of wheat organogenesis before filling reduce the biological effectiveness of treatment, and sowing treated seeds in insufficiently moist soil can lead to a decrease in yield and grain quality compared to the untreated control.

Thus, in breeding for resistance to Fusarium wilt of spring rape, an infectious background should be widely used, which makes it impossible to make mistakes when evaluating the source material. When creating such a background, it is possible to use complex compositions of pathogen populations that are as close as possible to the natural one existing in a given soil and climatic zone. The introduction of materials into the soil of the infectious nursery should be carried out simultaneously with sowing seeds.

Table 3.8

Effect of fungicide treatment of spring rape seeds (type "000") on Fusarium infection [61]

Variant	Consumption rate, l/t, kg/t	Plants affected by Fusarium, %				Average biological efficiency, %
		2001	2002	2003	average	
Control (without processing)	–	77.2	99.6	57.9	78.2	–
TMTD, SP (800 g/kg), etalon	5.0	27.6	95.3	59.6	60.8	22.8
Korbel, KE (750 g/l)+NaCMC	1.0	34.4	94.5	39.9	56.3	30.3
Vincite, SC (25+25 g/l)	2.0	25.9	92.4	46.2	54.8	31.7
Dividend, CS (300 g/l)	2.0	27.4	93.1	44.0	54.8	32.0
Sportac, CE (450 g/l) + NaKMC	2.0	32.9	92.7	30.0	51.9	38.6

The temperature optimum for infection of yellow-seeded spring rape with F. oxysporum is within 14–16 °C, which is 6–10 °C lower than for infection of blue-seeded rape. At early terms of spring sowing of "000" type rape, conditions more favorable for infection are created (Table 3.10).

As a criterion for the feasibility of using fungicides, it is proposed to take into account the excess of the cost of a possible crop shortfall over the cost of applying the fungicide twice. If the cost of a lost harvest is less than the cost of two treatments, it is not advisable to use chemical protection on rapeseed.

Table 3.9

Seed quality of spring rape seeds (type *'000") after treatment with different fungicides, 2001–2003 [61]

Variant	Consumption rate of preparative, l/t, kg/t	Germination energy of the seed, %				Seed germination, %							
						laboratorial				fieldwork			
		2001	2002	2003	Xavr	2001	2002	2003	Xavr	2001	2002	2003	Xavr
Control	–	66.0	95.0	92.0	84.0	72.0	96.0	94.0	87.0	51.0	69.0	76.0	65.0
TMTD, SP (800 g/kg), benchmark	5.0	70.0	91.0	91.0	84.0	77.0	95.0	93.0	88.0	53.0	72.0	74.0	66.0
Korbel, KE (750 g/l) +NaKMC	1.0	49.0	96.0	92.0	79.0	75.0	98.0	94.0	89.0	53.0	74.0	75.0	67.0
Vincite, SC (25+25 g/l)	2.0	57.0	93.0	91.0	80.0	74.0	95.0	91.0	87.0	52.0	67.0	79.0	66.0
Dividend, CS (300 g/l)	2.0	67.0	93.0	90.0	83.0	75.0	94.0	91.0	87.0	53.0	73.0	73.0	66.0
Sportak, CE (450 g/l) + NaKMC	2.0	32.0	96.0	89.0	72.0	69.0	96.0	93.0	83.0	48.0	74.0	76.0	66.0
Premium, CS (25 g/l)	2.0	35.0	86.0	–	60.0	64.0	86.0	–	75.0	41.0	64.0	–	53.0
Folicur BT, KE (125+100 g/l) + NaKMC	1.0	20.0	74.0	–	47.0	53.0	78.0		66.0	39.0	58.0	–	49.0

Seed of varieties unstable to phomosis should be treated with a mixture of bitertanol and tebuconazole (12 g and 0.2 g of d.v./g of seed, respectively). If necessary, it is also advisable to treat the plants in the fall (in some cases twice). Spring treatments are also possible, but in general they are much less effective than autumn treatments. Fungicide treatment should be combined with insecticide treatment, as mechanical damage by insects contributes to the development of phomosis.

In the UK, the fungicides Prochloraz and Sportak provided satisfactory results against canker when applied in late fall or spring at recommended rates.

Table 3.10

Efficiency of fungicide application in the treatment of spring rape seeds (type "000") against Fusarium head blight [61]

Variant	Consumption rate, l/t, kg/t	Yields, t/ha	Oil content in seeds, %.	Oil yield, t/ha	Content of glucosinolates, µmol/g	Weight of 1000 seeds, g
Control	–	0.22	42.7	0.083	22.2	2.3
TMTD, SP (800 g/kg), benchmark	5.0	0.23	42.8	0.087	22.7	2.4
Korbel, KE (750 g/l) +NaKMC	1.0	0.28	42.7	0.105	22.7	2.4
Vincite, SC (25+25 g/l)	2.0	0.27	42.9	0.102	22.1	2.3
Dividend, CS (300 g/l)	2.0	0.28	42.8	0.105	20.3	2.4
Sportak, CE (450 g/l) + NaKMC	2.0	0.29	42.8	0.109	21.8	2.5

There was no increase in the effectiveness of prochloraz when the recommended rate was applied in several terms. However, this disease did not significantly affect the seed yield, which may be due to its relatively weak development [68–69].

Sopra (France) is building protection of rapeseed crops on the use of fungicides with flutriafol and procyamidone as active ingredients, which belong to different groups of chemical compounds, have different modes of action, and an additional spectrum of activity. Both substances can be mixed with other drugs (e.g., Deroprene FL, Deroprene 80 WC). Flutriafol

is highly effective against *Ps. capsellae*, *C. concentrium, A. brassicae*. Procyamidone is a highly effective agent against A. brassicae and S. sclerotiorum. In the developed strategy, the concentrations of flutriafol and procimidone were reduced by 20 and 25% (94 g of flutriafol and 375 g of procimidone). The use of flutriafol and procimidone allows to protect rapeseed crops during the entire growing season [70].

Folicur (tebuconazole) effectively inhibited the development of *S. sclerotiorum, L. maculans*, *Pyrenopeziza brassicae*, Alternaria spp., Verticillium spp., *Mycosphaerella brassicicola*, *B. cinerea, B. concentricum* when the fungicide was applied in the flowering and early seed ripening phases [71].

Application of Folicur before flowering of rapeseed reduced lodging of the crop regardless of the presence of the disease, and the retardant effect of the drug increased with increasing dose. The effectiveness of tebuconazole against stem diseases and its ability to prevent lodging of rapeseed significantly decreased during treatment after flowering. Double application of tebuconazole before and after flowering not only provided complete protection of the crop from diseases and delayed lodging, but also led to a significant increase in yield. It is believed that the reduction of lodging in oilseed rape by tebuconazole may be due to both the suppression of stem disease development and the ability of the fungicide to inhibit the aging of green tissues [72].

With a high infection background of Alternaria spp. and *B. cinerea*, the best results can be obtained with early treatments (at the beginning of flowering) with the following fungicides: fluzilazole + carbendazim, procyamidone, tebuconazole, metconazole and azoxystrobin [73].

Ronilan (1.5 l/ha), Torak (0.6 l/ha), Sumislex (0.7–1.0 l/ha), Verizan (2–3 kg/ha), Rovral (1.0–1.5 l/ha) are recommended for controlling Phoma, Verticillium and S. sclerotiorum fungi.

In the protection of rapeseed from *S. sclerotiorum*, *A. brassicae, B. cinerea*, which affect plants at the beginning of flowering, a mixture of prochloraz (133 g/l) and iprodione (133 g/l) at a dose of 3 l/ha is effective [74].

Sportak PF (1 and 1.5 l/ha) and bavistin (0.5 l/ha) with double treatment, carbendazim and rovral were effective fungicides against white leaf spot on winter rape crops.

At the recommended doses, the dinitroaniline herbicides Sytoxidium and Cyclosidium, which are most often used on rapeseed in Iran, have the highest antifungal activity against S. sclerotiorum in vitro on toxic CAA media [75].

In Schleswig-Holstein, the area under rapeseed reached 90 thousand hectares. One of the problems of the industry is the fight against fungal diseases, among which the first place is occupied by *S. sclerotiorum* stem damage. The fungicides Ronilan, Sumilex, Verizan, and Rovral were used to combat sclerotinia. The optimal time for using fungicides is in the phase of full flowering (5–10 days after the beginning of flowering). These drugs are effective against Botrytis, Alternaria, *C, concentricum* fungi. In 1983–1986, aerial fungicide treatment in the Lübeck region was carried out on 5.6–20 thousand hectares of rapeseed crops. On average, up to 100–150 marks/ha is spent in the area to combat fungal diseases of rapeseed.

Spraying with one of the fungicides carbendazim (0.55 kg d.in./ha), iprodione (0.5 kg d.in./ha), vinclozalin (0.5 kg d.in./ha) or mixtures of iprodione with thiophanate-methyl (0.5+0.5 kg d.in./ha) significantly reduces the infection of S. sclerotiorum. Fungicide treatment did not affect the weight of 1000 seeds. The treatment is optimal in late April and early May before the humidity increases [76].

Against downy mildew, during the growing season, crops are sprayed twice with Aliet, SP (800 g/kg) at the rate of 1.2–1.8 kg/ha. The first – 12–15 days after germination, the second – during the budding period, mainly on crops for seed production. It is recommended to apply these sprays in combination with insecticides to kill pests. No second chemical treatment is applied to crops intended for green mass production. When powdery mildew appears, the crops are treated with 1% colloidal sulphur at the rate of 2.5–3.5 kg of the product per 1 ha. This work is completed later, 6–7 days before harvesting.

Since the primary source of infection can be infected rapeseed, it must be cleaned, calibrated and treated. For this purpose, the same treatments mentioned above are used: TMTD, 80% NPK 5–6 kg/t and Vitavax 200, 75% NPK 2–3 kg/t, which contribute to the long-lasting protection of rapeseed against Fusarium and Alternaria [77]. It is also recommended to use a complex preparation – Rapkol, TK – 25 kg/t. According to [78]. This product not only protects rapeseed seedlings from diseases, but also

prevents damage by cruciferous fleas. In addition to the above-mentioned products, other fungicides have been tested in the fight against Fusarium. The biological effectiveness in the fight against seed infection of Fusarium and Alternaria was 97.4% for Vincit, 96.2% for Baytan-Universal, 98.7% for Vitavax + boric acid, and 96.2% for boric acid + $MnSO_4$ [79–80]. Trace elements, being nutrients, increase plant productivity and resistance [81–83]

In addition, there are recommendations to use such preparations as Rovral, 3 kg/ha and Folicur, 1 kg/ha for the treatment of plants during the growing season, which prevents damage from Alternaria [84]. With a high degree of spread of this disease, the best results were obtained with early treatment of plants (at the beginning of flowering) with solutions of the following fungicides: procyamidone, tebu conazole, metconazole and azoxystrobin or a tank mixture – flusilazole + carbendazim.

To protect crops from rot, it is recommended to use products from the carboxamide class, boscalid, 200 g/l. The use of chemicals from the class of benzimidazoles, carbendazim, 500 g/l, is almost universal. This is a systemic preparation recommended against a complex of diseases. The fungicide is aimed at inhibiting the process of nucleation in fungal cells. It is most effective against diseases of vegetative organs, as well as a complex of seed-borne phytopathogens, and is often used for pre-sowing seed treatment. Also effective in this class are fungicides with benomyl-based formulations, 500 g/kg, with combined action.

High efficiency is characterised by systemic triazole preparations: triadimefon, 250 g/l; metconazole, 60 g/l; propiconazole, 250 g/l; tebuconazole, 250 g/l, which are effective against peronosporosis, alternaria, phomosis, powdery mildew, and suppress root rot, smut fungi and seed mould.

Variants of fungicide combinations on winter rape and different seeding rates were also studied [85]. Thus, the use of fungicides in autumn had a pronounced positive impact on reducing the development of stem blight. Thus, against the background of a sowing rate of 1 million germinating seeds/ha, the level of biological efficiency of fungicides against stem blight was 33–92%, and against the background of 1.8 million germinating seeds/ha – 40–93%.

Among the fungicides studied, against the background of a seeding rate of 5 kg/ha, the maximum value of biological effectiveness against stem

blight was on the variants Rex C and Impact, and in thickened crops – when using Zenon Aero and Impact.With an increase in the seeding rate, the damage to the leaves by fomites also increased slightly. The difference was especially significant in the rosette phase in spring (immediately after the resumption of vegetation) [86].

In the phase of 6 leaves (3 pairs of true leaves), such preparations as Zenon Aero and Impact stood out among the fungicides studied in the first background. At the increased seeding rate, the lowest development of the disease was observed when treating crops with Zenon Aero, Impact and Falcon. The maximum biological effectiveness of fungicides was in the rosette phase in spring. By the flowering stage, the effect of autumn fungicide treatment ceased. There were no significant differences in the value of biological efficiency, depending on the seeding rate. On the backgrounds with different seeding rates, the maximum value of biological efficiency was observed when using Zenon Aero and Impact.

Autumn application of fungicides on winter rape did not give a positive result in controlling Alternaria leaf blight of winter rape. Seeding rate had the greatest impact on this disease. In particular, with an increase in the seeding rate, the prevalence of Alternaria increased by 1.36 times (Table 3.11).

With the increase in sowing density, the phytosanitary condition of the seeds of the new crop deteriorated. This effect was especially significant for Alternaria. All the fungicides studied did not affect the infection of seeds with Alternaria, but somewhat reduced the infection of seeds with Phomosis. Here, too, Impact had a slight advantage. The use of fungicides helped to increase the safety of plants in the autumn and winter period. At the increased seeding rate, the highest plant survival was observed when using Rex Duo, while Zenon Aero stood out against the background of the seeding rate. At the same time, there were no significant differences in plant density in spring between the variants of experiments with fungicides.

To assess the mechanisms of fungicides influence on winter hardiness in autumn before going to wintering, the main indicators affecting the winter hardiness of rape were determined (Table 3.12). Spraying winter rape plants with fungicides in most cases led to a decrease in the height of the growth point from the surface. At higher seeding rates, this effect was most intense in the cases of Falcon and Zenon Aero, and at lower seeding rates –

Alto Super and Zenon Aero. In general, the results obtained indicate the pronounced growth-regulating properties of triazole fungicides on winter rape. Data on seed yields (Table 3.12) show that increasing the seeding rate of winter rape from 1 to 1.8 million Germinating seeds per 1 ha leads to a significant decrease in crop yield.

Table 3.11

Values of biometric parameters affecting winter hardiness of winter rape [86]

Variant	Number of leaves, pcs/plant	Root collar diameter, mm	Height of the growth point, mm
Seeding rate 1 million germinating seeds/ha			
Control	8.3	5.30	19.6
Alto super	8.6	5.49	17.5*
Rex S	8.4	5.51	18.3*
Rex Duo	8.5	5.42	18.0*
Zenon Aero	8.9	5.60*	17.7*
Impact	8.3	5.09	18.8
Falcon	8.7	5.50	18.4*
Seeding rate of 1.8 million germinating seeds/ha			
Control	7.6	4.00	18.2
Alto super	8.0	4.00	18.0
Rex S	7.6	4.82*	17.6*
Rex Duo	8.1	4.45*	17.3*
Zenon Aero	8.3	4.00	16.9*
Impact	8.6	6.18*	18.5
Falcon	8.1	4.91*	16.0*

Note: * – not significant before controlling for P = 0.05.

Thus, in the control variant, at a seeding rate of 8 kg/ha, the yield of winter rape decreased by 1.87 t/ha. Treatment with fungicides slightly increased the yield of rape against this background, but in this case it was 1.61–1.82 t/ha less than when sown at a seeding rate of 5 kg/ha.

Among the studied variants of fungicide treatment, the most effective in terms of plant productivity was Zenon Aero against the background of a seeding rate of 5 kg/ha. In this variant, the biological yield for two years reached 4.43 t/ha, and the increase from the treatment was 0.73 t/ha. The return on treatment was slightly lower when Falcon was used (+0.65 t/ha

compared to the control). The positive effect of autumn fungicide treatment of plants is primarily manifested in an increase in the number of pods per plant and the weight of 1000 seeds.

Table 3.12

Biological yield of winter oilseed rape under different fungicide treatments, t/ha [86]

Variant	Year		Average	Growth from fungicide	Deviations in seeding rate
	2007	2008			
Seeding rate 1 million germinating seeds/ha					
Control	3.98	3.41	3.7	–	–
Alto super	4.85	3.68	4.27	0.57	–
Rex S	4.41	3.52	3.97	0.27	–
Rex Duo	4.46	3.84	4.15	0.45	–
Zenon Aero	4.84	4.01	4.43	0.73	–
Impact	4.37	3.59	3.98	0.28	–
Falcon	4.48	4.21	4.35	0.65	–
Seeding rate of 1.8 million germinating seeds/ha					
Control	1.92	1.74	1.83	–	–1.87
Alto super	2.61	2.71	2.66	0.83	–1.61
Rex S	2.45	2.12	2.29	0.46	–1.68
Rex Duo	2.19	2.46	2.33	0.5	–1.82
Zenon Aero	2.44	2.74	2.59	0.76	–1.84
Impact	2.46	2.12	2.29	0.46	–1.69
Falcon	2.8	2.54	2.67	0.84	–1.68
$SSD_{05}A$	0.75	0.65			
$SSD_{05}B$	0.26	0.17			

Fungicides based on aluminium fosetyl (800 g/kg), which are organophosphate compounds, are also used against downy mildew.

Interesting results were obtained in the following studies [86] to study the impact of diseases (downy mildew and phomosis) on the development and productivity of winter rape plants depending on sowing dates, row spacing and density, and mineral fertiliser application. Three sowing dates were studied: early – 7–10.08; optimal – 19–22.08 and late – 28–31.08. The data on the effect of sowing dates on the damage of winter rape of the Xaverivskyi variety and its productivity are presented in Table. The analysis of the table data shows that downy mildew and phomosis affect rape plants

differently depending on the sowing date. The maximum damage by downy mildew was observed at an early sowing date. The disease spread was 65%, and its development was 11.4%. When using the late sowing date, the spread of downy mildew was lower and amounted to 38%, and the development – 8.5%. The phomosis incidence increased from 32% to 41% when switching from early to late sowing, and the disease development increased by 1.3 times. The yield of rapeseed seeds at late sowing dates was 6.2 centner/ha higher than at early sowing dates. The difference in seed yields between early and late sowing dates can be explained by optimal weather conditions in autumn, as well as the influence of diseases, as downy mildew affects young rapeseed plants, and phomosis affects plants of later vegetation.

The data on the impact of seeding rates in the wide-row sowing method on the disease incidence and productivity of winter rape are presented in Tables 9.13–9.14. The analysis of these tables shows that the lowest efficiency was found in the variant with a seeding rate of 2.5 million seeds per 1 ha. The incidence of downy mildew in this variant was 80%, phomosis – 69%, and the development of diseases was 12.1 and 4.7%, respectively. The seed yield of this variant was the lowest – 16.4 centner/ ha. Excellent results were obtained in the variant with the optimal rate of 1.5 million seeds per 1 ha. The disease incidence and development of this variant was within the optimal range compared to other variants. The seed yield was maximum and amounted to 18.4 centner/ha.

Table 3.13

Influence of sowing dates on disease infection of winter rape of Xaverivskyi variety and its productivity (NUBiP agricultural station) [87]

Sowing dates	Downy mildew		Phomosis		Productivity seeds, centners / ha
	affected plants, %	disease progression, %	affected plants, %	disease progression, %	
Early	65	11.4	32	2.6	17.5
Optimal	52	10.0	28	2.5	18.3
Late	38	8.5	41	3.5	23.7
SSD_{05}	1.5	2.2	1.7	0.9	4.5

Similar studies have shown the dependence of spring oilseed rape on the timing of sowing.

Table 3.14

Effect of sowing dates of spring oilseed rape of Vasylkivskyi variety on the severity of downy mildew [87]

Sowing dates	Phase 2–3 leaves		The budding phase	
	affected plants, %	disease progression, %	affected plants, %	disease progression, %
5th April	15.0–30.0	0.5–7.8	30.0–43.5	0.7–10.5
25th April	30.0–43.6	0.6–10.2	44.0–59.2	1.7–15.4

The data in the table shows that the development of downy mildew in spring rape increases at late sowing dates. Thus, at the early sowing date (5 April) compared to the late sowing date (25 April), the number of affected plants was 13.5–15% less in the 2–3 leaf stage and 11.0–15.7% less in the budding stage, respectively, and the development of the disease was 0,1% and 2,4% less in the 2–3 leaf stage and 1,5–4.9% less in the budding stage.

Table 3.15 shows the results of studies of seeding rates of narrow-row sowing method and their influence on disease severity and productivity of winter rape seeds of Xaverivskyi variety. The data in the table indicate that the severity of downy mildew and phomosis differed only slightly compared to the wide-row sowing method. The maximum seed yield was observed in the variant with a seeding rate of 1 million seeds per 1 ha, which is optimal.

Table 3.15

Influence of seeding rates on disease incidence and productivity of winter rape variety Xaverivskyi under wide-row sowing method (NUBiP agricultural station) [87]

Seeding rates (million seeds/ha)	Downy mildew		Phomosis		Seed yield, centners / ha
	affected plants, %	disease progression, %	affected plants, %	disease progression, %	
0,5	33	6.1	44	3.5	16.1
1,0	41	7.0	40	3.4	17.3
1,5	50	7.8	52	3.7	18.4
2,0	72	11.8	68	4.5	18.1
2,5	80	12.1	69	4.7	16.0
SSD_{05}	1.2	2.0	4.5	0.8	3.3

Table 3.17 shows the results of studies of the effect of mineral fertiliser doses on disease incidence in winter rape of the Xaverivskyi variety and its productivity. Analysis of the data shows that the incidence of downy mildew and phomosis increases with an increase in the dose of nitrogen fertiliser. Thus, when applying the optimal rate of mineral fertilisers $N_{60}P_{60}K_{60}$, the damage and development of downy mildew and phomosis was at the level of control (without fertilisers).

Table 3.16

Influence of seeding rates on disease incidence and productivity of winter rape variety Xaverivskyi at narrow-row sowing [87]

Seeding rates (million seeds/ha)	Downy mildew		Phomosis		Seed yield, centners/ha
	affected plants, %	disease progression, %	affected plants, %	disease progression, %	
0,5	50	8.9	53	2.8	18.9
1,0	55	9.5	50	2.8	21.1
1,5	66	10.0	60	3.6	20.1
2,0	70	11.5	66	3.9	19.1
2,5	76	12.6	72	4.1	18.9
HIP_{05}	5.4	1.8	4.3	1.2	1.9

The seed yield in this variant exceeded the control by 1.6 centners /ha. In the variant where the same doses were applied, only nitrogen was applied half under the main cultivation and the other half in the spring, the disease incidence was also at the level of the previous variant. And the seed yield of this variant exceeded the control by 3.9 centners /ha. And in the variant with an increased dose of potash fertiliser $N_{60}P_{60}K_{90}$, the disease incidence, on the contrary, decreased by 18% compared to the control, and phomosis – by 12%. The development of diseases was also lower by 2.3 and 1,7%, respectively. Seed yields exceeded the control by 3.2 centner/ha. Further increase in nitrogen fertiliser doses in the $N_{90}P_{90}K_{90}$ variant showed that the incidence of downy mildew increased by 8% compared to the control, and phomosis by 15%. The development of diseases was respectively 3.8 and 1.8% higher.

Similar studies were conducted on spring rape in relation to downy mildew (Tables 3.17–3.18).

Table 3.17

The role of fertilisation of spring rape of Vasylkivskyi variety on the damage by downy mildew [87]

Fertiliser rates	Phase 2-3 leaves		The budding phase	
	affected plants, %	disease progression, %	affected plants, %	disease progression, %
Control	20.5–46.0	0.7–10.5	35.2–61.0	2.4–18.3
$N_{60}P_{60}K_{90}$	15.4–34.0	0.5–8.2	25.0–50.0	0.9–14.2
$N_{120}P_{120}K_{120}$	12.8–35.0	0.3–7.1	23.3–43.0	0.8–13.5
SSD_{05}	2.2–7.2	0.3–0.5	0.6–4.1	0.4–0.8

The results of the records of plant damage by the pathogen downy mildew indicate that the disease developed less in the experimental variants where fertilisers were applied. It was noted that the highest resistance of rapeseed plants to the disease was in the areas where a double dose of mineral fertilisers was applied. At the same time, the results showed that the use of a double dose of mineral fertilisers has no effect, i.e. the threshold for applying mineral fertilisers $N_{60}P_{60}K_{90}$ in spring rape was found, given the limited spread of downy mildew.

Thus, in order to increase plant disease resistance, the correct use of mineral fertilisers is an integral part of the developed system of disease control measures.

By the author [87] the following generalisations have been made:

1. Disease development in winter rape of the Xaverivsky variety depends on the sowing date. The pathogen of downy mildew developed more intensively at early sowing. The phomosis pathogen, on the contrary, developed more intensively at a later sowing date. This phenomenon can be explained by the biological characteristics of pathogens. For example, downy mildew develops more intensively on young rapeseed plants (budding phase), while phomosis, on the contrary, develops more intensively on rapeseed plants in later stages of development (flowering and podding phase). The advantage of rapeseed yields at late sowing compared to early sowing is explained by the climatic conditions prevailing during the autumn growing season. Plants of early sowing of winter rape are overgrown, poorly adapted to wintering, and are more severely affected by root bacteriosis, which is one of the factors of yield loss.

Table 3.18

Effect of mineral fertiliser doses on disease incidence in winter rape of Xaverivskyi variety and its productivity [87]

Variants with fertilisers	Downy mildew		Phomosis		Seed yield, centners/ha
	affected plants, %	disease progression, %	affected plants, %	disease progression, %	
Control (no fertiliser)	70	11.5	48	3.8	17.5
$N_{60}P_{60}K_{60}$	68	11.0	45	3.5	19.1
$N_{30}P_{60}K_{60}+N_{30}$	72	11.2	43	3.2	21.4
$N_{60}P_{60}K_{90}$	52	9.2	36	2.1	20.7
$N_{90}P_{90}K_{90}$	78	15.3	63	5.6	21.6
SSD_{05}	4.0	1.9	5.1	2.2	2.25

2. In experiments to study the effect of sowing rates in wide-row and narrow-row sowing, it was found that the most intense damage and development of diseases was observed in the variant with a sowing rate of 2.5 million seeds per 1 ha. Excellent results in terms of both disease resistance and seed yield were obtained in the variant with a sowing rate of 1.5 million seeds per 1 ha in a wide-row sowing method with a row spacing of 0.45 m.

The development of pathogens was similar in the narrow-row sowing method. The optimum seeding rate of winter rape was established at 1 million seeds per 1 ha with a row spacing of 0.15 m (narrow-row sowing method), in which the development of diseases was moderate and the seed yield was 21.1 centners /ha.

3. In an experiment to study the effect of mineral fertiliser doses on the development of diseases of winter rape of the Xaverivskyi variety and its productivity, the optimal rate of mineral fertiliser application $N_{30}P_{60}K_{60}+ N_{30}$ in spring was established. At this dose, a moderate development of downy mildew and phomosis pathogens was recorded. The seed yield under this variant was 21.4 centners /ha. In the control variant without fertilisers – 17.5 centners /ha. The dose of mineral fertiliser $N_{60}P_{60}K_{90}$ is also worthy of note. This rate helped to reduce the development of diseases, and the seed yield was 20.7 centners /ha.

The use of the maximum dose of mineral fertiliser $N_{90}P_{90}K_{90}$ was not effective, as it contributed to an increase in the damage to rapeseed plants by pathogens of downy mildew and phomosis.

In Slovakia, Hungary, and the Czech Republic, the biological preparation AZOTER SC® is recommended to reduce the infectious pressure of the sclerotinia pathogen, which, along with nitrogen-fixing and phosphorus-mobilising bacteria, contains the fungus *Coniothyrium minita*ns. The fungus parasitises sclerotia and thus reduces the infection load during the initial infection of rapeseed with ascospores. Regular use of the biological product can significantly reduce the infectious potential in the soil, which leads to a decrease in the degree of damage to the roots and stems of plants. At the same time, the top layer of soil is cleared of sclerotia and root infection is prevented, which is not achieved by applying fungicides. However, in the case of strong infectious pressure of the pathogen, the use of this product is not enough (Table 3.19).

It should not be forgotten that the use of chemical methods of protecting cruciferous plant species from diseases is mostly of preventive value, since the treatment of plants with chemicals is carried out on the assumption that the pathogen will be destroyed before it penetrates the tissue. Therefore, chemicals are used to treat the outer surface of plants, which provides external protection against pathogens.

Table 3.19

Effect of fungicide on sclerotinia infection and yield of winter oilseed rape [28]

Experimental conditions	Degree of damage		Seed yield, centners / ha	
	Control	Application of the fungicide	Control	Application of the fungicide
4 years with low damage	16	3	33.4	36.5
6 years with medium damage	42	11	31.6	36.4
2 years with severe damage	74	20	23.8	30.0

In addition to external protection, the chemical method can be used for plant immunisation, as a result of which plants are able to actively prevent pathogens from entering the body. Chemicals are injected into the interior of plants (or seeds). The treated plants become resistant to parasitic organisms. Chemicals are used to kill pathogens on the surface of plants or seeds, so the chemical method is active, unlike the passive

agronomic method. The chemical method is particularly effective in case of massive disease manifestation, its epiphytosis, when by spraying the affected fields the pathogen is destroyed over large areas and thus the harvest is preserved.

Over the past 40 years, a number of active ingredients have been studied to determine the effectiveness of fungicides for their integrated use. Thus, in 1995–2000, a study was conducted to investigate the effectiveness of their individual formulations in Ukraine. such preparations as sportak 45% c.e., alliette 80% w.p. were studied, and polycarbacin 80% w.p. was used as a control.

The first treatment of winter rape plants was carried out in autumn at the stage of 3–5 leaves. The second one was in spring, before budding. The application was based on the consumption of the working solution – 400 l/ha. Table 3.20 shows the results of treatment of winter rape plants with chemicals to limit the development of downy mildew and phomosis diseases. High effectiveness against downy mildew and phomosis of such fungicides as Aliette 80% w.p. at the rate of 1б5 kg/ha and Sportak 45% w.p. – 1 l/ha was established. The reduction in disease incidence was 1б8 and 2 times compared to the control, respectively.

The data of the yield results obtained in the variants of winter rape treatment with different fungicides are presented. Aliette exceeded the standard by 2б6 centner/ha; Sportak – by 2б7 centner/ha. Thus, the above research data indicate the need to use fungicides against cruciferous diseases as a preventive measure of plant protection.

Depending on the number of apothecia formed and the local and annual weather conditions, fungicides should be applied during flowering. The effectiveness of chemical control of sclerotinia is shown in Table 3.21, which summarises the results of an 11-year trial.

Treatment of Alternaria in rapeseed is based on timely application of fungicides. To do this, use products with active ingredients [85]:

– Tebuconazole. Preparations with this active ingredient from the triazole class protect the crop from Alternaria and Phomosis. In plant cell membranes, tebuconazole inhibits ergosterol biosynthesis of phytopathogens by inhibiting demethylation at the C-14 position. The difference from other triazoles is the effect on metabolism. Growth-regulating effect is an additional effect of the use of drugs with this active ingredient.

– Propiconazole. Propiconazole also acts as an inhibitor of ergosterol biosynthesis in the membranes of phytopathogen cells. After application, the cell walls of pathogens are destroyed, mycelium growth stops, and then it dies. Movement occurs acropetally.

– Azoxystrobin, a fungicide from the strobilurin class, inhibits mitochondrial respiration in pathogen cells. Drugs based on this active ingredient are contact-based and have a therapeutic effect, as well as a partially systemic effect. It will be especially effective in the early stages of infection development – azoxystrobin fights the growth of conidia, the initial growth of fungal mycelium and prevents spore formation.

Table 3.20

Influence of different chemicals on the development of winter rape diseases (Agronomic Research Station NUBiP) [87]

Experimental variants	Disease incidence, %	
	Downy mildew	Phomosis
Control (no treatment)	10.2	6.4
Polycarbacin 80% w/w 2.4 kg/ha	6.0	3.8
Aliette, 80% w.p. 1.5 kg/ha	5.6	3.7
Sportak, 45% c.e. 1 litre/ha	5.1	3.1
SSD_{05}	2.2	1.8

Table 3.21

Effect of different chemicals on the yield of winter oilseed rape seeds (Agronomic Experimental Station of NUBiP) [87]

Experimental variants	Seed yield, centners / ha
Control (no treatment)	20.2
Polycarbacin, 80% w/w, 2.4 kg/ha	22.6
Aliette, 80% w.p., 1.5 kg/ha	22.8
Sportak, 45% c.e., 1 litre/ha	22.9
SSD_{05}	2.7

To limit the development of pathogens of this disease and the spread of Alternaria itself, it is recommended to use the following fungicides:

– Bukat, CS – 0.5 l/ha (tebuconazole) from IFAGRI;

– Veto, CE – 0.5 l/ha (propiconazole) from IFAGRI;
– Azociper Neo, CS – 0.75–1 l/ha (azoxytrobin + ciproconazole);
– Clark, WG – 0.25-0.4 kg/ha (azoxytrobin);
– Confirm, SE – 1–1.4 l/ha (thiophanate-methyl + tebuconazole + cyflufenamide) from Sumi Agro;

To improve the wetting of the working solution and increase its effectiveness, we recommend the following adjuvants/SAS:
– MultiMaster (0.08 – 0.16 l/ha);
– Silixan 106 (0.05 – 0.1 l/ha).

It is also worth noting the experience of Ukrainian producers in protecting spring and winter rape from major diseases.

Thus, it is noted [88-151], that among a number of factors that limit the potential productivity of winter rape varieties and hybrids is a violation of cultivation technology, in particular the crop protection system, which leads to a shortfall of 30–40% of the seed yield. Diseases and pests cause great damage to crops, causing significant losses and reducing product quality. The damage caused by the intensive development of diseases and massive pest infestation is the early and premature death of leaves, buds, and pods, which significantly reduces the quantity and quality of the crop. The introduction of a highly effective system of plant protection against a complex of pests is the most important stage of modern technology for growing winter rape.

It is noted that during 2005–2022 in Ukraine, the most common and harmful diseases of spring and winter rape are snow mould (typhoid), black leg (rhizoctonia), downy mildew (peronosporosis), black spot (alternaria), stem cancer or root neck necrosis (phomosis), white rot or sclerotinia (white stem) grey rot (botrytis), light spot (cylindrosporium), verticillium wilt (verticillium blight), fusarium wilt (fusarium), winter rape root bacteriosis, and spring rape mucilage bacteriosis. Less common are white spotting (ring spotting, or grey stem), powdery mildew, clubroot, common mosaic, wrinkled mosaic, black ring spotting, turnip yellow virus, and greening of flowers.

The shortfall in seed yields due to diseases, depending on the hybrid and its cultivation technology, ranges from 15 to 70% or more, and the sowing and technological qualities of rapeseed are significantly affected. Scientists have found that white rot and phomosis cause the greatest yield losses – 20–60%.

Alternaria and cylindrosporium can cause yield losses of 15-30%, peronosporium – 15–25%, and grey rot – 10–20%.

Diseases also significantly affect the biochemical composition of rapeseed plants and seeds. For example, peronosporosis, Alternaria, Phomosis, and Cylindrosporium significantly reduce the content of vitamin C, protein, fat, sugar, essential amino acids, and oil in rapeseed.

Recent long-term studies have shown that the spread and development of most diseases depends on the weather conditions of the growing season and the technology of growing winter and spring rapeseed. Under conditions of high humidity, heavy dewfall at night and an average daily air temperature of 8...15°C, plants are likely to be affected by downy mildew, and with frequent light rains – by cylindrosporium. High air humidity, frequent rains with wind at air temperatures of 15...24°C during the day and 12...18°C at night contribute to the development of Alternaria and Phomosis. In warm and humid weather (temperature 17...26°C, relative humidity – 80–100%, frequent rains, thickened crops), rapeseed plants are most often affected by white and grey rot, bacteriosis.

For timely detection of rapeseed diseases, it is necessary to systematically monitor crops throughout the growing season. This will facilitate decision-making on the use of fungicides.

It is advisable to carry out preventive chemical measures on winter rape in autumn: in the stages of plant development ES 17 (2nd true leaf) – ES 23 (6th true leaf) against downy mildew with plant damage of more than 5% in conditions of high air humidity (90–100%) and average daily temperature of 8. ...12°C; against Alternaria and Phomosis in warm, long autumn, with air humidity of 80% and above, plant damage intensity of up to 2% and disease spread of more than 10%; against Cylindrosporium – with plant damage of up to 10% in conditions of high humidity, frequent light rains with wind. Chemical protection of winter oilseed rape in spring against diseases is advisable in the plant development stages ES 33 (beginning of budding) – ES 57 (elongation of the pedicel, end of budding): 30 – against downy mildew with plant damage of more than 10% and development above 1%, under conditions of high humidity and average daily air temperature of 8...15°C; – against Alternaria, Phomosis – with plant damage up to 30% and development above 5%, under conditions of high humidity, frequent precipitation and air temperature during the day

15...24°C and at night – 12... 18°C; – against cylindrosporiosis – in case of plant damage of more than 30% and development above 1%, high humidity or prolonged stay of water droplets on plants, frequent rains with wind, heavy dew at night and average daily air temperature of 10...15°C; – against white and grey rot – in years with warm and humid weather (temperature 17...26°C, relative humidity – 80-100%, frequent rains, thickened crops). In order to increase the technical efficiency of fungicides and seed productivity of plants, one of the biostimulants is added to the working suspensions or emulsions: Biotransformer, (300–400 granules/ha); Biosil (Emistim C), v.p., (5–10 ml/ha); Vermistim K, v.p., (5-8 l/ha); Redostim, v.p., (50 ml/ha); Stabilan 750 SL, v.p., (1.5–2.0 l/ha).

An effective measure on winter rape in autumn, in the phase of 4-6 rosette leaves, against root bacteriosis, snow mould, Alternaria, Phoma, Cylindrospora, grey and white rot, against overgrowth of plants before they enter winter, suspension of vegetative mass growth and increase of their winter hardiness is spraying rape with one of the fungicides – inhibitors of rape leaves growth based on active substances: metconazole, 60 g/l (Karamba, in. p.); tebuconazole, 250 g/l (Mystic, c.e.; Orius 250, c.e.; Folicur 250 EW, c.e.; Fortress ES, c.e.; Unique, c.s., Amulet, c.e.; Alpha-Tebuzol, c.e.; Berkut, c.e.; Kolosal, c.e.; Polygard, c.e.; Cerfun, m.v.e.); propiconazole, 250 g/l (Tilt 250 ES, c.e.; Tinazole, c.e.) and a mixture of active ingredients – protioconazole, 80 g/l + tebuconazole, 160 g/l (Tilmor 240 ES, c.e.). It is advisable to combine these treatments with foliar feeding of plants with microelements, especially boron (0.5 kg/ha). The deficiency of this trace element in the soil reduces plant resistance to infectious diseases and low temperatures, intensive leaf and plant growth point death, slows down the development of generative organs, and reduces seed productivity.

An effective measure against mould, white and grey rot is timely harvesting, desiccation of crops, thorough cleaning and drying of seeds, if necessary. To prevent seed spoilage as a result of diseases (mould, blackleg, white and grey rot), the moisture content of commercial seeds is brought to 7–8% before storage, and that of seed seeds to 8–10% and stored at a temperature not exceeding 10...15°C. Ploughing or ploughing up post-harvest crop residues significantly reduces the infection stock in the soil. Timely and high-quality implementation of these measures significantly

limits the spread and development of diseases and minimises the use of chemical protection products on rapeseed.

By spraying spring rape crops with fungicides together with growth stimulants, we reduce pest and disease damage and increase seed yields. With the combined use of the fungicide Ridomil Gold and the growth stimulator Emistim, the damage by Alteriosis is reduced by 6.3%; peronosporosis – by 5,2%; phomosis – by 6.1%, grey rot – by 6.5% [152]. The growth-regulating fungicide Karamba Turbo with a consumption rate of 1.0 l/ha and 1.2 l/ha ensures the absence of diseases on plants throughout the growing season. Rapeseed lateral shoots develop evenly, flowering occurs simultaneously, which leads to uniform pods setting and their filling with seeds [153].

According to Basf research, the use of Pictor fungicide on crops reliably protects the crop from major fungal diseases, promotes uniform pod maturation, and reduces seed losses during the pre-harvest and harvest periods [154].

The ideal time to treat crops with Piktor systemic fungicide at a rate of 0,5 l/ha is the full flowering stage. Due to the innovative active ingredient boscalid (200 g/l) in combination with dimoxystrobin (200 l/ha), this product perfectly controls the spread of Alternaria, Phoma and Sclerotinia. In addition to protecting crops from diseases, this product provides a "physiological effect" that slows down plant aging (less ethylene accumulates), activates photosynthesis, nitrogenase activity (conversion of nitrate nitrogen into protein nitrogen), optimises gas exchange and moisture transfer in plants, and thus prolongs the period of generative development. As a result, plants lay more seeds per pod, increase the weight of 1000 seeds, and accumulate more fatty acids. In his research, V.P. Savenkov found that the use of a mixture of Piktor fungicide and Karamba growth regulator (during the flowering phase) affects plant height and stem diameter, as well as pod preservation. The mixture of products increases the number of lateral branches and the weight of 1000 seeds [155]. Scientists of the breeding and genetics institute [156] confidently state that the combined use of Alterno and Pictor fungicides has proven to have an unsurpassed destructive effect on a wide range of pathogens. Also, these products make it possible to obtain healthy rapeseed plants of ideal shape with a strong structure and no lodging. In their own research, the authors of the monograph [157–158]

It is noted that in order to realise the productivity potential of rapeseed, it is important to form optimal structural organs in disease-free plants as the basis of the photosynthetic biological system. This is achieved through effective chemical protection in compliance with all agronomic practices. Fungicides have a positive effect on limiting the development of winter rape diseases (Table 3.22).

Thus, the use of fungicides after the vegetation recovery allows to increase the yield of winter rape by 4.6–5.6 centner/ha. In this regard, the best results were shown by the use of the fungicide Architect SE, where the yield exceeded the control variant by 5.6 centner/ha (Table 3.23).

Table 3.22

Influence of fungicides on diseases of winter rape plants, % (average for 2018–2020) [160]

Variant	Disease development, %					
	Alternariosis		Pho-mosis	White rot	Grey rot	Cylindro sporiosis
	leaves	pods				
Control (without processing)	24	78	30	12	26	8
Pictor KS, 0,5 l/ha	14	32	18	10	18	3
Architect CE, 2,0 l/ha	8.1	12	8	6	14	2
Alterno KE, 1,0 l/ha	15	36	19	12	20	3

Other preparations had a less significant effect on the above parameters, exceeding the yield of the control variant by 4.6–5.1 centner/ha. The weight of 1000 seeds varied depending on the fungicide used and was the highest when using Architect SE, where it was 5.1 g, and the lowest when using Alterno CE, where it was 4.1 g. Ensuring high economic efficiency of winter rape production can be achieved through the use of aggregate factors, among which the introduction of intensive crop cultivation technologies is important.

Based on the data obtained, it was concluded that to control the spread of diseases in the rapeseed agrophytocenosis, it is advisable to use the preparation Architect SE (pyraclostrobin 100 g/l + calcium prohexadione 25 g/l + mepiquat chloride 150 g/l) at a rate of 2.0 l/ha, which significantly reduced the damage to winter rape by major diseases and had

a therapeutic effect, while ensuring a yield of 25.1 centner/ha. Compliance with technological measures of rape cultivation in combination with the correct application of an integrated system of protection against pests can significantly increase the efficiency of cultivation technology and minimise crop losses.

Table 3.23

Effect of fungicides on seed yield, weight of 1000 seeds and biometric parameters of rapeseed (average for 2018–2020) [160]

Variants	Plant density, pcs/m^2	Plant height, cm	Pods formed per plant, pcs.	Length of pods, mm	Seeds per pod, pcs.	Weight of 1000 seeds, g	Yield, centners/ha
Control (without processing)	43.9	180	95	69	20	2.1	19.5
Pictor KS, 0.5 l/ha	48.0	175	220	91	26	4.5	24.6
Architect CE, 2.0 l/ha	49.2	168	276	106	31	5.1	25.1
Alterno KE, 1.0 l/ha	48.4	170	234	87	25	4.1	24.1
SSD_{05}							1.49

Some variants of these schemes have been actively researched recently. Thus, according to the results of a study by a master's student of Vinnytsia Agrarian University [159] the effectiveness of a certain combination of fungicides on winter rape crops was investigated. According to the scheme of these studies, in autumn, when winter rape plants developed in the phase of 4–6 leaves, they were treated with Folicur 250 EW, EV and 42 Karamba, c. When analysing the development of winter rape plants of the Artus variety in the experimental variants, it was found that the fungicides used in comparison with the control variant inhibited the development of the crop. Thus, the number of leaves before entering the winter increased on average per 1 plant: in the control variant to 10–12 pcs, and in the variants with fungicide treatment – only to 8–9 pcs (Table 3.24). After overwintering, the number of leaves per plant decreased in all experimental variants, which is due to the critical conditions that occurred during overwintering.

The analysis of wintering of winter rape plants showed that the use of fungicides had a positive effect on the preservation of plants during

wintering. Thus, in the variant without fungicides, up to 14.5% of rape plants did not survive the winter, and in the variants with Karamba, v. and Folicur 250 EW, EV about 7%. The explanation for this may be not only the fungicidal effect of the preparation, but also the inhibitory effect of the preparations, thus preventing the rape plants from outgrowing (Table 3.25).

Table 3.24

Development of plants of winter rape variety Artus depending on the use of fungicides, average for 2021–2022 [160]

№	Experimental variant	Number of leaves of winter rape, on average per 1 plant, pcs.			
		before processing	14 days after treatment	before entering winter	after the resumption of vegetation
1	Control (without processing)	4–6	8–9	10–12	8–10
2	Caramba, v., 1.25 g/l	4–6	6–7	8–9	7–8
3	Folicur 250 EW, EW, 1 l/ha	4–6	6–7	8–9	7–8

Table 3.25

Overwintering of winter rape plants of the Artus variety depending on the use of fungicides, average for 2021–2022 [160]

№	Experimental variant	Density of winter rape plants, pcs./m²	
		before entering winter	after the resumption of vegetation
1	Control (without processing)	48	41
2	Caramba, v., 1.25 g/l	48	45
3	Folicur 250 EW, EW, 1 l/ha	48	45

The analysis of the data showed that the disease incidence of winter rape plants before entering the winter in the control was: downy mildew – 11.5% and Alternaria – 16.7% and Fusarium – 8.0%. Spraying of winter wheat crops with Karamba fungicide reduces the development of downy mildew by 10.1%, alternaria by 14.9% and phomosis by 6.8% compared to the control. The use of Folicur 250 EW, EV fungicide reduces the damage to winter rape plants by 10.4%, downy mildew by 15.3% and phomosis

by 7.1% compared to the control. After the resumption of winter rape vegetation in spring, repeated surveys revealed that the number of affected plants slightly increased.

Thus, in the variant without the use of fungicides, the incidence of downy mildew was 15.5%, alternaria – 19.8% and fusarium – 10.1%. Spraying of winter wheat crops with Karamba, v. fungicide reduces the development of downy mildew by 12%, alternaria by 17.1% and phomosis by 7.3% compared to the control. The use of Folikur 250 EW, EV fungicide reduces the damage to winter rape plants by 12.4%, downy mildew by 17.6% and phomosis by 7.1% compared to the control.

Table 3.26

Disease incidence of winter rape plants depending on the use of fungicides in the conditions of the farm "Havest", Chudniv district, Zhytomyr region, average for 2021-2022 [160]

Experimental variant	Disease development, %		
	downy mildew	alternariosis	phomosis
before entering winter			
Control (without processing)	11.5	16.7	8.0
Caramba, v., 1.25 g/l	1.4	1.8	1.2
Folicur 250 EW,EW, 1 l/ha	1.1	1.4	0.9
after the resumption of vegetation			
Control (without processing)	15.5	19.8	10.1
Caramba, v., 1.25 g/l	3.5	2.7	2.8
Folicur 250 EW,EW, 1 l/ha	3.1	2.2	2.5

The technical efficiency of the use of growth-regulating fungicides on winter rape crops is shown in Table 9.26. The highest efficiency before entering the winter – 92% among the studied fungicides was provided by Folicur 250 EW, EV in protection against Alternaria, which is 3% more than Karamba.

After the restoration of winter rape vegetation in spring, it was found that the technical efficiency of Folikur 250 EW, EV against diseases was 75-89%. The technical efficiency of Karamba, v. against downy mildew was 77%, alternaria – 86%, phomosis – 72%.

Figure 3.1 – Growth point height of rapeseed plants treated with Karamba Turbo 1.0 l/ha (right) compared to control (left) [160]

Table 3.27

Technical efficiency of fungicide application in winter rape agrophytocenosis, average for 2021–2022 [160]

Experimental variant	Technical efficiency, %		
	downy mildew	alternariosis	phomosis
before entering winter			
Control (without processing)	–	–	–
Caramba, v., 1.25 g/l	88	89	85
Folicur 250 EW,EW, 1 l/ha	90	92	89
after the resumption of vegetation			
Control (without processing)	–	–	–
Caramba, v., 1.25 g/l	77	86	72
Folicur 250 EW,EW, 1 l/ha	80	89	75

To ensure high and sustainable yields of winter rape seeds, it is necessary to minimise plant stress during critical periods of growth, which will allow to preserve a larger number of pods per plant and, as a result, increase crop productivity. The analysis of the data obtained shows that depending on the spraying of winter rape crops with fungicides, the number of pods per plant varies from 125.5 to 138.3 pcs, the number of seeds per pod from 17.6 to 18.5 pcs, the weight of 1000 seeds from 7.9 to 9.5 g, the weight of seeds per plant from 7.9 to 9.5 g (Tables 3.28–3.29).

The use of Folikur 250 EW, EV fungicide increases the number of pods per plant by 12.8 pcs, the number of seeds per pod by 0.9 g, the weight of 1000 seeds by 0.4 g, and the weight of seeds per plant by 1.6 g.

Reducing the incidence of powdery mildew had a positive effect on improving the yield structure.

The use of fungicide Karamba, v., 1.25 g/l increased the yield of winter rape seeds by 0.46 t/ha or 18.5% compared to the control. The treatment of winter rape crops of the Artus variety with the fungicide Folicur 250 EW, EV provides an increase in seed yield by 0.53 t/ha or 21.4% compared to the control.

Table 3.28

Formation of elements of winter rape yield structure depending on fungicide application in the conditions of the farm 'Havest', Chudnivskyi district, Zhytomyr region, average for 2021–2022 [160]

Experimental variant	Number of pods per plant, pcs.	Number of seeds per pod, pcs.	Weight of 1000 seeds, g	Seed weight per plant, g
Control (without processing)	125.5	17.6	3.5	7.9
Caramba, v., 1.25 g/l	135.8	18.1	3.7	9.2
Folicur 250 EW, EW, 1 l/ha	138.3	18.5	3.9	9.5

Thus, the use of fungicides in autumn, which have a protective and growth-stimulating effect on winter rape plants, allows to effectively protect plants from pathogens of the crop (Alternaria, Phoma, downy mildew) and improve the wintering of the crop. This allows us to increase the productivity of winter rape and solve the issue of providing producers with raw materials for oil production.

Another study conducted in another region of Ukraine also confirms the effectiveness of the above options for using fungicides.

As an example of studying the effectiveness of different variants of fungicide use in protecting cruciferous crops from diseases, we present the results of a study of the effectiveness of fungicides on winter rape in the Ivano-Frankivsk branch of the agricultural company Continental Farmers Group.

Table 3.29

Yield of winter rape depending on the use of fungicides in the conditions of the farm "Havest", Chudniv district, Zhytomyr region, average for 2021–2022 [160]

Experimental variant	Seed yield, t/ha				
	2021	2022	average	± to control	in % to control
Control (without processing)	2.31	2.65	2.48	–	–
Caramba, v., 1.25 g/l	2.78	3.1	2.94	+ 0.46	18.5
Folicur 250 EW,EW, 1 l/ha	2.86	3.16	3.01	+ 0.53	21.4

For this purpose, an experiment with fungicidal preparations belonging to the new generation of drugs was conducted in the field. The first spraying was carried out with fungicides Taler, 25% c.e. – 1.0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha, Architect, 37.5% c.e. – 1.5 l/ha in autumn at the stage of 3–5 true leaves to protect plants from diseases and to prevent overgrowth of plants. The second spraying in the spring at a crop height of 20–25 cm was carried out with Taler, 25% e.e. – 1.0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha, Architect, 37.5% e.e. – 1.0 l/ha. During the flowering period in the experimental variants, the plants were sprayed with Amistar Extra fungicide, 28% c.e. – 1.0 l/ha.

Taler, 25% c.e., which has the active ingredient tebuconazole 250 g/l, is a systemic fungicide from the triazole group, the mechanism of action of which is to block the biosynthesis of ergosterol, which is an important structural component of fungal cell membranes. The product is moderately toxic and belongs to the third hazard class. The maximum number of treatments is two. In Ukraine, it is registered and authorised for use on winter rape at a consumption rate of 1.0 l/ha.

Camzol 6% r.c. contains the active ingredient metconazole 80 g/l, also from the triazole group, and is characterised by a systemic therapeutic effect. The mechanism of action of metconazole is also to block ergosterol biosynthesis. The drug is moderately toxic, hazard class III. It has a systemic therapeutic effect. In Ukraine, it is registered and authorised for use on winter rape at a consumption rate of 1.25 l/ha.

Architect, 37.5% w/w, which contains three active ingredients, namely pyraclostrobin 100 g/l + mepiquat chloride 150 g/l + calcium prohexadione

25 g/l, is a combined fungicide. It has systemic and translaminar action. Pyraclostrobin belongs to the group of strobilurins, the mechanism of action of which is to block the cellular mitochondrial respiration of fungi. It is moderately toxic, belongs to the third hazard class. In Ukraine, it is registered and approved for use on winter rape at a consumption rate of 1.0–1.5 litres/ha.

Amistar Extra, 28% h.p., is also a combined action fungicide, as it contains two active ingredients: ciproconazole 80 g/l from the triazole group and azoxystrobin 200 g/l from the storobilurin group. It is moderately toxic, belongs to hazard class III. The drug is characterised by systemic and translaminar action. In Ukraine, it is registered and approved for use on winter rape at a consumption rate of 1.0 l/ha.

In autumn, winter rape plants showed signs of phomosis and downy mildew, and symptoms of diseases such as powdery mildew, Alternaria and sclerotinia appeared in spring.

In autumn, after the application of Taler, 25% c.e. – 1.0 l/ha, Kamzol, 6% c.e. – 1.25 l/ha and Architect, 37.5% c.e. – 1.5 l/ha, on the experimental variants, a low degree of damage to winter rape plants by phomosis and downy mildew was noted compared to the control. Thus, the development of these diseases in the variants after spraying with the studied fungicides was: phomosis was within 1.0-1.1%, and in the control – 6.7%, peronosporosis – 1.2–1.3%, and in the control – 6.1%. The application of fungicidal preparations with morphoregulatory properties in autumn effectively restrained plant growth: the height of plants on the preparations was 11.5–11.9 cm less than on the control. In addition, the sprayed plants formed a 1.9–2.3 mm thicker root collar in autumn, which contributed to their better wintering. In the spring, during the period of plant vegetation recovery, this difference persisted: the thickness of the root collar in the variants with the preparations was 4.1–3.4 mm thicker (Table 3.30).

The effectiveness of autumn application of fungicidal preparations was: against phomosis was in the range of 83.6-85.1%, against downy mildew – in the range of 78.7¬80.3% (Table 3.31).

Thus, the application of fungicidal preparations Taler, 25% c.e. – 1.0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha and Architect, 37.5% c.e. – 1.5 l/ha in autumn on winter rape prevented plant damage by diseases, as well as contributed to their enhanced root formation and improved wintering.

Table 3.30

Effect of autumn fungicide application on biometric parameters and disease development of winter rape plants [160]

Experimental variant	Product consumption rate, l/ha	Plant height, cm	Root neck thickness, mm		Disease development, %	
			on the 15th day	vege-tation recovery	phomosis	perono-sporosis
Control (spraying with with water)	–	37.8	5.1	11.7	6.7	6.1
Thaler, 25% c.e.	1.0	26.0	7.0	15.1	1.0	1.2
Camisole, 6% p.a.	1.25	25.9	7.4	15.8	1.0	1.2
Architecture, 37.5% c.e.	1.5	26.3	7.2	15.7	1.1	1.3

Table 3.31

Effectiveness of autumn fungicide application against diseases of winter rape [160]

Experimental variant	Product consum-ption rate, l/ha	Efficiency of the drug action, %	
		phomosis	peronosporosis
Control (spraying with with water)	–	–	–
Thaler, 25% c.e.	1.0	85.1	80.3
Camisole, 6% p.a.	1.25	85.1	80.3
Architecture, 37.5% c.e.	1.5	83.6	78.7

In the research [162] also determined the effectiveness of application in spring at a plant height of 20-25 cm of fungicidal preparations Thaler, 25% c.e. – 1.0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha, Architect, 37.5% c.e. – 1.0 l/ha and during flowering of Amistar Extra, 28% c.e.s. – 1.0 l/ha against diseases such as phomosis, peronosporosis, sclerotinia, powdery mildew and alternaria, as the damage to plants by the pathogens of these diseases increased in spring.

After spraying with pesticides, the damage to plants by the main diseases was recorded at the beginning of flowering after the second spraying and during the formation of pods after the third spraying.

The results of the records of phomosis development in the experimental variants are presented in Table 3.32.

Table 3.32

Technical effectiveness of fungicides against phomosis [160]

Experimental variant	Disease progression, %		Effectiveness of the drug, %	
	beginning of flowering	pod formation	beginning of flowering	pod formation
Control (spraying with with water)	15.0	21.6	–	–
Taler, 25% hp – 1,0 l/ha, Taler, 25% hp – 1,0 l/ha, Amistar Extra, 28% hp – 1,0 l/ha	1.7	3.3	88.7	84.7
Camzol, 6% p.c. – 1,25 l/ha,, Camzol, 6% p.c. – 1,25 l/ha, Amistar Extra, 28% h.p. – 1,0 l/ha	1.4	3.1	90.7	85.6
Architect, 37.5% e.m. – 1,5 l/ha, Architect, 37.5% e.m. – 1,0 l/ha, Amistar Extra, 28% hp – 1,0 l/ha	2.1	4.4	86.0	79.6

The development of phomosis in the experimental variants where fungicidal preparations were used at the beginning of flowering was in the range of 1.4–2.1%, in the phase of pod formation – 3.1–4.4%, while in the control there was a significant damage to plants of 15.0% and 21.6%, respectively. The technical efficiency of the preparations at the beginning of flowering was in the range of 86.0–90.7%, during pod formation – 79.6–85.6%.

The results of the records of peronosporosis development on the experimental variants are presented in Table 3.33.

The development of downy mildew in the experimental variants where fungicidal preparations were used at the beginning of flowering was in the range of 1.3–1.6%, in the phase of pod formation – 2.2–3.0%, while in the control there was a significant damage to plants of 11.4% and 17.4%, respectively. The technical efficiency of the preparations at the beginning of flowering was in the range of 86.0–88.6%, during the formation of pods – 82.8–87.4%.

Table 3.33

Technical efficacy of fungicides against downy mildew [160]

Experimental variant	Disease progression, %		Effectiveness of the drug, %	
	beginning of flowering	pod formation	beginning of flowering	pod formation
Control (spraying with with water)	11.4	17.4	–	–
Taler, 25% hp – 1,0 l/ha, Taler, 25% hp – 1,0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	1.6	3.0	86.0	82.8
Camzol, 6% p.c. – 1.25 l/ha, Camzol, 6% p.c. – 1.25 l/ha, Amistar Extra, 28% h.p. – 1.0 l/ha	1.3	2.2	88.6	87.4
Architect, 37.5% e.m. – 1.5 l/ha, Architect, 37.5% e.m. – 1.0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	1.4	2.3	87.7	86.8

The results of the accounting of Alternaria development on the experimental variants are presented in Table 3.34.

The development of Alternaria in the experimental variants where fungicidal preparations were used at the beginning of flowering was in the range of 2.3–3.7%, in the phase of pod formation – 4.5–5.1, while in the control there was a significant damage to plants of 25.9% and 35.5%, respectively. The technical efficiency of the preparations at the beginning of flowering was in the range of 80.3–85.7%, during pod formation – 85.6–87.3%.

The results of powdery mildew development on the experimental variants are presented in Table 3.35.

The development of powdery mildew in the experimental variants where fungicidal preparations were used at the beginning of flowering was in the range of 1.3–2.7%, in the phase of pod formation – 2.5-4.1%, while in the control there was a significant damage to plants of 22.5% and 30.1%, respectively. The technical efficiency of the preparations at the beginning of flowering was in the range of 88.0–94.2%, during pod formation – 86.4–91.7%.

Sclerotinia is the most harmful disease of winter rape plants, as it causes significant losses in seed yield even at a relatively low level of its development. The highest development of sclerotinia was observed at the beginning of pod formation.

Table 3.34

Technical effectiveness of fungicides against Alternaria [160]

Experimental variant	Disease progression, %		Effectiveness of the drug, %	
	beginning of flowering	pod formation	beginning of flowering	pod formation
Control (spraying with water)	25.9	35.5	–	–
Taler, 25% hp – 1,0 l/ha, Taler, 25% hp – 1,0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	3.7	5.1	85.7	85.6
Camzol, 6% p.c. – 1.25 l/ha, Camzol, 6% p.c. – 1.25 l/ha, Amistar Extra, 28% h.p. – 1.0 l/ha	2.3	4.5	91.1	87.3
Architect, 37.5% e.m. – 1.5 l/ha, Architect, 37.5% e.m. – 1.0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	2.7	4.6	80.3	87.0

The results of the records of the development of sclerotinia in the experimental variants are presented in Table 3.36.

The development of sclerotinia in the experimental variants where fungicidal preparations were used at the beginning of flowering was in the range of 1,1–2,1%, in the phase of pod formation – 135–3.2%, while in the control there was a significant damage to plants of 7.8% and 10.0%, respectively.The technical efficiency of the preparations at the beginning of flowering was in the range of 73.1–85.9%, during pod formation – 68.0–85.0%.

A fairly low level of damage compared to the control was also observed in the variant where we applied Architect, 37.5% s.e. in autumn at a rate of 1.5 l/ha, Architect, 37.5% s.e. in spring at a rate of 1.0 l/ha, and Amistar Extra, 28% h.p. – 1.0 l/ha during flowering. In this variant, the development

of phomosis was 4.4%, downy mildew – 2.3%, alternaria – 4.6%, powdery mildew – 2.9%, sclerotinia – 3.2%.

A low level of development of the main diseases on winter rape plants compared to the control was also recorded in the variant where we applied Taler, 25% h.e. – 1.0 l/ha in autumn and spring, and Amistar Extra, 28% h.p. – 1.0 l/ha during flowering. The development of phomosis on this variant was 3.3%, downy mildew – 3.0%, Alternaria – 5.1%, powdery mildew – 4.1%, sclerotinia – 2.1%.

Table 3.35

Technical efficiency of fungicidal preparations against powdery mildew [160]

Experimental variant	Disease progression, %		Effectiveness of the drug, %	
	beginning of flowering	pod formation	beginning of flowering	pod formation
Control (spraying with with water)	22.5	30.1	–	–
Taler, 25% hp – 1,0 l/ha, Taler, 25% hp – 1,0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	2.7	4.1	88.0	86.4
Camzol, 6% p.c. – 1.25 l/ha, , Camzol, 6% p.c. – 1.25 l/ha, Amistar Extra, 28% h.p. – 1.0 l/ha	1.3	2.5	94.2	91.7
Architect, 37.5% e.m. – 1.5 l/ha, Architect, 37.5% e.m. – 1.0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	1.7	2.9	92.4	90.4

As a result of the surveys, we found that the best results in reducing the level of development of the main diseases on winter rape plants were recorded in the experimental variant, where in autumn in the phase of 3–5 true leaves and in spring at a plant height of 20–25 cm we applied the drug Kamzol, 6% p.c. – 1.25 l/ha, and during flowering – Amistar Extra, 28% h.p. – 1.0 l/ha. Thus, in this variant of the experiment, the degree of plant damage was as follows: phomosis – 3.1%, downy mildew – 2.2%, alternaria – 4.5%, powdery mildew – 2.5%, sclerotinia – 1.5%.

The use of the scheme, which provided for the application in autumn in the phase of 3–5 true leaves and in spring at a plant height of 20-25 cm of the fungicide Kamzol, 6% p.c. – 1.25 l/ha and during flowering – Amistar Extra, 28% h.p. – 1.0 l/ha, provided for the highest technical efficiency of the preparations, which exceeded 85%. The effectiveness of this scheme of fungicide application against phomosis was 85.6%, downy mildew – 87,4%, Alternaria – 87.3%, powdery mildew – 91.7%, sclerotinia – 85%.

The scheme of spraying plants, which included the use of Thaler, 25% c.e. – 1.0 l/ha in autumn and spring and Amistar Extra, 28% c.e. – 1.0 l/ha during flowering, provided efficiency against phomosis at the level of 84.7%, peronosporosis – 82.8%, alternaria – 85.6%, powdery mildew – 86.4%, sclerotinia – 79.0%.

Table 3.36

Technical efficacy of fungicides against sclerotinia [160]

Experimental variant	Disease progression, %		Effectiveness of the drug, %	
	beginning of flowering	pod formation	beginning of flowering	pod formation
Control (spraying with with water)	7.8	10.0	–	–
Taler, 25% hp – 1,0 l/ha, Taler, 25% hp – 1,0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	1.5	2.1	80.8	79.0
Camzol, 6% p.c. – 1.25 l/ha, Camzol, 6% p.c. – 1.25 l/ha, Amistar Extra, 28% h.p. – 1.0 l/ha	1.1	1.5	85.9	85.0
Architect, 37.5% e.m. – 1.5 l/ha, Architect, 37.5% e.m. – 1.0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	2.1	3.2	73.1	68.0

The spraying scheme, which included the application of Architect, 37,5% s.e. – 1.5 l/ha in autumn, and Architect, 37.5% s.e. – 1.0 l/ha in spring and Amistar Extra, 28% h.p. during flowering. – 1.0 l/ha also provided a relatively sufficient level of protection: against phomosis –

79.6%, downy mildew – 86.8%, alternaria – 87.0%, powdery mildew – 90.4%, sclerotinia – 68.0%. The obtained research results and their analysis indicate the expediency of introducing into the system of protection of winter rape crops from the main diseases, preparations of systemic protective and therapeutic action Taler, 25% c.e., Kamzol, 6% p.c, Architect, 37.5% c.e. and Amistar Extra, 28% c.e. The first spraying of plants should be carried out in autumn in the phase of 3-5 true leaves with fungicides Taler, 25% c.e. – 1.0 l/ha, or Kamzol, 6% p.c. k. – 1.25 l/ha, or Architect, 37.5% s.e. – 1.5 l/ha, not only to protect plants from diseases such as phomosis and downy mildew, but also to prevent their overgrowth. The second spraying against further development of phomosis, downy mildew, as well as against diseases such as powdery mildew, Alternaria and sclerotinia should be carried out in spring at a crop height of 20–25 cm also with Taler, 25% e.p. – 1.0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha, Architect, 37.5% e.p. – 1.0 l/ha. During the flowering period, plants should be sprayed with Amistar Extra fungicide, 28% h.p. – 1.0 l/ha, mainly against Alternaria and Sclerotinia.

According to the scheme of the experiment, the first spraying of plants was carried out in autumn in the phase of 3-5 true leaves with fungicides Taler, 25% c.e. – 1,0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha, Architect, 37.5% c.e. – 1.5 l/ha. The second spraying was also carried out with Taler, 25% c.e. – 1,0 l/ha, Kamzol, 6% p.c. – 1.25 l/ha, Architect, 37.5% c.e. – 1.0 l/ha in spring at a crop height of 20–25 cm. And during the flowering period, the plants were sprayed with Amistar Extra fungicide, 28% c.p. – 1.0 l/ha.

As a result of the studies, it was found that the yield of the Athora hybrid in 2021 was higher than in 2020. The yield of winter rape seeds in variants with fungicide plant protection systems was significantly higher than in the control. The application of Taler, 25% c.e., Kamzol, 6% p.c., Architect, 37.5% c.e. in the phase of 3–5 true leaves and at a plant height of 20–25 cm and Amistar Extra, 28% c.e. in the flowering phase had a positive effect on plant productivity. The yield of the control without fungicides was significantly lower and amounted to only 27.6 centner/ha.

The economic efficiency of the studied systems of protection of winter rape against diseases is presented in Table 3.37.

Table 3.37

Economic efficiency of different fungicide application schemes on winter oilseed rape, hybrid Athora [160]

Experimental variant	Weight of 1000 seeds, g	Yield, centner/ha			± to control
		2020	2021	cep.	centner/ha
Control (spraying with with water)	3.7	24.9	30.2	27.6	–
Taler, 25% hp – 1,0 l/ha, Taler, 25% hp – 1,0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	4.5	36.5	38.3	37.4	9.8
Camzol, 6% p.c. – 1.25 l/ha, Camzol, 6% p.c. – 1.25 l/ha, Amistar Extra, 28% h.p. – 1.0 l/ha	4.7	39.4	40.1	39.8	12.2
Architect, 37.5% e.m. – 1.5 l/ha, Architect, 37.5% e.m. – 1.0 l/ha, Amistar Extra, 28% hp – 1.0 l/ha	4.6	37.8	39.8	38.9	11.3
SSD_{05}	0.31	1.8	2.8	2.8	

The highest yield of the hybrid Athora in the amount of 39.8 centner/ha was obtained in the experimental variant, where in autumn and spring we applied Kamzol, 6% p.c. – 1.25 l/ha, and in flowering Amistar Extra, 28% p.c. – 1.0 l/ha, which was 12.2 centner/ha higher than in the control.

On the variant of the experiment, which was applied in autumn and spring Thaler, 25% hp – 1.0 l/ha and during flowering Amistar Extra, 28% hp – 1.0 l/ha, the yield was slightly lower and amounted to 37.4 centner/ha, which was 11.3 centner/ha higher than in the control.

On the variant of the experiment, where in autumn the Architect, 37.5% e.s. was applied at a rate of 1.5 l/ha, and in spring the Architect, 37.5% e.s. at a rate of 1.0 l/ha, the yield was also high compared to the control, but lower compared to the other two variants and amounted to 37.4 centner/ha, which was 9.8 centner/ha higher than the control.

The increase in the yield of winter rape hybrid Athora with the use of fungicides in the system of plant protection against diseases provided better indicators of 1000 seeds weight compared to the control. The weight of 1000 seeds in the variants with fungicidal preparations was 1.0–0.8 g higher than in the control.

Between the variants of the experiment with fungicides, the actual difference in yield and weight of 1000 seeds did not go beyond the smallest significant difference, that is, it was not reliable and was within the error.

Thus, the results of the presented studies indicate that the use of plant protection systems for winter rape against diseases, which include the application of Taler, 25% c.e., Kamzol, 6% p.c., Architect, 37.5% c.e. and in the flowering phase – Amistar Extra, 28% c.e. – 1.0 l/ha in autumn and spring, allows to reliably preserve the seed yield. The best results in terms of the impact of fungicide application on winter rape were provided by the experimental variant: Kamzol, 6% p.c. – 1.25 l/ha in autumn in the phase of 3–5 true leaves + Kamzol, 6% p.c. – 1.25 l/ha in spring at a plant height of 20–25 cm + Amistar Extra, 28% h.p. – 1.0 l/ha during flowering.

In general, for the control of major diseases in cruciferous crops agrocenoses, different variants of disinfectants and fungicides can be used in accordance with the recommended list of those approved for use in Ukraine (Figure 3.2).

It is worth noting the specifics of the oil radish disease protection system. The first element of the disease protection system is the use of resistant varieties and the cultivation of healthy seed material. The second point is to observe the correct crop rotation with a return to the previous place no earlier than three to four years later and spatial isolation between cruciferous crops (at least 1 km). This is especially important against Fusarium wilt and phomosis. After stubble harvesting, the fields are peeled with disc harrows to a depth of 6–8 cm in a unit with harrows, and ten to twelve days later they are cultivated using the technology recommended for each zone. Another important element is the use of treated seeds. This prevents the development of many diseases of seedlings and seedlings. The optimal timing and seeding rates are also of phytopathological importance. In addition, rolling the field before and immediately after sowing with heavy rollers reduces the development of root diseases. Adherence to the optimal seeding rate and sowing technology (row, wide-row) reduces losses from phomosis, Alternaria, white and grey rot, and white spot, which are typical for thickened crops. When seedlings appear, shallow loosening of row spacings in wide-row crops or harrowing across rows in continuous crops is recommended to limit the development of blackleg and phomosis, as well as to control weeds.

Name of active substance (dosage form)	Norms consumption rates l.kg/ha,	What diseases are treated against	Method, processing time, limitations	Duration of the last treatment (days) and maximum number of treatments (times)
Duration of the last treatment (days) and maximum number of treatments (times)	0,75-1,0	Alternaria, phomosis, downy mildew, white and grey rot	Spraying during the growing season	30(2)
Becocil, 500 g/kg (w/w)	0,5-0,6	Powdery mildew, phomosis	Spraying during the growing season	20(2)
Dimoxystrobin, 200 g/l + Boscalid 200 g/l (h.p.)	OS	Alternaria, phomosis, sclerotinia	Spraying during the growing season	30(1)
Diphenoconol, 2S0, g/l + paclobutrazol, 125 g/l (q.s.)	0,3-0,5	Alternaria, downy mildew, phomosis	Spraying during the growing season. Inhibition of growth of the suckers, increased resistance to extreme weather conditions, simultaneous flowering	50(1-2)
Carbendazim, 500 g/l {hp)	0,6	Alternaria, phomosis	Spraying during the growing season	(2)
Metelaxle – M,40 g/kg mancoceb, 640 g/kg (&g.)	2¿	Alternaria, peronosporium	Spraying during the growing season	30(3)
Munkotseb, 800 g/kg (w/w)	23-3,0	Alternaria	Spraying during the growing season	30(2)
Metcocazole, 60 g/l (b.p.)	0,75-1,25	Alternaria, phomosis, white rot	Spraying during the growing season, as well as in the phase of 4-6 leaves of the crop to prevent overgrowth and improve wintering	55(2)
Picoxistrobin, 200 g/l ciproconazole, 80 g/l (c.s.)	0,5-1,0	Alternaria, phomosis, downy mildew, cylindrosporium, white and grey rot	Spraying during the growing season	-(2)
Propiconazole, 250 g/l (c.e.)	0,5	Inhibition of plant growth, increased resistance to extreme weather conditions	Spraying in the phase of 4-5 litres/stock	30(2)
Propiconazole, 300 g/l + tebuconazole 200 g/l (m.e.)	0,4-0,6	Alternatively, phomosis, powdery mildew, sclerotinia	Spraying during the growing season	50(2)

Figure 3.2 – List of fungicides recommended in Ukraine for the control of cruciferous crops [161–164]

On the 12–15th day after germination, it is important to treat the crops with one of the recommended fungicides against downy mildew and phomosis. The second treatment (preferably with preparations based on a different active ingredient) is carried out on the crops during the budding period to obtain full-fledged healthy seeds. It reduces the development of Alternaria, white spot, grey and white rot. Whenever possible, both sprays are combined with insecticides, taking into account the timing of the likely occurrence of diseases and the forecast of pest populations. Crops intended for growing green mass are not treated a second time.

Leaf desiccation is also important, as it not only accelerates seed ripening but also reduces the degree of infection with pathogens such as Alternaria, Phoma and, especially, white and grey rot. This measure is carried out 7 to 10 days before harvesting with one of the recommended products. Another point is the short harvesting time for oil radish (reducing losses from Alternaria, phomosis, white and grey rot). Crops are mowed when the seeds are ripe, and the swaths are threshed at a moisture content of no more than 12%. For direct combining, the moisture content limit is up to 15%.

The last step is to care for the seeds after threshing, as they have high moisture content and can become covered with mould, which in turn will lead to a loss of germination and a decrease in the quality of oil and meal. To prevent this, the seeds are dried immediately after harvesting in a layer no thicker than 1 cm with frequent stirring. It is recommended to dry the seeds to a moisture content of no more than 7–8%. During drying, it is important to adjust the temperature of the heat carrier correctly. It should be 35°C if the seed moisture content is 35–40%, and 40°C if the moisture content is 25%. The system of measures to protect rapeseed from pests and diseases is presented in Table 3.38–3.39.

The recommendations of C. Hablak [165] on the model example of winter rape. The following are the recommendations of these studies in the author's version. The choice of fungicide is based on information about the sources of primary and secondary infection, the time of infection and the rate of infection growth. When justifying the choice of fungicide, the species composition of pathogens should be carefully analysed and the choice should be made on the product that suppresses the pathogen that causes the greatest losses and yield.

Table 3.38

System of measures to protect rapeseed from pests and diseases [165]

Terms of carrying out, phase of develop-ment	Pests, diseases, Economic threshold of harm-fulness	Activities	Preparation, norm of vitrates, l, kg/ha, kg, l/t
1	2	3	4
Annually	Different pathogens	Organisational, economic and agrotechnical measures	Growing disease-resistant varieties and hybrids of rapeseed; saturation of crop rotation with beetroot and cabbage crops no more than 25%, growing rapeseed after these and other crops in 4-5 years, the best predecessors are annual and perennial legumes, cereal grains, clean and busy fallow, distance from last year's cabbage fields 1 km, preparing the field for sowing using a soil cultivation system typical for the area, applying fertilisers and herbicides. Control of the phytosanitary condition of the crops
July (winter (winter rape). January-February (spring rape)	Diseases (mould, black foot, phomosis, alternaria, bacteriosis, downy mildew, rot)	Mordanting cleaned and calibrated conditioned seeds, use of regulators growth	InSet, VG, 2.5-3.5 l/t; Kaiser, TN, 4 l/t; Comanche WG, VG, 5 kg/t; Contador Maxi, TN, 3-6 l/t; Cruiser 350 FS, TN, 4 l/t; Cruiser 600 FS, TN, 2 l/t; Cruiser OSR 322 FS, TN, 15 l/t; Lumiposa, TN, 17 l/t; Lord, VG, 2. 5-3.5 kg/t; Meeder Pro, TN, 3 /t; Modesto Plus 510 FS, TN, 16.7 l/t; Nuprid 600, TN, 3-6 l/t; Sidoprid 600, TN, 4 l/t; Tabu, KS, 6-8 l/t; Masterpiece, KS, 4 l/t; Acrobat, ZP, 2 kg/t; Vaxa, CS, 2-3 kg/t; Vispar, CS, 2-3 kg/t; TMTD, CS, 3 l/t; Fire, TN, 2.5-3 kg/t
The end of August and early September. Seedlings winter rape	Black leg	Loosening row spacing, harrowing	–

(End of Table 3.38)

1	2	3	4
4-6 leaves of the culture	Alternaria, cylindros-poriosis, phomosis, white spotting, sclerotinia	Spraying with with fungicides upon presence of infection and for restraining leaf growth preventing overgrowth of plants, increasing resistance to extreme weather conditions and improving overwintering	Alterno, KE, 0.5-1 l/ha; Aperol, KE, 05-1 l/ha; Berkut, KE, 1 l/ha; Ekhnaton, KE, 1 l/ha; Ikarus 250, EW, 1 l/ha; Karamba, KE, 0.75-1.25 l/ha; Lekar BT, KS, 0.5-1 l/ha; Ludik 250, EW, 1 l/ha; Orbit, EW, 1 l/ha; Pegasus, EF, 0.5-0.75 l/ha; Polygard, EF, 0.5-0.75 l/ha; Retardin EW, EF, 0-0.75 l/ha; Setar 375, SO, CS, 0.3-0.5 l/ha; Tebukur 250, EF, 0.75-1 l/ha; Tebufor, EF, 1 l/ha; 1 l/ha; Tilmor 240 ES, EF, 0.75-0.9 l/ha; Tilt 250 ES, CE, 0.5 l/ha, Furil, KS, 1 l/ha; Fortress Total ES, KE, 1 l/ha; etc.
September-October 2-4 leaves – rosette formation of winter rape	Downy mildew, Alternaria, phomosis, cylindros-porium, white spot, etc. etc.	Treatment with fungicides (in case of signs of disease and favourable weather conditions for their development)	Acanto plus 28, CS, 0.5-1 l/ha; Aliette 80 WP, WP, 1.2-1.8 kg/ha; Amistar Extra 280 SC, CS, 0.75-1 l/ha; Alterno, CE, 0.5-1 l/ha; Evito T, CS, 0.5-1 l/ha; Impact T, CS, 1 l/ha; Kolosal, CE, 0.75-1 l/ha; Kustodia, CS, 1-1.2 l/ha; Pictor, CS, 0.5 l/ha; Propuls 250 SE, SE, 0.8-0.9 l/ha; Retardin EW, EF, 0.5-0.75 kg/ha; Simetra 325 SC, CS, 0.5-1 l/ha; Starpro, CS, 0.45-0.6 l/ha; Suprem, EF, 1-1.5 l/ha; Title Duo, KKR, 0.25-0.3 l/ha; Universal, WP, 0.25-0.35 kg/ha; Faraday, VG, 0.4-0.5 kg/ha; Fital, RK, 2-3 l/ha; Fast and Furious, CS, 0.6 l/ha; Fungicur, VG, 0.25-0.5 kg/ha; Hilton, CS, 0.6 l/ha; Healer, WP, 1.8-2.5 kg/ha; Yutaka, SE, 1.0-1.4 l/ha, etc. Use of growth regulators during the growing season
n the spring, winter crops resume vegetation and spring rape sprouts appear. Seedlings – 2-4 leaves of spring rape	Blackleg, bacteriosis, snow mould mould. Cruciferous fleas, 3-5 specimens per square metre	Loosening of the of row spacing. Harrowing, fertilising with nitrogen fertilisers (winter). Spraying with with insecticides	Alfagard 100, CE, 0.15 l/ha; Atrix, CE, 0.1-0.15 l/ha; Bestseller Turbo 200, KC, 0.05-0.08 l/ha; Biskaia 240 OD, MD, 0.3-0.4 l/ha; Break, ME, 0.05-0.07 l/ha; Versar, KE, 0.6 l/ha; Destroy, KC, 0.1 l/ha; KAIZO, VG, 0.15-0.2 kg/ha; Karate Zeon 050 CS, SC, 0.15 l/ha; Corsair, VG, 0.05-0.07 kg/ha; Lamdex, SC, 0.15 l/ha; Lord, VG, 0.05-0.07 kg/ha; Mavrik, EV, 0.2-0.3/ha; Mospilan, VP, 0.1-0.12 kg/ha; Sirocco, KE, 0.7-1.2 l/ha; Tom, KE, 0.1-0.15 l/ha; Fisheka, TB, 2 tab. /ha; Fury, BE, 0.1 l/ha; Caesar, CE, 0.125-0.15 l/ha; Shaman, CE, 0.6 l/ha or others.

(End of Table 3.38)

1	2	3	4
Seedlings – rosette of spring rape; stalking – budding of winter rape	Phomosis, downy mildew, cylindros-porium, white spot, alternaria, etc.	Fungicide treatment (in case of disease manifestation and favourable weather conditions for their development)	Acanto plus 28, CS, 0.5-1.0 l/ha; Aliette 80* WP, WP, 1.2-1.8 kg/ha; Amistar Extra 280 SC, CS, 0.75-1 l/ha; Alterno, CE, 0.5-1 l/ha; Evito T, CS, 0.5-1 l/ha; Impact T, CS, 1 l/ha; Kolosal, CE, 0.75-1 l/ha; Kustodia, CS, 1-1.2 l/ha; Pictor, CS, 0.5 l/ha; Propuls 250 SE, CE, 0.8–0.9 l/ha; Retardin, VG, 0.4-0.5 kg/ha; Simetra 325 SC, CS, 0.5-1 l/ha; Starpro, CS, 0.3-0.6 l/ha; Suprem, EV, 1-1.5 l/ha; Tebaz Pro, CS, 0.5-1 l/ha; Title Duo, LF, 0.25-0.3 l/ha; Topazio, LF, 3-4 kg/ha; Universal, LF, 0.25-0.35 kg/ha; Faraday, LF, 0.4-0.5 kg/ha; Fitial, RK, 2.0-3.0 l/ha; Fast. KC, 0.6 l/ha; Fungicur, VG, 0.25-0.5 kg/ha; Hilton, KC, 0.6 l/ha; Healer, WP, 1.8-2.5 kg/ha; Yutaka, SE, 1-1.4 l/ha, etc.
Stemming phase – budding of plants (at a height of 10-15 cm) of spring rape	Alternaria, phomosis, etc. diseases	Spraying with fungicides with retardant properties, which promotes branching of lateral shoots, simultaneous of flowering, formation	Karamba, CE, 0.75-1.25 l/ha; Setar 375 SC, CS, 0.3-0.5 l/ha; Tebufor, CE, 0.5-1; Triafer T 300, CS, 0.6-1.0 l/ha; Tilmore 240 ES, CE, 0.75-0.9 l/ha; Fital, RK, 2.0-3.0 l/ha and analogues
Before harvesting	Alternaria, phomosis, grey rot	Desiccation for 70% browning of pods and wet weather	6-7 days before harvesting harvest – Diquat, RK, 1.5-3 l/ha; Zhar BT, RK, 2-3 l/ha; Reglon Super 150 SL, RK, 2-3 l/ha; Retro 150 SL, RK, 2-3 l/ha; Squar, RK, 2-3 l/ha;; Ra, PK, 2-3 l/ha; Desikash, PK, 3 l/ha; Reglon Air 200 SL, PK, 1-2 l/ha; Reglon Forte 200 SL, PK, 1.5-2.25 l/ha; Sukhoviy Next, PK, 1.3-2.0 l/ha; 10 days before harvesting harvest – Basta 150 SL, RK, 2-2.5 l/ha; 14 days before harvesting Glyphogan, RK, 3 l/ha; Volcano Plus, RK, 3 l/ha; Extraclin 607, RK, 2.4 l/ha; Clinic, RK, 3 l/ha; Clinic Extreme, RK, 2-3 l/ha; Richard, RK, 3 l/ha; Roundup Extra, RK, 2.6 l/ha; Roundup Max, RK, 2.4 l/ha; Tornado 500, RK, 2 l/ha; Roundup Power, RG, 1,5 kg/ha.

*It is forbidden to use straw for animal feed and oil for food purposes.

The diseases of rapeseed are ranked in the following order by their damage potential:

– Alternaria;
– phomosis;
– cylindrosporium;
– root bacteriosis;
– snow mould;
– downy mildew;
– black leg;
– white rot;
– grey rot;
– white spotting;
– Fusarium wilt;
– Verticillium wilt.

Table 3.39

System of protection of classical winter rape against weeds, diseases and pests for the Forest-Steppe, Polissya with a yield of 4–5 t/ha [161–165]

Phase	Product	Active ingredient	Rate, l (kg)/ha	Analogue products	Range of action
1	2	3	4	5	6
After sowing	Butisan Star	metazachlor 333 g/l, quinmerac 83 g/l	2	Tranche Super	
Autumn protection	Kropex	clomazone 480 g/l	0,2	Kalif	
2-4 leaves / BBCH 12-14 to 8 leaves / BBCH 18 (either in autumn or spring)	Galley Super	clopyralid 267 g/l, picloram 80 g/l, aminopyralid 17 g/l	0,3	Trier	Annual dicotyledons and perennials, including root and sprouting weeds
2-4 leaves / BBCH 12-14 to 6 leaves / BBCH 16. Appearance of carrion (2 leaves in cereals)	Fusilade Forte	Fluazifop-p-butyl, 150 g/l	1,5	Miura, Gramidin, Agil	Perennial, annual cereal weeds

(End of Table 3.39)

1	2	3	4	5	6
(either in autumn or spring)	Caramba Turbo	methconazole 30 g/l, mepiquat chloride 210 g/l	0,7–1,4	Folikur	Rastregulation
4-6 leaves / BBCH 14-16 T_o	Acro's opercular	lambda-cyhalothrin 300 g/l imidacloprid iodine g/l	0,25	Contador Duo	Cruciferous flea beetle, rapeseed sawfly
	Boric acid		1,0		Boron-containing fertiliser
6-8 leaves / BBCH 16-18, T_1	Folikur	tebuconazole, 250 g/l	1,0		Rastregulation
	Boric acid		1,0		Boron-containing fertiliser
Spring protection	Dr Krop	carbendazim, 500 g/l	1,0	Derosal	Alternaria, septoria, phomosis Rapeseed flower beetle, cruciferous fleas
Restoration of vegetation / BBCH 20-29 – BBCH 30-39, T_3	Fastak	Alpha-cypermethrin, 100 g/litre	0,15	Karatezone	
	Boric acid		1,0		Boron fertiliser
Restoration of vegetation (either in autumn or spring) / BBCH 20–29	Galley Super	clopyralid 267 g/l, picloram 80 g/l, aminopyralid 17 g/l	0,3	Trier	Annual dicotyledons and perennials, including root and sprouting weeds
Restoration of vegetation (either in autumn or spring) BBCH 20-29	Fusilade Forte	fluazifop-p-butyl, 150 g/l	1,5	Flora	Perennial, annual cereal weeds
	Folikur	tebuconazole, 250 g/l	1,0		Resistance to lodging and better formation of side shoots
	Magne-sium sulphate		0,003		Fertiliser

(End of Table 3.39)

1	2	3	4	5	6
Stemming – green bud / BBCH 40-49 – BBCH 50-59, T_4	Razit	imidacloprid, 140 g/l + acetamiprid, ibo g/l + alpha-cypermethrin, 100 g/l	0,1		Insects, mites and soil pests
	Bortrak			Humi-friend (0.5 l/ha)	Boron fertiliser
	Humifield BP18		0,4	Ligno-gumat BM (0.3 l/ha), Ukrainian humates (0.2 l/ha)	Microfertiliser
	Alterno	methconazole, 80 g/l, pyraclos-trobin, 130 g/l			Grey rot, phomosis, sclerotinia, cylindrical sporulation
Beginning and end of flowering BBCH 60-69, T_5	Biscay	thiacloprid, 240 g/l	0,4		Seed beetle, rapeseed gall midge, aphids, rapeseed borer, fleas
Green pod (in the presence of pests) / BBCH 70-79	Acro opercular Urea	lambda-cyhalothrin, 300 g/l, imidacloprid, 100 g/l	0,1 0,02	Contador Duo	Aphids, cereal flies Fertiliser
Desiccation / BBCH 85-87,70% of browned pods (seed moisture content not more than 25-30%)	Reglon Super	diquat, 150 g/l	2,5	Diquat, Reglon Spectrum	Desiccant

In recent years, crop rotation disturbances have contributed to the spread of grey and white rot, Fusarium and Verticillium wilt, snow mould, blackleg, clubroot, viral and mycoplasma diseases.

The disease control system may include fungicide treatments during the growing season and seed treatment with seed dressing during the following phases [165]:

T_{00} – pre-sowing seed treatment;

T_0 – the first treatment with a fungicide-retardant (4–6 leaves (development of leaf rosette) / BBCH 14–16);

T_1 – second treatment with a fungicide-retardant (6–8 leaves (BBCH 16–18);

T_2 – the third treatment with a fungicide-retardant (8–10 leaves / BBCH 18–20);

T_3 – the first fungicide treatment (development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39);

T_4 – the second fungicide treatment (growth in length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59);

T_5 – the third fungicide treatment (beginning to end of flowering / BBCH 60–69).

The second treatment with T_4 fungicide, which is carried out in the phase 40–49 to 50–59, and the third spraying with T5 in the period 60–69, which reduces pod damage and increases oil content by 1.3–3.4 times, play an important role.

The first treatment with T_3 fungicide in the period 20–29 to 30–39 is recommended in case of rainy summers and a high infection load with diseases that damage young plants, or in the absence of high-clearance sprayers, as well as with no-till and strip-till technologies.

It is important to note that crops should be treated against phomosis, downy mildew, Alternaria, and cylindrosporium in T_0 – the first treatment with a retardant fungicide (4–6 leaves (development of a leaf rosette) / BBCH 14–16) and T_3 – the first treatment with a fungicide (development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39).

Schemes for protecting winter rape from downy mildew [165]:

It would like to note that triazoles with retardant effect do not protect against secondary (local) leaf damage by downy mildew. Instead, fungicides with the active ingredients dimethomorph, metalaxyl, cymoxanil, aluminium fosetyl, azoxystrobin, picoxystrobin, dimoxystrobin, and

propamocarb hydrochloride provide preventive protection. These are the following drugs: azoxystrobin, 250 g/l (Taser, 0,5–1 l/ha), dimethomorph, 180 g/l + cymoxanil, 125 g/l (Fregat 0.6–1.0 l/ha), carbendazim, 200 g/l + metalaxyl, 100 g/l (Metacarb 1–1.2 l/ha), metalaxyl, 80 g/kg + mancoceb, 640 g/kg (Healer 2.5 kg/ha), picoxystrobin, 200 g/kg + ciproconazole, 80 g/kg (Acanto Plus 0.5–1 l/ha). Only aluminium fosetyl, 800 g/kg (Aliette 1.2–1.8 kg/ha) can move basipetally from the shoot to the root system, where the primary infection with the peronospora pathogen occurs through root hairs.

Primary infection of winter rape with downy mildew occurs latently in the soil through root hairs of the root system. Then the pathogen freely penetrates the roots, stems, leaves, spreads in the intercellular space, and out through the stomatal openings on the underside of the leaves, sporulation (zoosporangia with zoospores), which we see as a light coating. Such diseased plants cannot be treated and will not produce a crop. From plants affected by primary infection, the infection spreads by rain, wind, insects and water over long distances (up to 500 m), causing secondary (local) leaf damage at very high humidity, penetrating healthy plants through leaf stomata.

The main protection against seed and soil infection of downy mildew is provided by effective treatments made of active ingredients or their combinations (metalaxyl-m, fluopicolide, fluoxastrobin, thiram): fluopicolide, 120 g/l + fluoxastrobin, 90 g/l + clothianidin, 300 g/l (Modesto Plus 8 l/t), metalaxyl-m, 350 g/l (Metalax 2 l/t), metalaxyl-m, 116 g/l + thiabendazole, 20 g/l + thiram, 400 g/l (Faer 2.5 l/1t).

The next protection against downy mildew is to protect crops with fungicides against secondary infection from the 4–6 leaf stage.

Treatment of winter rape crops against phomosis, grey rot, powdery mildew should be carried out in T_4 – the second fungicide treatment (growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59). Against grey rot, powdery mildew, sclerotinia (white rot), Alternaria, cylindrosporium, the treatment should be carried out in T_5 – the third fungicide treatment (beginning to end of flowering / BBCH 60–69). Moreover, against sclerotinia, fungicides can be applied at the beginning of flowering of the main tassel, and against Alternaria, it can be carried out at a later date – at the end of flowering, when the tops of the inflorescences are ripe.

Depending on the fungicide disease control programme, the following fungicide application schemes are possible for winter oilseed rape [165]:

– 1-time application (variant A) – growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59 (T_4);

– 1-time application (variant B) – beginning to end of flowering / BBCH 60–69 (T_5);

– 1-time application (variant B) – development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 (T_3);

– 2-fold (variant A) – development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 (T_3) + growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59 (T_4);

– 2-fold (variant B) – development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 (T_3) + beginning-end of flowering / BBCH 60–69 (T_5);

– 2-fold (variant B) – growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59 (T_4) + beginning-end of flowering / BBCH 60–69 (T_5);

– 3 times – development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 (T_3) + growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59 (T_4) + beginning-end of flowering / BBCH 60–69 (T_5).

Types of active ingredients of fungicides by the nature of their action [165]:

According to the nature of their action (not to be confused with the mechanism of action and mobility in the plant), fungicides are divided into: preventive action, also known as "protective action", curative, eradicating and immunising. All contact fungicides with protective action (mancoceb, copper hydroxide, thiram) and fungicides with low systemicity (translaminar or local-systemic) from the group of strobilurins, benzamidazoles (benomyl), dicarboximides (iprodione), phenylpyrroles (fludioxonil) are used prophylactically in the initial stages of the disease (spore germination on the leaf), the beginning of penetration into the leaf (germ tube elongation, apsorium formation).

Curative (curative, therapeutic) systemic fungicides (xylem-mobile and phloem-mobile) act on the pathogen from inside the plant, from the moment

of penetration. The greatest effectiveness is approximately until the middle of the latent (hidden) period of disease development and germination, when no visible signs have yet appeared in the leaf. These include triazoles, imidazoles, phenylamines (mefenoxam), some strobilurins (azoxystrobin, fluaxostrobin), etc. The activity of triazoles against diseases decreases in descending order: rust – septoria – powdery mildew. Imidazoles: Septoria – Fusarium. Morpholins: powdery mildew – rust.

The most effective powdery mildew products are fungicides from the morpholin group (spiroxamine, fenpropidin, fenpropimorph). A distinctive feature of morpholines is their high volatility (vapour pressure at 20 ºC), and in spiroxamine it is 500 times higher than in the most volatile strobilurin. The biology of powdery mildew development is such that the mycelium is located on the leaf surface, not inside, and to effectively combat this surface pathogen, either contact fungicides or systemic fungicides with high volatility are used. This is the so-called "vapour phase" effect, when the active ingredient of the fungicide is active not only at the point of direct application, but also beyond it. Picoxystrobin and trifloxystrobin also have vapour phase activity, but it is much less.

Eradicating fungicides (antisporulants) inhibit the formation of spores. They include strobilurins and some contact fungicides.

Immunising fungicides activate defence mechanisms in the plant itself, also known as elicitors. They include some contact fungicides (copper-based), phosphonic acid fungicides (aluminium fosetyl).

Many combined fungicides mostly combine active ingredients with preventive and curative effects with different mechanisms of action on the pathogen: strobilurins with triazoles, carboxamides with triazoles, triazoles with benzimidazoles. This allows us to expand the spectrum of fungicide activity and gives us more flexibility in the timing of treatment.

Features of application [165]:

Often, questions arise about the strategy of using two-component products from different classes with preventive and curative properties or one-component fungicides with preventive (carboxamides, strobilurins) or curative action (triazoles). A fungicide with a broad spectrum and long-lasting protective effect (strobilurins + triazoles, carbendazim + triazoles) is preferable for treatment during the period of growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59 (T_4), as such a fungicide

will smooth out the aftereffects of errors in the selection and application of the first fungicide in the spring during the development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 (T_3), and will give time to analyse the phytosanitary situation.

Strobilurins and carboxamides are usually used prophylactically in T_3 or T_4 against foliar diseases. Triazoles are used in T_4 or T_5, usually curatively when the EMP of foliar diseases is reached. In the absence of disease, triazoles are usually not effective.

Strobilurins are used prophylactically, they prevent germination of pathogen spores, but do not cure when the fungus has already penetrated. Triazoles, on the contrary, treat, but do not affect spore germination. Strobilurins can work prophylactically for up to 6 weeks, while triazoles are much less effective (2–3 weeks). At the same time, the use of one-component strobilurins or two-component fungicides with protective and curative effects (strobilurins + triazoles, carbendazim + triazoles) on winter rape in T_4 is the second fungicide treatment (growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59), T_5 – the third fungicide treatment (beginning to end of flowering / BBCH 60–69) often at high temperatures lead to the closure of leaf stomata by the contact components of the preparation and disruption of their transpiration, wilting of leaves.

Temperature minimums at which fungicides can be used [165]:

– 5 °C – morpholines (fenpropidin, fenpropimorph); dithiocarbamates (mancoceb); imidazoles (prochloraz); quinazolines (proquinazid);

– 10 °C – strobilurins (generic azoxystrobin, picoxystrobin, etc.);

– 10–12 °C – triazoles (propiconazole, tebuconazole, ciproconazole, protioconazole, metconazole, etc.).

The indicated temperatures are the limit within which they are effective. Ideally, they should be applied at 18–20 °C in cloudy weather without rain.

Triazoles are more soluble in water, so they have a higher systemicity than strobilurins and morpholins. Strobilurins have a higher lipophilicity, which means they provide better protection at the point of fungal penetration into the plant. Morpholins are more volatile, which means that protection is provided not only at the point where the fungicide has been applied, but also around it, which is important for controlling surface pathogens.

There are also questions about the effectiveness of combining triazoles with strobilurins in two-component formulations, as well as triazoles with carboxamides with reduced doses of active ingredients compared to single-component triazoles, strobilurins, carboxamides in full doses. For example, a single-component fungicide with a higher dosage of Azoxin 0.6–0.8 l/ha (azoxystrobin, 250 g/l) is more effective compared to a multi-component fungicide with lower doses of active ingredients Kapital 1–1.2 l/ha (azoxystrobin 150 g/l + ciproconazole, 60 g/l + epoxiconazole, 50 g/l). When used prophylactically in T_3, T_4 in the absence of disease, triazoles in two-component formulations will be useless, as triazoles are used in the presence of disease. Only the second component of the product (strobilurins or carboxamides) will act prophylactically, and it will be in a reduced dosage compared to a one-component fungicide. It is believed that one-component fungicides are more effective because they contain higher doses of active ingredients than half the doses of active ingredients in two-component products.

In addition, we should not forget about the resistance of the disease to the fungicide. Disease resistance to the active ingredient, and then to all active ingredients of this chemical class through one site of action in the cell, occurs most rapidly when two-component fungicides from different classes are used at lower half doses compared to a single-component product with a full dose of the active ingredient. For example, if a disease has developed resistance to azoxystrobin from the strobilurin class, then it will also develop resistance to other members of the strobilurin class (dimoxystrobin, picoxystrobin, etc.). At the same time, fungal organisms also adapt very quickly to single-site, single-component drugs. As a result, resistant forms of diseases to pure strobilurin fungicides have emerged. After that, strobilurins were used only in combination with other chemical classes, but at half the rates to save money. In my opinion, two-component fungicides from different classes with full rates, as in one-component fungicides, are not profitable from a cost perspective.

It is advisable to purchase fungicides in advance for the new season for combined active ingredients (strobilurins with triazoles, carboxamides with triazole), which can be used universally for pre-infection and post-infection treatment. Usually, purchasing triazoles in advance to save money and for preventive use is not an effective measure.

Wet weather during the ripening period requires at least two applications of the fungicide on winter rape. In dry weather, one treatment may be sufficient. Thus, in the regions of Ukraine that are characterised by 400 millimetres of precipitation or more per year, it is better to apply the fungicide twice: T_3 – the first fungicide treatment (development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30-39), T_4 – the second fungicide treatment (growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59).

For winter rape in the western region of Ukraine, 2–3 fungicide treatments during the growing season are the norm, although 3 treatments are more common: T_3 – the first fungicide treatment (development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30-39), T_4 – the second fungicide treatment (growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59), T_5 – the third fungicide treatment (beginning-end of flowering / BBCH 60–69).

In the east and south of Ukraine, one application may be sufficient in the phase of lateral shoot development (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 or during the period of growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59.

In the south of Ukraine, only one fungicide treatment is usually applied to winter rape grown on bogar. However, if there is frequent precipitation during the growing season, the number of treatments may be increased to two.

Fungal infections in oilseed rape and fungicides against them [165]:

Some pathogens enter the plant directly through the epidermis. These are, for example, the causative agents of downy mildew – fungi from the marsupial class. Once on the plant, the spores of these fungi germinate and drill through the cuticle with their seedlings, penetrate the tissue, providing nutrition and staying on the affected surface. This fungus develops on the surface of plants (exoparasite). In most cases, the infection, once in the plant, develops inside it, either in the intercellular spaces or in the cell (endoparasite). Typical endoparasites are the causative agents of cabbage clubroot, potato cancer and fungi that cause downy mildew. The development of parasites inside the plant makes it difficult to destroy them, so the protective measures used are more often aimed at preventing infection of plants than at destroying pathogens that have already penetrated.

All fungicides are divided into two groups according to their selectivity: fungicides effective against downy mildew fungi (Oomycetes) and fungicides effective against true powdery mildew fungi (Ascomycetes, Basidiomycetes, Deuteromycetes).

The following fungicides are used against downy mildew (peronospora) in winter rape: Azoxin 0.6–0.8 l/ha (azoxystrobin. 250 g/l); Capital 1–1.2 l/ha (azoxystrobin. 150 g/l + ciproconazole. 60 g/l + epoxiconazole. 50 g/l); Simetra 0.5–1 l/ha (azoxystrobin. 200 g/l + isopyrazam. 125 g/l); Arbalet 0.6–1 l/ha (azoxystrobin. 200 g/l + flutriafol. 120 g/l); Frigate 0.6–1.2 l/ha (dimethomorph. 180 g/l + cymoxanil. 125 g/l); Healer 1.8–2.5 kg/ha (metalaxyl. 80 g/kg + mancoceb. 640 g/kg); Acanto Plus 0.5–1 litres/ha (picoxystrobin. 200 g/l + ciproconazole. 80 g/l); Custodia 1–1.2 litres/ha (tebuconazole. 200 g/l + azoxystrobin. 120 g/l); Bolivar Forte 0.5–1 l/ha (tebuconazole. 240 g/l + cresoxim-methyl. 125 g/l); Aliette 1.2–1.8 kg/ha (aluminium fosetyl. 800 g/kg); Amistar Extra. 0.75–1 l/ha (azoxystrobin. 200 g/l + ciproconazole. 80 g/l).

The following fungicides are used against true powdery mildew fungi (Ascomycetes, Basidiomycetes, Deuteromycetes) in winter rape: Azoxin 0.6–0.8 l/ha; Capital 1–1.2 l/ha; Simetra 0.5–1 l/ha; Arbalet 0.6–1 l/ha; Spirit 0.5–0.7 l/ha (epoxiconazole. 160 g/l + azoxystrobin. 240 g/l); Forsazh 0.5 l/ha (carbendazim. 500 g/l); Kamzol 1–1.5 l/ha (metconazole. 60 g/l); Acanto Plus 0.5–1 l/ha; Pictor 0.5 l/ha (boscalid. 200 g/l + dimoxystrobin. 200 g/l); Tinazol. 0.5 l/ha (propiconazole. 250 g/l); Tilmore 0.9–1 l/ha (protioconazole. 80 g/l + tebuconazole. 160 g/l); Thaler 0.5–1 l/ha (tebuconazole. 250 g/l); Suprem 1–1.5 l/ha (tebuconazole. 133 g/l + prochlorazole. 267 g/l); Kiper 0.8–1 l/ha (tebuconazole. 162.5 g/l + thiabendazole. 250 g/l); Custodia 1–1.2 l/ha; Bolivar Forte 0.5–1 l/ha; Acadia 0.8–1 l/ha (tebuconazole. 200 g/l + azoxystrobin. 120 g/l + biological complex Acts 350); Yutaka 1–1.4 l/ha (thiophanate-methyl. 350 g/l + tebuconazole. 100 g/l + cyflufenamide. 6.3 g/l); Bayzafon 0.5–1 kg/ha (triadimefon. 250 g/kg); Alterno 0.5–1 l/ha (pyraclostrobin. 130 g/l + metconazole. 80 g/l); Propulse 0.8–0.9 l/ha (fluopyram. 125 g/l + protioconazole. 125 g/l); FlutriVit 0.5 l/ha (flutriafol. 250 g/l); Impact T 0.6–1 l/ha (flutriafol. 117.5 g/l + carbendazim. 250 g/l); Phoenix Duo 0.5–0.6 l/ha (flutriafol. 187 g/l + thiophanate-methyl. 310 g/l); Amistar Extra. 0.75–1 l/ha.

Table 3.40

Classification of fungicides used in oilseed rape by chemical composition and mechanism of action on the pathogen [165]

Class	Active ingredient	By method of penetration	Mechanism of action on the pathogen
Benzimidazoles	Benomyl	Systemic	Group B (FRAC) – inhibitors of cell division
	Carbendazim	Systemic	
	Thiabendazole	Systemic	
Thiophanates of urea phenyl	Thiourea methyl	Systemic	Group B (FRAC) – inhibitors of cell division
Dithiocarbamates	Maikotseb	Contact	Group M (FRAC) – contact fungicides with multi-site action
	Azoxystrobin	Systemic	
	Dimoxystrobin	Systemic	
Strobilurins	Cresoxim-methyl	Systemic	Група С (FRAC) – inhibitors клітинного дихання
	Picoxystrobin	Systemic	
	Pyraclostrobin	Contact	
Imidazoles	Prochloraz	Systemic	Group G (FRAC) – inhibitors of sterol synthesis in the membrane
Pyrazole carboxamides	Isopyrazam	Systemic	Group C (FRAC) – inhibitors of cellular respiration
Pyridine carboxamides	Boscalid	Systemic	Group C (FRAC) – inhibitors of cellular respiration
Pyridine-ethyl benzamides	Fluopyram	Systemic	Group C (FRAC) – inhibitors of cellular respiration
	Diphenoconazole	Systemic	
	Epoxiconazole	Systemic	
	Metconazole	Systemic	
	Protocoiazole	Systemic	
Triazoles	Propiconazole	Systemic	Group G (FRAC) – inhibitors of sterol synthesis in the membrane
	Tebuconazole	Systemic	
	‘Griadimephon	Systemic	
	Ciproconazole	Systemic	
	Flutriafol	Systemic	
Phenylamines (acylalanines)	Metalaxyl-m	Systemic	Group G (FRAC) – inhibitors of sterol synthesis in the membrane
Phenylacetamides	Diglufenamide	Systemic	Inhibition of apresorium formation, spore formation, mycelium development and growth of fungal colonies
Ethyl phosphonates	Aluminium phosphate	Systemic	Group U (FRAC) – fungicides of unknown mode of action

There are practically no fungicides that can control downy mildew (peronosporosis), sclerotinia (white rot) and grey rot at a high level.

During the development of lateral shoots (renewal of vegetation in spring) – growth in the length of the main shoot / BBCH 20–29 – BBCH 30–39 (T_3) on winter rape, it is recommended to apply one-component preventive preparations or two-component contact-systemic fungicides: Azoxin 0.6–0.8 l/ha; Kapital 1–1.2 l/ha; Simetra 0.5–1 l/ha; Arbalet 0.6–1 l/ha; Fregat 0.6–1.2 l/ha; Spirit 0.5–0.7 l/ha; Healer 1.8–2.5 kg/ha; Acanto Plus 0.5–1 l/ha; Custodia 1–1.2 l/ha; Bolivar Forte 0.5–1 l/ha; Aliette 1.2–1.8 kg/ha; Amistar Extra. 0.75–1 l/ha; Lametil 0.5–0.6 l/ha; Fast and Furious 0.5 l/ha; Thaler 0.5–1 l/ha.

In the stage of growth in the length of lateral shoots – budding / BBCH 40–49 – BBCH 50–59 (T_4), it is proposed to spray plants with two-component contact-systemic preparations or systemic fungicides: Capital 1–1.2 l/ha; Simetra 0.5-1 l/ha; Crossbow 0.6–1 l/ha; Spirit 0.5–0.7 l/ha; ealer 1.8–2.5 kg/ha; Acanto Plus 0.5–1 l/ha; Kustodia 1–1.2 l/ha; Bolivar Forte 0.5–1 l/ha; Amistar Extra. 0.75–1 l/ha; Kamzol 1–1.5 l/ha; Thaler 0.5–1 l/ha; Flutivit. 0.5 l/ha; Bayzafon 0.5–1 kg/ha.

In the period from the beginning to the end of flowering / BBCH 60–69 (T_5), it is recommended to apply systemic fungicides or contact-systemic preparations: Capital 1–1.2 l/ha; Arbalet 0.6–1 l/ha; Spirit 0.5–0.7 l/ha; Acanto Plus 0.5–1 l/ha; Custodia 1–1.2 l/ha; Bolivar Forte 0.5–1 l/ha; Amistar Extra. 0.75–1 l/ha; Kamzol 1–1.5 l/ha; Bayzafon 0.5–1 kg/ha.

The world experience of controlling some diseases in cruciferous crops is also valuable (Table 3.42). For example, against white rust, the results showed that all preparations significantly outperformed the untreated control in reducing the intensity of the disease. The treatment, which included foliar spraying with mancozeb 75% WP 0.2% followed by metallaxyl 8% + mancozeb 64% WP 0.2%, was the most effective among all treatments in controlling the disease, where the lowest disease intensity (1.40%) and the highest disease reduction (90.43%) were recorded compared to the control.

The treatment, which included foliar application of mancozeb 75% WP 0.2% followed by hexaconazole 5% EC 0.05% and foliar application of mancozeb 75% WP 0.2% followed by propiconazole 25% EC 0.05%, which were statistically not inferior to each other in terms of disease control, showed a decrease in disease intensity by 2.77 and 3.23 percentage

points of disease intensity and 81.07 and 77,92% compared to the control, respectively. The other foliar treatments showed low to moderate disease control efficacy, while spraying with mancozeb 75% WP alone was the least effective.

These results are in line with previous studies that found the effectiveness of metalaxyl 8% + mancozeb 64% WP (Ridomil MZ) in controlling the intensity of white rust development on mustard leaves. Similar to these results, it was also reported on the effectiveness of hexaconazole and propiconazole in the fight against white rust of mustard.

The data presented in Table 3.41 showed that spraying different fungicides separately or each fungicide in sequence with mancozeb 75% WP (0,2%) significantly reduced the incidence of Alternaria compared to the control, but the level of effectiveness varied depending on the treatment, In general, combinations of two fungicide sprays, i,e, mancozeb 75% WP at 45 days after emergence followed by four other fungicide sprays at 45 days after emergence until 60-65 days after emergence, reduced the degree of Alternaria damage compared to all treatments with a single spray,

The treatment, which included foliar spraying with mancozeb 75% WP 0.2% followed by spraying with hexaconazole 5% EC 0.05%, was the best among all treatments in the fight against the disease, where the lowest disease intensity (2.07%) and the maximum disease reduction (75.44%) were recorded compared to the control, The variant containing foliar application of mancozeb 75% WP 0.2% followed by propiconazole 25% EC 0.05% differed slightly from the control, with a disease intensity of 2.10% and protection against the disease of 75.09% compared to the control.

Foliar application of mancozeb 75% WP 0,2% followed by difenconazole 25% EC 0,05%, which is the next most effective treatment against the disease, showed 2.33 per cent disease development and 72.36 per cent reduction in disease intensity compared to the control.

Other products showed low or moderate efficacy against the disease, allowing to achieve from 2.33 to 4.63 per cent of disease development. Among the single sprays, hexaconazole 5% EC 0.05% was the best in reducing disease severity (67.14%) compared to the control. The obtained results coincide with the data of previous researchers, who claimed that spraying with mancozeb followed by spraying with hexaconazole reduced the degree of mustard damage by Alternaria.

Table 3.41

Combination of active ingredients of fungicides used in oilseed rape [165–172]

Active substance (single use)	In combination with other research	In combination with two doctoral degrees
Benomyl	–	–
Carbendazim	Flutriafol	–
Thiabendazole	Tebuconazole	–
Thiophanate-methyl	Flutriafol	Tebuconazole + digitalis
Mankotseb	Metalaxyl-m	–
Azoxystrobin	Isopyrazam, Flutriafol	Ciproconazole + epoxiconazole
	Epoxiconazole Tebuconazole Ciproconazole	–
Dimoxystrobin	Boscalid	–
Cresoxim-methyl	Tebuconazole	–
Picoxystrobin	Ciproconazole	–
Pyraclostrobin	Metconazole	Calcium prohexadione + mepiquat chloride
Prochloraz	Tebuconazole	–
Isopyrazam	Azoxystrobin	–
Boscalid	Dimoxystrobin	–
Fluopyram	Protoconazole	–
Diphenoconazole	Paclobutrazole	–
Epoxiconazole	Azoxystrobin Mepiquat chloride	Azoxystrobin + ciproconazole
Metconazole	Tebuconazole Pyraclostrobin	–
Protoconazole	Tebuconazole Fluopyram	–
Propiconazole	Tebuconazole	–
Tebuconazole	Propiconazole	–
Triadimephon	–	–
Ciproconazole	Picoxistrobin Azoxystrobin Azoxystrobin	Azoxystrobin + epoxiconazole
Flutriafol	Carbendazim Thiophanate-methyl	–
Metalaxyl-m	Mankotseb	–
Diglufenamide	–	Thiophanag-methyl + tebuconazole
Aluminium phosphate	–	–

Similar to our results, they reported, that propiconazole is an effective fungicide in the control of Alternaria lesions of mustard.

The treatment, which included foliar spraying with mancozeb 75% WP 0.2% followed by metallaxyl 8% + mancozeb 64% WP 0.2%, provided a maximum average yield of 13.48 centner/ha, which is 59.15% higher than the control, slightly inferior to the treatment, which included foliar spraying with mancozeb 75% WP 0.2% followed by hexaconazole 5% c.e. e. 0.05%, where the yield was 12.94 centner/ha. The foliar application of mancozeb 75% WP 0.2% followed by propiconazole 25% EC 0.05% was the next most potentially effective in providing a yield of 11.90 centner/ha (Table 3.42). The highest incremental cost-benefit ratio of 9.57 was achieved with a foliar spray of hexaconazole 5% EC 0.05%, followed by a treatment that included a spray of mancozeb 75% w/w 0.2% followed by hexaconazole 5% c.e. 0.05% and foliar application of mancozeb 75% c.e. 0.2% followed by propiconazole 25% c.e. 0.05%, which provided a cost-benefit ratio of 5.42 and 3.21, respectively.

These results are supported by several previous studies that reported higher mustard yields when foliar sprayed with mancozeb 75% w.c., hexaconazole 5% w.c. and mancozeb 75% w.c. at 0,2% w.c., propiconazole 25% w.c. and metalaxyl 8% + mancozeb 64% w.c. [172]. In general, the active ingredients of fungicides and biological control agents for cruciferous diseases that were studied during 1965–2022 are presented in Tables 3.43 and 3.44.

It should also be noted [173], that an informal top list of fungicides for the protection of cruciferous crops has been compiled based on the results of long-term evaluations and trials. This top list includes the following fungicides in Ukraine:

Amistar Extra fungicide by Syngenta. Active ingredients: ciproconazole, 80 g/l, azoxystrobin, 200 g/l. The product guarantees high profits and yields by preventively acting on most pathogens (grey and white rot, phomosis). It provides vegetation extension and high photostability. It is applied two times during the growing season. Most effective in the early stages of diseases. Compatible with most pesticides.

Fungicide *Acanto Plus* by Corteva Agriscience. A product from the chemical group of strobilurins + triazoles (picoxystrobin, 200 g/l, ciproconazole, 80 g/l) that will protect the potential yield. It provides a pronounced physiological effect in intensive crop cultivation technologies.

Reduces its sensitivity to stress factors and pests. Guarantees healthy growth and normal development. Overcomes Alternaria and Cylindrosporium. It is necessary to spray the field with seedlings twice.

Table 3.42

Effectiveness of different fungicides against common diseases of mustard oilseed rape in the field [165–172]

Variant number	Variants of fungicide application	White rust		Alternariosis		Harvest centner/ hectare	Severity higher than control (%)	Yield to control ratio
		Percentage of disease intensity	Decrease to control (%)	Percentage of disease intensity	Decrease to control (%)			
T 1	One-time spraying of mancoceb 5% WP 0,2%	10.70 (19.08)	26.86	5.40 (13.41)	35.94	9.51	12.28	1: 1.35
T 2	Single spraying of metalaxyl 8% + mancozeb 64% WP 0,2%	4.17 (11.72)	71.50	4.63 (12.40)	45.08	10.87	28.34	1: 1.16
T 3	Single spray hexaconazole 5% EC 0,05%	5.80 (13.87)	60.36	2.77 (9.54)	67.14	11.17	31.88	1: 9.57
T 4	Single spraying of difenconazole 25% EC 0.05%	7.87 (16.32)	46.21	4.57 (12.44)	45.79	9.79	15.58	1: 0.64
T 5	Single spray propiconazole 25% EC 0.05%	6.47 (14.71)	55.78	3.60 (10.86)	57.30	10.18	20.19	1: 3.21
T 6	T–1 + T–2	1.40 (6.16)	90.43	2.40 (8.87)	71.53	13.48	59.15	1: 2.22
T 7	T–1 +T–3	2.77 (9.55)	81.07	2.07 (8.26)	75.44	12.94	52.77	1: 5.42
T 8	T–1 + T–4	4.57 (12.29)	68.76	2.33 (8.72)	72.36	10.45	23.38	1: 0.59
T 9	T–1 + T–5	3.23 (10.33)	77.92	2.10 (8.33)	75.09	11.90	40.50	1: 3.03
T 10	Control (water spraying)	14.63 (22.49)	–	8.43 (16.87)	–	8.47	–	1: 1.35
	SSD ($P = 0.05$)	2.10		1.76		2.46		
	CV (%)	8.97		9.33		13.20		

Table 3.43

Screening of active ingredients of fungicides used and studied in the world practice against the main diseases of cruciferous crops (for the period 1965–2022) [174]

Active ingredient of the fungicide	Phomosis	Sclerotoniosis	Sclerotoniosis	Alternariosis	Clubroot	Grey rot	TuYV virus	Vericillium wilt	Peronosporosis
Tebuconazole	+	+	+	+					
Boscalide	+	+	+	+		+		+	
Prochloraz	+	+	+	+		+			+
Azoxystrobin	+	+	+	+		+		+	
Metconazole	+	+	+	+					
Proticonazole	+	+	+						
Dimoxistrobin	+	+		+		+		+	
Flutriafol	+								
Kiproconazole	+	+	+						
Difenoconazole	+	+	+						
Fluazinam		+			+				
Cazofamide					+				
Fluquinconazole	+								
Imazalil	+		+						
Lambda-cyhalothrin							+		
Metalaxyl	+		+						
Thiabendazole	+		+						
Trifloxystrobin		+	+						
Beta-ciflutrin	+								
Carbetamide			+						
Cantranilipron							+		
Fludioxonil		+							
Fluxapiroxad	+								
Imidacloprid	+								
Mepiquat	+								
Propizamide			+						
Pyraclostrobin	+								
Teflutriene							+		
Thiophanatemethyl		+							

Camzol Defenda fungicide. Moderately hazardous agent of the third class (chemical group of triazoles, active ingredient methconazole, 60 g/l) of toxicity, produced in the form of a soluble concentrate. It has a number of advantages:

– forms a branched and strong root system;

– Does not lose its properties under adverse weather conditions;

– eliminates variegation during the growing season and increases the chances of a high-quality harvest;

– increases the seed ripening cycle.

It is able to destroy the cell membranes of pathogens, distributing in the plant acropetally. Prevents the formation of mycelium and has a therapeutic effect. Stops yellowing of crops It is not recommended to mix with preparations that form a strongly alkaline environment. Before complex use, conduct a compatibility test.

BASF fungicide Pictor. The active ingredients are boscalid and dimoxystrobin. It promotes successful crop cultivation and stable yields, actively destroys pathogens of major diseases. It is characterised by high biological efficacy and long-term preventive effect. It is safe for bees. One field treatment is enough. It is used most often after the flower petals fall off.

Bayer's Propulse fungicide. A two-component product that is used during the flowering period and contains the latest active ingredients fluopyram and protioconazole. Provides a high weight of 1000 seeds of the crop. Blocks mitochondrial respiration of pathogen cells, blocks ergosterol. If necessary, combine with liquid fertilisers, insecticides, growth regulators.

Thaler Defenda fungicide. A preparation (active ingredient tebuconazole, 250 g/l) with a pronounced stop effect, which has a preventive effect of growth inhibitors. Active against a wide range of pathogens, not phytotoxic.

Quickly stops the growth of mycelium, penetrating into plants in 1–2 hours. It is resistant to rainfall washout. It is able to stop the growth of winter mass and improve winter hardiness characteristics, ensure high-quality formation of lateral shoots. The last treatment before harvesting should be carried out no later than 30 days before harvest.

Agronomists recommend using flutriafol and oritebuconazole-based protectants on rapeseed crops. These active ingredients penetrate the leaf surface and additionally protect other parts of the plant. Systemic fungicides even protect young shoots that appear after treatment.

Spraying winter rape in autumn prolongs plant photosynthesis and stops the growth of ground mass. Plastic substances accumulate in the root collar of the crop, and branched roots accelerate their growth.

The use of combined preparations allows sowing rapeseed in the early stages and increasing the crop's winter hardiness. Single-component fungicides do not have this effect.

The fungicidal effect of strobilurins (azoxystrobin) is due to their ability to inhibit mitochondrial respiration of pathogen cells. Strobilurins are most effective when used in the early stages of infection, as they inhibit conidial germination, initial mycelial growth and prevent spore formation [175–176].

Table 3.44

Microorganisms and counter-pathogens used in the world practice against major diseases of cruciferous plants (for the period 1965–2022) [175–179]

Biological control agent	Sclerotoniosis	Phomosis	Vericillium wilt	Alternaria	Clubroot	Peronosporosis	White spotting
Bacillus subtilis	+	+		+	+	+	+
Azotobacter	+	+		+		+	
Coniothyrium minitans	+	+					
Trichoderma asperellum	+	+		+		+	
Paecilomyces lilacinus	+	+					
Pseudomonas fluorescens	+	+	+				
Serratia plymuthica	+	+	+				
Trichoderma harzianum	+	+					
Trichoderma sp.	+	+					
Bacillus cereus	+	+					
Bacillus megaterium	+	+					
Gliocladium catenulatum					+		
Leptosphaeria biglobosa	+	+					
Paenibacillus polymyxa			+				
Stenotrophomas maltophilia			+				
Talaromyces falvus	+	+					
Trichoderma viride	+	+					

Compounds from the triazole class (tebuconazole), penetrating into the fungal cell, inhibit the synthesis of ergosterol, a compound necessary for the fungus to exist [177–178]. Ergosterol, the main sterol of many fungi, is essential for the formation and functioning of biomembranes, cell division, growth and reproduction [179].

Attention should also be paid to preventive measures for disease control in cruciferous crops. Preventive measures to protect spring and winter cruciferous crops from diseases include, first of all, compliance with scientifically sound crop rotation with return to the previous place of cultivation not earlier than in 3–4 years. In particular, it is noted that the main cause of plant diseases is improper crop rotation. For example, it is better to sow rape after legumes, early potatoes, and annual grasses. Undesirable predecessors are radish, mustard, and cabbage.

Notes [180], that all sown areas in Ukraine cover 32 million hectares. Scientifically based crop rotations suggest that 10% of the area, or 3 million hectares, should be allocated to rapeseed. Together, sunflower and rapeseed account for a fifth of the sown area. That is, almost twice as much land is planted to these "heavy" industrial crops as is allowed by crop rotation standards. The author of the study also notes that there is a negative aspect to growing the crop: the likelihood of competition between bioenergy crops, including rapeseed, and consumer plants. After all, growing rapeseed for many years in one place (without change) leads to a violation of biological balance and soil degradation. The lack of appropriate cultivation technologies for this crop provokes the undesirable consequences.

Cruciferous crops are of great agrotechnological and agrobiological importance in crop rotation. For example, winter rape is able to penetrate deeply (more than 2 m) into the lower soil layers with its root system, ensuring the supply of autumn and winter moisture, its retention and improving soil aeration. Rapeseed has a highly developed taproot, which reaches a diameter of 1–3 cm in the upper part, but is very sensitive to soil compaction in the tilth and subsoil layers. Strong lateral roots extend from the central taproot. The development of fine roots and root hairs is weak, which explains the slow absorption of nutrients and their significant use, with the exception of phosphorus. Provided that the crops are well cared for, it cleans the field of weeds, improves the agrophysical properties of the soil, and releases the field early. Ploughing green mass has a positive

effect on the content of organic matter, nitrogen, phosphorus, potassium, and trace elements in the soil, and prevents the development of root rot, which causes great damage to grain crops, especially wheat. Rapeseed is a good precursor for winter wheat and for summer sowing of perennial grasses, including alfalfa and post-harvest buckwheat. Rapeseed should not be returned to its original place in the crop rotation until 4–5 years later. Under the current structure of sown areas, winter rape is sown after winter cereals. For winter rapeseed, it is most advisable to create specialised rapeseed-grain crop rotations with maximum saturation with these crops. This improves the phytosanitary condition of the soil, the phytosanitary condition of subsequent grain crops, and reduces the damage to these crops by root rot, various leaf and stem spots by 15–20%, as its root residues have a detrimental effect on pathogens in the soil. Due to the content of sulphur compounds (glucosinolates) in the plant, rapeseed has a fumigant effect when decomposed in the soil, disinfecting the soil for subsequent crops. It significantly improves the soil structure and loosens it, as almost 90% of the roots are concentrated in the topsoil at a depth of 20 cm. The increase in grain yields after winter rape reaches 3-6 centner/ha without additional costs for the purchase and application of fertilisers. The biological activity of the soil increases by 10–15%, nutrient losses with infiltration water under the leaching regime of the soil are reduced by 50%, disease damage to wheat sown on a layer of perennial grasses is reduced by 30–50%, and grain yields increase by 5–10 centner/ha.

In the research of the same author [181], it is noted that the return of winter rape and other cabbage crops in the crop rotation to their previous place no earlier than 4–6 years later significantly improves the phytosanitary condition of the soil. Scientifically based inclusion of rapeseed in crop rotation is essential for high and sustainable yields and economically viable production. Therefore, the maximum permissible saturation of the crop rotation with rapeseed and the necessary pause during its cultivation and the choice of a predecessor are also essential. According to D. Shpaar, the possible concentration of rapeseed crops in the crop rotation is 20–25% of arable land, but with a mandatory three- to four-year break. Studies have shown that a one-year pause in rapeseed cultivation can reduce yields by up to 60%. When rape is planted after rapeseed, the seed yield is reduced by 25% compared to the yield in the

crop rotation. If sugar beet is grown in the crop rotation, the time gap between rapeseed crops increases to 5–6 years.

In practice, one field should be occupied by four- and five-field crop rotations. The introduction of such crop rotations has a positive effect on the productivity of other crops.

The predecessor of winter rape should be a crop that is harvested early so that tillage and sowing can be carried out in time. The best predecessors of winter rape are annual grasses, early harvested cereals and legumes, perennial grasses after the first mowing, and early potatoes. Cereal grasses, cereals – wheat, rye, triticale – are considered poor predecessors of rapeseed.

Spring rape is also an excellent predecessor in the crop rotation. Although the root system penetration is not as deep as that of winter rape, it covers the soil surface better than winter rape due to the high density of plants in the topsoil. After harvesting, the crop residues are much smaller and therefore better able to release nutrients that remain for the next crop in the rotation. Spring rape leaves behind looser soil, thus creating optimal conditions for minimal tillage for the next crop (an element of biologisation of agriculture). Its value as a predecessor is similar to that of winter rape. In a scientifically based crop rotation, the share of rape should not exceed 20–25% of the total area [182].

Mustard crops are placed after black or busy fallow, cereal grains and legumes. Mustard should not be sown after rapeseed, oilseed flax, beetroot, sunflower, millet and annual grasses, although mustard itself plays a positive role in crop rotation. It can be returned to the previous place of cultivation only after 4–5 years. Heavy, flooded and saline soils are unsuitable for sowing mustard.

Mustard requires high-quality soil cultivation, so its preparation is aimed at accumulating moisture, accelerating the decomposition of plant residues, destroying pathogens and weeds, and creating a levelled moist soil layer at the depth of seed placement. Pre-sowing tillage, which is carried out when the soil is physically ripe, also plays an important role. If for some reason the soil was not levelled in the autumn, harrowing is required. To create an optimum seedbed, the field is cultivated to a depth of 4–5 cm across or at an angle to the ploughing. The unevenness of the cultivation depth should not exceed ± 1 cm. The best effect can be achieved by using combined tillage tools.

Thus, mustard is placed in the crop rotation after those crops that allow for good soil preparation, but the ideal predecessor is fallow. It is not recommended to grow it after cabbage crops and sunflower. It is an excellent predecessor for many crops. Mustard can be returned to its original place in the crop rotation after four years at the earliest.

In field crop rotations, spring ryegrass is best planted after cereals and row crops. It is a good predecessor for spring wheat.

Be sure to remember [181], that crop rotation modelling is one of the most important tasks in modern agriculture. It can both create difficulties for farmers and open up new opportunities for them, in particular in the effective preventive control of the prevalence of cruciferous crop diseases. The complexities and requirements for crop rotation in agriculture are constantly growing: due to their effective crop protection and economic pressure, crop rotations are dominated by particularly high-yielding and cost-effective crops. For example, due to increasing resistance to weeds and pests and the shrinking scope for chemical crop protection, short rotations are becoming obsolete. Expanding crop rotations to include new crops is not always economically feasible.

Extended crop rotation can contribute to solving these agricultural problems through its flexibility and diversity. Of course, economic aspects should also be taken into account in crop rotation modelling [182]:

– Maintaining soil and crops in a healthy state;
– promoting species and biodiversity;
– reducing vulnerability to pests and diseases;
– sustainable business success.

In addition to being as versatile as possible, attention is paid to crop rotations, in which crops that are not very compatible with each other are separated from each other for long periods of time. Crop rotation also needs to be adapted to the terrain and other operating conditions and must meet economic requirements. Positive effects can be achieved, for example, by alternating leafy vegetable and stem crops and by alternating spring and winter crops. This offers advantages in the control of common and cereal weeds. Different sowing dates can counteract the overproduction of certain species, as weeds also include species that germinate in autumn or spring. In addition, the weed control options in the context of crop protection can be expanded as a result.

It is noted that [183], that pathogens of fungal or animal origin that are favoured by short rotation crop rotation can be summarised under the term "crop rotation diseases". They occur in almost all types of crops. Important crop rotation diseases include, for example, blackleg in cereals, root and stem rot in rapeseed or sugar beet nematodes. The emergence of problematic weeds, such as foxtail, is favoured by short rotations. Controlling them is becoming increasingly difficult due to their increasing resistance to many active ingredients.

This resistance is built up over many years through the use of pesticides with similar mechanisms of action and is found in fungal, animal and plant pests. As crop-specific pathogens are more likely to occur in short rotations and are treated with the same range of active ingredients, the effects of crop protection product resistance are exacerbated. In addition, there are increasingly stringent regulations on the approval of new and prohibition of already approved plant protection products, which further restrict the change of active substance.

In accordance with the EU's Common Agricultural Policy, European farmers are already obliged to implement crop rotations on their farms. In addition to the mandatory approach, the economic and environmental benefits of a balanced crop rotation also play a role. Breaks in the cultivation of the same crop can significantly reduce common crop rotation diseases by interrupting pathogen infection cycles. This will help to save pesticide costs and, due to the less frequent use of the active ingredient, protect against the loss of product effectiveness.

In the case of cruciferous vegetables, yields can also be limited by infection with clubroot, a soil-borne pathogen that can survive for years thanks to its permanent spores. Verticillium blight is caused by fungal pathogens and leads to painful ripening. Only an integrated concept based on agricultural measures such as cultivating varieties (hybrids) that are well resistant to verticillium or varieties (hybrids) that are resistant to Eremonotus myriocarpus can help to control these pathogens in the long term. A break of at least 3 years is recommended when growing rapeseed. In addition, no other type of cruciferous plant should be introduced into the crop rotation.

A balanced rotation between stem and leaf crops is the basis of a good crop rotation, and the same crop should always be grown intermittently to break the cycles of infection by fungal and animal pathogens.

Growing resistant varieties such as oil radish and mustard in a rotation with beetroot can reduce the number of nematodes in the soil. Choosing the wrong green manure crop can also increase the impact of diseases. In the case of oilseed rape and beetroot, growing cruciferous crops as green manure promotes the spread of clubroot, so oil radish and mustard are not suitable as green manure crops. Farmers also have a need: the decision on what to grow should not only depend on the marginal income from the main crop, but should also take into account the benefits for the entire crop rotation when choosing crop types.

Cruciferous crop residues should also be taken into account (due to the reservation of pathogens common to all cruciferous species), in particular the well-known problem of the active and long period of germination capacity of cruciferous crop residues due to the reserve of seeds in the soil [182].

In all rapeseed growing zones, seeds that fall into the soil during harvesting can germinate in autumn and spring if moisture is available. Winter rapeseed residue overwinters very well in winter crops and resumes vegetation in spring. The sprouted cruciferous carrion is a reserve pathogen and contributes to the re-infection of cruciferous crops when they are returned to the same field with an interval of less than 3–4 years. Rapeseed fall is a serious problem, especially in broadleaf crops. Therefore, it is best to grow winter wheat or other cereals after rape. In cereal crops, rape residue is well destroyed by simple herbicides based on 2,4-D, dicamba, florasulam or mixed preparations containing these active ingredients. Crop rotation is therefore the most effective and cheapest method of controlling rape carrion. Rapeseed carrion plants that appear in other crops are weeds and cause the same damage as weeds.

When planning to control rapeseed carrion with herbicides, you must first clarify which hybrid was sown on the field – conventional or Clearfield (herbicide-resistant), and only then buy the product.

Rapeseed stubble can germinate even after several years. This phenomenon often occurs after ploughing, when the lower layers of soil containing rapeseed are exposed to the surface.

In any farming system, rapeseed from the previous season can germinate and compete for valuable resources such as water and nutrients with the main crop, as well as become a potential host for diseases and insects.

Preventing carrion from becoming a problem requires advance planning and the use of the right control methods.

To which herbicides can rapeseed resist?

Rapeseed varieties and hybrids with different resistance to herbicides are widespread in the world:

– Conventional rapeseed without herbicide resistance is available in Ukraine;
– IMI-resistant/Nopasaran/Clearfield/CL – available in Ukraine;
– Resistant to glyphosate/GT/RR (GMO);
– Resistant to triazine/TT (GMO);
– With double resistance to glyphosate and triazine (TT + RR);
– With double resistance to Clearfield and triazine (CL + TT).

In general, the choice of rape fall control method will depend on what crop will be grown after rape [182].

During desiccation, a special adhesive, Elastik, can be added to the tank mixture (0.8–1.0 l/ha) to reduce seed shedding during harvesting. The use of modern combines and specialised rapeseed harvesters (rapeseed table) helps to minimise seed losses. In this case, it may not be necessary to use herbicides to control the fallen crop.

The most effective method of controlling rapeseed fallow, in particular herbicide-resistant fallow, is to maintain crop rotation.

Rapeseed is a broadleaf crop, so it is best to sow cereals (grains) after it. In cereal crops, it is quite easy to destroy rapeseed carrion. If broad-leaved crops (rape, sunflower, soybeans, sugar beet, vegetables, flax, safflower, chickpeas, peas, etc.) are sown after rape, then it will be difficult and expensive to control the fallen crop. In addition, the accumulation of common diseases (e.g. sclerotinia) and pests can reduce the yield of the following crop. Therefore, to avoid unnecessary costs and yield losses, it is better not to sow broadleaf crops after rape.

When planning a crop rotation after Clearfield rape, you should also keep in mind the crop rotation restrictions.

In addition, effective methods of preventing and limiting the spread of pathogens in cruciferous crops include

– liming acidic soils;
– deep ploughing as part of the main tillage system;
– application of the calculated dose of phosphorus and potassium fertilisers and no more than 20% of the required nitrogen fertilisers for sowing;

– mandatory soil compaction before sowing;
– pre-sowing seed treatment.

It is also necessary to introduce the main approaches of crop residue management in cruciferous crop production technology. Rapeseed residues in particular are becoming a real incubator. After all, on crops that producers do not plan to treat with a cracking preventive agent, up to 30% of seeds can fall off per hectare (at a yield of 35 centner/ha, this amounts to almost a tonne of untreated infected seeds). On such a field, you can find a whole bunch of diseases that partially remain in the soil and partially spread to neighbouring fields. The situation is even worse with sclerotinia. This disease is insidious because of its extremely high damage (up to 50% of losses), the inability to remedy the situation when signs of disease have already appeared, and the extended spore life in the soil (six to eight years).

Thus, an effective integrated system for protecting cruciferous crops from diseases must combine several components:

– Crop rotation is the main preventive measure that improves the phytosanitary condition of crops and naturally regulates the dynamics of pests.
– Soil cultivation: stubble peeling and ploughing help to decompose crop residues, which contain pathogens; maintaining the optimal sowing depth, which promotes friendly germination.
– Fertilisation.
– Seed treatment.
– Sowing only zoned varieties and hybrids.
– Fungicide treatments.

The strategy of fungicide protection [183] should be based on preventive control, before the onset of disease symptoms. If, for various reasons, a preventive fungicide was not applied in time, it is necessary to use products that have a strong therapeutic effect. Thus, in terms of fungicide use, preventive fungicide treatments are possible and appropriate. In particular, the experience of using such treatments on winter rape is valuable. As a rule, in this case, a certain selected preparation is used 10–14 days before the projected date of the long-term development cycle of the relevant pathogen based on the already mentioned forecast of pests and diseases for a particular region. In many cases, this method requires constant monitoring of agrophytocenoses for signs of certain pathogens, as well as daily monitoring

of plant condition and hydrothermal conditions for 5–7 days. For example, winter rape is affected by diseases throughout the growing season. Already in autumn, in the 2–6 leaf stage, powdery mildew, cylindrosporium, downy mildew, alternaria, and phomosis can occur. By the way, owners rarely pay attention to disease damage in autumn, mistakenly believing that autumn disease damage will not carry over to spring. However, spring phomosis is always a consequence of autumn infection. The first mature ascospores are formed on the remains of winter rape in autumn, and sporulation continues in spring. Ascospores are spread by air currents and, unlike conidia, can travel long distances. And during the period of vegetation recovery, the damage caused by certain diseases has often already become systemic and tissue-based, and subsequent fungicide application will be significantly less effective and efficient.

In the case of winter cruciferous crops, and in particular the most important representative of winter rape, the strategy for its protection against diseases is based on monitoring data and forecasts of their spread depending on the weather conditions prevailing during the autumn period.

Timely monitoring of winter rape crops is extremely important: autumn weed infestation, pest damage and disease infestation of young plants leads to a significant loss of the assimilation surface of plants, undesirable removal of the growth point above the soil surface, slower development of the root system, and reduced plant resistance to adverse environmental conditions, all of which significantly increases the risk of plant death and freezing in winter, and contributes to the damage to plants in spring by snow mould, root bacteriosis, blackleg, alternaria, downy mildew, phomosis, Fusarium and Verticillium wilt, white and grey rot and other diseases. These diseases are very dangerous for winter oilseed rape and require constant monitoring and plant protection.

The most effective protection of winter rapeseed against diseases will only be achieved if measures in the autumn period are aimed primarily at radically limiting or eliminating the source of infection, blocking or slowing down the spread of infection during the early vegetation period, increasing plant resistance to infectious diseases and adverse weather factors.

In order to obtain objective data on the phytosanitary condition of winter rape seedlings in terms of disease spread, it is necessary to clearly

distinguish between the diagnostic signs of each disease. It is from this point of view that the previous sections of the monograph will be useful here.

The expediency of chemical protection of winter oilseed rape crops in autumn against diseases and the timing of crop treatment is usually associated with the phenological phases of plant development that are most favourable for infection by their pathogens. Two criteria should be taken into account when dealing with rapeseed diseases: the spread of the disease, the degree of plant damage and the short-term forecast of each disease.

The product is selected based on the species composition of pathogens. At early sowing dates, when there is a risk of overgrowth of plants and a consequent decrease in their winter hardiness, fungicides based on active ingredients with retardant properties are preferred (metconazole; tebuconazole and its mixtures with other active ingredients, mixtures of difenoconazole and paclobutrazole; protioconazole and fluopyram). These products not only effectively inhibit the spread and development of Alternaria, phomosis and other plant diseases, but also inhibit leaf growth and increase plant resistance to extreme weather conditions. They are primarily used on early winter rape crops, thickened crops, in the presence of carrion in crops, and when excessive doses of nitrogen fertilisers are applied, when there is a risk of overgrowth and reduced winter hardiness.

To increase the technical effectiveness of fungicides, one of the plant growth regulators is added to the working suspensions or emulsions, which promote strong plant development, formation of a larger photosynthetic surface, and thickening of the root system. Usually, plants treated with one of these regulators have a healthy appearance, with rosette leaves of dark green colour.

It is important to control pests of cruciferous crops in parallel with planning the use of fungicides. Therefore, it is important to plan for the combined use of insecticides with fungicide treatments, as most cryptic bugs, cruciferous fleas, rapeseed borer, weevils and leaf-eating pests are highly active at the beginning of the growing season, and control of these pests prevents mechanical damage to rapeseed tissues. These mechanical damages are responsible for 90% of fungal infections in rapeseed plants.

It is also important to assess the degree of infection with cruciferous disease in previous years, as the most dangerous pathogens can persist in

the soil for up to 7–10 years. If rapeseed is returned to its original place in the crop rotation after 3–4 years (typical for Ukraine), the disease is provoked. It can be provoked by cracks caused by spring frosts – when there is intensive regrowth and a sharp drop in temperature at night – the parenchymal tissue cracks and infection passes through the cracks.

With regard to crop rotation, it should be borne in mind that crop rotation is the main preventive and necessary agronomic measure. Crop rotation allows you to regulate the number of potential, mostly specialised pests and significantly limit their development. Rapeseed should be returned to the same place no earlier than in 4–5 years. According to I.P. Markov, high and stable yields of winter and spring rapeseed are obtained by introducing specialised rapeseed crop rotations with maximum saturation with grain crops, where the share of rapeseed is up to 20–25%. At the same time, the best predecessors of cruciferous crops are black and fallow land, legumes, cereal crops, potatoes, corn, annual and perennial grasses. The spatial isolation of this year's cruciferous crops from last year's crops also limits the spread of aerogenous infection by pathogens. It is also important to increase the resistance of plants to pathogens by optimising their nutrition. In this regard, the use of a mixture of humates and trace elements (boron, magnesium, manganese) is extremely effective, especially in early spring foliar feeding, as it provides an additional incentive for plants to grow more rapidly, form generative organs, and stimulate chloroplast activity, while humic and fulvic acids act as antistressants after nighttime temperature drops and after herbicide treatments. The actual system of fungicide application and their possible combination in the form of tank mixtures should also be properly planned. They allow to increase the economic efficiency of measures, improve labour productivity, minimise the pesticide load on the soil by reducing the consumption rates of each product and reduce the number of treatments and, accordingly, mechanical damage to crops. The preparation of a tank mix is not a mechanical mixing of randomly selected components. This is a field of complex organic chemistry combined with the requirements of agronomic science.

Tank mixtures are divided into groups according to their purpose:

Mixtures of single-functional products (herbicide + herbicide), but with different mechanisms of action. Multifunctional preparations for the simultaneous destruction of various harmful objects (herbicide + insecticide,

fungicide + retardant). Mixtures of mineral fertilisers with pesticides. Mixtures of fungicides, micronutrient fertilisers and retardants for seed treatment, etc. When planning tank mixtures, the stage of crop development should be taken into account. The timing of application of all components of the tank mix should coincide. It is also necessary to ensure that the crop is not stressed at the time of treatment. Only compatible products should be used for the preparation of tank mixtures. Incompatible are those pesticides that, when mixed, change physical properties, have a phytotoxic effect on the crop or reduce the effectiveness against harmful objects. And one more note, for winter cruciferous crops, in terms of disease control, first of all, it is necessary to pay attention to those crops that were overgrown when they came in for wintering. As such plants are most often affected by a complex of pathogens of root rot, phomosis, typhoid and other pathogens. At the same time, it should be remembered that protection against diseases and pests is only one of the levers for obtaining a high quality rapeseed crop – for this, all elements of technology must be followed. Therefore, if a producer's main goal is to get a consistently high crop yield, it is impossible to save on technology and neglect the timing of the necessary treatments with protection products and mineral fertilisers.

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CHAPTER 4. INTEGRATED SYSTEMS OF PROTECTION OF CRUCIFEROUS CROPS AGAINST MAJOR DISEASES (DOMESTIC AND INTERNATIONAL EXPERIENCE)

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DOI: https://doi.org/10.30525/978-9934-26-358-3-4

4.1. Integrated systems and methods of Alternaria control in agrocenoses of cruciferous crops (generalised world experience)

Modern intensive technologies of oilseed rape cultivation require clear, well-thought-out and decisive measures in the field of plant protection against diseases. Given the increase in rapeseed cultivation, there is a need to develop new effective systems and means of crop protection [1].

Monitoring of diseases of winter and spring rape in Ukraine over the past 5 years has shown that the most common and damaging disease is Alternaria [2]. The ability of the pathogen to persist in crop residues, seeds, and develop on winter and spring rape and other crops leads to the risk of epiphytic development of Alternaria under favourable conditions every year. This indicates the possibility of significant yield and quality losses.

It is noted [3]. that among the factors affecting crop yields, fungal diseases prevail, in particular, Alternaria, the symptoms of which appear throughout the growing season as spots on leaves, stems, and pods. Seeds affected by Alternaria pathogens die in the soil. In the early stages of ontogeny, Alternaria appears on seedlings in the form of dark brown spots, leading to their death. On the leaves, the disease is marked by light brown to dark brown, almost black spots of various sizes. The nature of the spots depends on the type of pathogen and the organ affected. On the stems, the spots are dark, on the pods – dark spots

that turn into ulcers, stretch marks over time, the pods are deformed and develop small seeds or do not form. If the top of the pod is affected or along the seams of the valves, it cracks, causing early yield losses [4]. In the literature on phytopathology, the following species are now more commonly described as pathogens of Alternaria: *Alternaria brassicae* (Berk.) Sacc., *A. brassicicola* (Schwein) Wiltshire and *A. japonica* Yoshii (Figure 4.1). In addition, alternaria pathogens are facultative parasites with a wide range of adaptive responses. As a rule, they are characterised by a saprophytic lifestyle, but when plants are weakened, they can switch to parasitism. Variability of pathogenicity of fungi of the genus Alternaria is known. For example, according to O.L. Gasych, out of 3 isolates of fungi of the genus *A. brassicae*, 11 varieties of rape showed pathogenicity to varying degrees on the leaves. The culture liquid of A. brassicae fungus can be phytotoxic to rapeseed sprouts. According to the research of F.B. Hannibal, A. alternata and A. tenuissima species are more toxic to plants than A. infectoria. Studies1058 conducted on Sarepta mustard indicate that A. brassicicola is more toxic than A. brassicae.

In the works of scientists who conducted research in Iran, Israel, Peru, and China, the pathogenicity of A. alternata fungi was noted [5–8].

Weak and damaged plants are more susceptible to damage, so it is important to select resistant, high-performance varieties for production, apply effective protection systems using pesticides and growth regulators to prevent damage at the initial stages of organogenesis [9].

In long-term studies of the structure of pathogenic alternaria in Poland and Ukraine [10] it is noted that the development of Alternaria in crops of varieties and hybrids undergoing competitive variety testing ranged from 1,8 to 43,3%, This indicator in winter rape crops, depending on the variety, reached in 2014 21,1% on leaves and 16,6% on pods; in 2015 – 4.5–22.1% and 6.9–8.8%; in 2016 – 3.5–13.6% and 12.4–24.4%; in 2017 – 8.5–12.1% on leaves and 35.6–48.8% on pods.

The harmfulness of Alternaria in winter rape crops is to reduce the length of the pod by 16.2–30.5%, the number of seeds in the pod by 13.8–31.0%, the weight per pod by 17.6–35.3%, the weight per plant by 53.3–81.4%, and the weight of 1000 seeds by 9.1–37.9%. It was noted that 64.3% of the plants examined were affected by the disease of moderate and severe degree. The main indicator that is significantly affected by Alternaria spp,

fungi is the weight of seeds per plant (r = -0.711). As the intensity of the disease increases, seed quality decreases: dry matter content – from 95.9 to 80.6%, fat – from 45.7 to 42.1%, but glucosinolates content – from 18.7 to 32,9% and protein content – from 17.7 to 20.5%.

The threshold of harmfulness of Alternaria or the level of disease development, from which a significant decrease in the weight of 1000 seeds is observed, is 2.7–6.1%, the relative harmfulness coefficient is 0.34–0.63.

Figure 4.1 – Alternaria (pathogen: *Alternaria brassicae, Alternaria brassicicola, Alternaria raphani* [11]

To clarify the species composition of fungi of the genus Alternaria, which parasitise winter rape, the following were isolated and analysed [5] more than 500 isolates. As a result of determining the species composition of Alternaria spp. isolated from parts of winter rape – leaves, stems, pods, roots, seeds, the dominance of isolates of *A. tenuissima* with a frequency of 32.3%, *A. brassicicola* – 26.6 and 19.6% – A. alternata was established. In the population structure of Alternaria spp. 21.5% of isolates caused difficulties in their identification.

It was found that the frequency of isolation of A. alternata in the maximum amount (83.9%) was noted when isolated from seeds, while the fungus was not isolated from the affected tissues of stems and pods (Table 4.1).

Table 4.1

Dominance structure of Alternaria spp. fungi isolated from parts of winter rape plants (laboratory experiment) [4]

Type	Frequency of occurrence, %			
	seed	leaves	stems	pod
A. brassicicola	40.5	45.3	7.1	7.1
A. tenuissima	33.3	33.3	21.6	11.8
A. alternata	83.9	16.1	0.0	0.0
Alternaria spp.	23.5	58.8	5.9	11.8

Table 4.2

Effect of Alternaria spp. isolates on the growth of sprouts and roots of winter rape (average for 2014–2017) [12]

Type	Number of isolates	Affected plant organs, %			
		sprouts		spines	
		length reduction	stimulation growth	length reduction	stimulation growth
A. brassicicola	42	90.5	9.5	95.2	4.8
A. tenuissima	51	82.3	17.7	86.3	13.7
A. alternata	31	96.8	3.2	96.8	3.2
Alternaria spp.	34	88.2	11.8	91.2	8.8

The fungus *A. brassicicola* was isolated from seeds (40.5%) and leaves (45.3%) with relatively equal frequency, the same dependence is characteristic of the fungus *A. tenuissima*, the latter was also isolated more often than others from the affected stem tissues (21.6%).

The differentiation of Alternaria spp. species isolated from the affected parts of winter rape plants by the frequency of occurrence necessitated the need to conduct studies to determine their effect on sprouts in case of seed damage.

The analysis of the data obtained indicates a significant suppressive effect of Alternaria spp. isolates on the length of sprouts and roots. Isolates of *A. alternata* reduced the length of the studied parameters in 96.8% of seedlings, while, for example, *A. brassicicola* – in 90.5% of sprouts and 95.2% of roots.

Isolates of A. tenuissima caused a decrease in the length of the sprout (82,3%) and roots (86.3%), and some isolates had a stimulating effect on seedlings. A higher number of such isolates was characteristic of A. tenuissima – 17.7%, which stimulated sprout growth, and 13.7% – root growth, for *A. alternata* isolates – 3.2 and 3.2%, respectively.

Symptoms of sprout damage by pathogenic fungi were in the form of dots and necrosis from brown to dark brown and black, located singly or in groups. The defeat of 50% or more of the sprout surface caused its decay or death. Symptoms of winter rape sprout damage are shown in Figure 4.2.

The analysis of Alternaria spp. isolates by pathogenicity showed (Table 4.3) that the overall population of Alternaria spp. is highly pathogenic.

All (100%) isolates of *A. brassicicola* and *A. tenuissima* are highly pathogenic, among the isolates of A. alternata group 83,9% are highly pathogenic, 9,7% are pathogenic and 6,4% are moderately pathogenic.

Figure 4.2 – Signs of fungal infestation of winter oilseed rape sprouts *Alternaria* spp [8]

Under artificial infection of winter rape plants with *A. brassicicola, A. tenuissima* and *A. alternata*, at different stages of crop development, their pathogenicity was confirmed and it was determined that the highest level of disease development on leaves was observed at the stage of BBCH 50 (appearance of the primary peduncle) and BBCH 61 (about 10% of open flowers on the main shoot, elongated peduncle, tightly closed by the upper leaves) – 45.9 and 72.9%, on pods – at stages 61 and 69 (end of flowering) – 72.7 and 84.2%.

The study of the effect of temperature on the growth of Alternaria spp. fungi revealed that the optimal temperatures for the growth of *A. alternata, A. tenuissima* and *A. brassicicola* are in the range of 20.0–25.0 °C.

The study of relationships between fungal pathogens of Alternaria during co-cultivation showed that the relationship between isolates of *A. brassicicola* and *A. alternata*, *A. tenuissima* is based on the type of territorial antagonism, and the pathogen *A. brassicicola* was the antagonist.

Table 4.3

Differentiation of Alternaria spp. fungal isolates by pathogenicity (laboratory test, average for 2014–2017) [13]

Type	Number of isolates	Proportion of isolates causing lesions, %					
		highly pathogenic	pathogenic	moderately pathogenic	moderately pathogenic	slightly pathogenic	avirulent
A. brassicicola	42	100	0.0	0.0	0.0	0.0	0.0
A. tenuissima	51	100	0.0	0.0	0.0	0.0	0.0
A. alternata	31	83.9	9.7	0.0	6.4	0.0	0.0
Alternaria spp.	34	91.2	8.8	0.0	0.0	0.0	0.0

The results obtained in clarifying the species composition of rapeseed pathogens, studying their developmental features, pathogenic properties and their impact on the crop made it possible to substantiate plant protection methods.

Oilseed crops are constantly exposed to a number of pathogens and, as a result, they have developed complex defence mechanisms to recognise and protect against a wide range of these pathogens through structural

defences [8] and induction of a complex of defence reactions that can defeat pathogens [14].

Table 4.4

Features of winter rape sprout damage due to infection with Alternaria pathogens [13]

Characteristics of the seedling impression	Occurrence (%) of seedling lesions, fungi		
	A. alternata	*A. brassicicola*	*A. tenuissima*
Healthy	28.6	4.0	5.0
Point necrosis of tissues	26.2	21.2	22.9
Necrosis of about 50 % of the surface	19.5	23.0	21.9
Total destruction	25.7	51.8	50.2

Structural defence against Alternaria is associated with factors that prevent conidia from being retained on the host surface, such as high epicuticular wax deposits that form a physical barrier in the form of a hydrophobic coating, which reduces the deposition of aqueous inoculum, reduces the rate of conidial germination and germ tube formation [15–16].

Species *B. napus, B. carinata* and *B. alba* have relatively more epicuticular wax than *B. rapa* and *B. juncea* and are generally less susceptible to infection by Alternaria pathogens [5].

It was found that biochemical defence against Alternaria of mustard leaves was associated with leaf enzymes related to the phenolic pathway and higher sugar content in the leaves. The resistance of Camelina sativa to A. brassicae was associated with the presence of chemical compounds, camalexins, somewhat similar to the fungicide available on the market. The resistance of Camelina sativa to A. brassicae through the production of the phytoalexin camalexin was also reported by Jejelowo et al. [10] and Thomma (1999) [7].

Camalexin also has an indirect effect on Alternaria resistance, as it was found that camalexin inhibits the production of the toxin destructin B in *A. brassicae* [5].

The cultivation of resistant varieties is important in controlling this pathogen. It has been established that the resistance index of cruciferous varieties has a significantly different value in different genotypes. For example, resistance to Alternaria was studied97 on 14 spring oilseed

rape varieties of domestic and foreign breeding at the Agronomic Research Station of the National University of Life and Environmental Sciences of Ukraine (NULES of Ukraine) (Table 4.5).

At the same time, these studies have established [8], that during the growing season, there was an increase in the values of indicators of the spread and development of the disease. According to the results of the research, a significant difference in the resistance of the studied varieties was found. No immune varieties were found.

If we place the studied varieties in order from lower to higher levels of resistance to Alternaria, this chain will look like this: Belinda, Salsa KL, Delight, Obriy, Olga, Magnat, Khuzar, Siesta F1, Oksamit, Aira, La Rissa, Cliff, Hidalgo, Maria. Thus, Belinda had the highest degree of damage (96.5% spread, 10.7% development), and Maria was the most resistant (54.5% and 4.7%, respectively). It is worth noting that weather conditions restrained the spread and development of the infection on plants, so the damage caused by Alternaria did not affect the yield data, with varietal characteristics playing a decisive role.

In long-term foreign studies on the virulence of Alternaria pathogens and the search for resistance donors, taking into account the chemistry of host-pathogen interaction, a number of important conclusions and generalisations have been made.

Due to the high losses caused by Alternaria in oilseeds, the goal of oilseed breeders is to develop Alternaria-resistant lines. Several attempts have been made in the past to identify sources of resistance to Alternaria, but no resistant sources have been identified in any of the cultivated castor oilseed rape species, but a high degree of resistance to Alternaria has been found in *B. alba,· Eruca sativa* [18] and *Sinapis alba* [19–22]

The highest degree of resistance to *A. brassicae* was found in wild relatives of cabbage outside the Brassicaceae tribe. This is false flax (*Camelina sativa*), shepherd's bag (*Capsella bursa-pastoris*) and panicle weed.

In search of sources of resistance for transferring resistance genes, thirty-eight species belonging to nine genera, including cultivated and wild cruciferous species, were evaluated under epiphytic conditions for two years. Eight species, namely *B. desnottesii, C. sativa, Coincya pseuderucastrum, Diplotaxis berthautii, Diplotaxis catholica, Diplotaxis cretacea, Diplotaxis erucoides* та *Erucastrum gallicum* were found to

be fully resistant, while others were classified as moderately resistant, susceptible and highly susceptible.

Table 4.5

Distribution and development of Alternaria in spring oilseed rape varieties [9]

Variety	Disease prevalence, %			Disease progression, %			Yield, t/ha
	Growth phase	Flowering	Achievements	Growth phase	Flowering	Achievements	
Belinda	39.6	43.4	96.5	5.4	6.3	10.7	2.03
Delight	33.0	34.2	99.0	4.8	6.0	9.9	1.69
Horizon	27.8	32.5	98.3	4.1	5.3	9.8	1.71
Cliff	19.1	22.1	84.8	2.8	3.2	7.0	2.18
Larissa	19.9	23.0	77.3	3.5	4.3	7.9	1.94
Siesta FI	23.3	34.9	94.8	3.6	5.5	9.2	2.45
Maria	13.1	21.8	54.5	1.6	2.2	4.7	2.37
Huzar	20.1	22.6	82.0	4.0	5.3	9.7	2.74
Olga	22.6	30.8	88.0	4.5	6.1	9.8	2.08
Velvet	18.3	24.3	79.8	2.7	3.4	9.0	1.82
Magnate	15.0	18.5	64.2	2.9	3.9	9.8	1.86
Hidalgo	14.1	26.3	75.4	1.8	2.6	5.9	2.68
Salsa KL	20.0	22.9	84.5	4.2	5.3	10.0	2.13
Aira	21.6	29.4	91.8	3.4	4.5	8.7	2.59
SSD_{05}	1.7	1.2	1.4	0.1	0.3	0.2	0.18

A wide range of variation was also observed among species of the genus *Diplotaxis*, but the genus Diplotaxis proved to be more resistant than the genus *Brassicas*. Based on this, we concluded that the sources of resistance to *A. brassicae* present within the cenotic species *Brassicas* (tribes), from which resistance genes can be introduced into cultivated cruciferous species. Seven species, except for *C. sativa*, have been identified as fully resistant to Alternaria leaf spot and belong to the cenotic species of Brassica (Brassicaceae). As resistance is not present in cultivated species, these eight

resistant wild species can be used as donor parents for introgression of resistance to Indian mustard leaf spot. The absence of a resistance gene in crossbred Brassica germplasm necessitates the use of genetic engineering strategies to develop genetic resistance to this pathogen.

Mondal et al. (2007) [23] obtained the integration and expression of the class 1 major glucanase gene in transgenic mustard plants and observed that the transgenes delayed hyphal growth of *A. brassicae* by 15–54%. Transfer of alternaria resistance genes in Brassica sp. Tuan and Garg (2001) [24] carried out gene transformation in Brassica sp. using particle bombardment. Cotyledons and hypocotyls of different Brassica species were used as target explants. Transient expression of the uidA gene was obtained by constructing it with CaMV35S or Actin promoters. The uid4 gene encodes enzyme 1, beta-glucuronidase (GUS). It is a reporter gene system, especially useful in plant molecular biology and microbiology. The highest expression was recorded between 10 and 15 hours after the bombardment. The plasmids pBI121, pBI221 and pDM803 were used to transfer the uidA gene. To obtain the highest transformation efficiency, further transformation steps are required.

Biochemical defence is triggered under any plant stress condition and is the most important tool of the plant defence mechanism. The hypersensitive reaction is one of the most effective plant defence reactions against pathogens [25]. Mustard Alternaria resistance has been reported to be associated with the synthesis of phenolic pathway-associated leaf enzymes and higher leaf sugar content. It was reported that the concentration of phenolic compounds at all stages of plant growth was higher in resistant genotypes compared to susceptible genotypes. However, the content of soluble sugars, reducing sugars and soluble nitrogen in resistant genotypes was lower [26–27]. Another study reported that total phenol, total sugar, reducing sugar, o-dihydroxyphenol, chlorophyll and flavonol content were higher in resistant genotypes. Plants can respond to pathogens by activating several defence responses that prevent the infection process. These include the production of reactive oxygen species (ROS), the accumulation of pathogenesis-related proteins (PRPs) and phytoalexins, and the synthesis of compounds that strengthen the plant cell wall [28]. In addition, the content of ascorbic acid, total phenol, enzymatic activity of superoxide dismutase and peroxidase, as well as cell-protective enzymes such as phenylalanine

ammonia kinase and polyphenol oxidase increased in resistant mustard genotypes [29]. β-Aminobutyric acid (BABA), a non-protein amino acid, is known to stimulate resistance to various pathogens in a number of plant species [30–31]. Pretreatment of Brassica oilseed rape plants with BABA-mediated resistance to the necrotrophic pathogen *A. brassicae* through enhanced expression of protein genes related to pathogenesis [32]. Higher and earlier accumulation of H_2O_2 was observed in resistant *C. sativa* and *S. alba* compared to *B. juncea*. Catalase activity increased in both *C. sativa* and *S. alba*, but in the case of *B. juncea*, the opposite phenomenon was observed [33].

Ethiopian mustard (B. carinata) has the highest level of resistance to Alternaria among cabbage crops. Among the wild cruciferous plants close to the genus Brassica, the highest level of resistance to *A. brassicae* was confirmed for white mustard (*Sinapis alba*) [34-37] However, the highest overall levels of resistance to Alternaria spp. were found in cruciferous plants more distant from Brassica, such as redhead (*Camelina sativa*; false flax), shepherd's purse (*Capsella bursa-pastoris*), arugula *(Eruca sativa*) and panicle mustard (*Neslia paniculata*) [38-39].

Resistance to Alternaria (black spot) has also been reported among other wild representatives of the family *Brassicacae* [40]: *Alliaria petiolata; Barbarea vulgaris; Brassica elongate, B. desnottessi, B. fruticulosa, B. maurorum, B. nigra, B. souliei, B. spinescens; Camelina sativa; Capsella bursa-pastoris; Coincya spp. berthautii, D. creacea, D. erucoides, D. tenuifolia; Erucastrum gallicum; Eruca vesicaria subsp. sativa; Hemicrambe fruticulosa, H. matronalis; Neslia paniculata; Rhaphanus sativus; S. alba ma S. arvensis*. Fully immune plants remained symptom-free both under natural field infection and controlled artificial inoculation. In comparison, broccoli and cauliflower varieties showed only moderate resistance to Alternaria, while cabbage was susceptible.

Depending on the plant material studied, *A. brassica/A. brassicicola* resistance is controlled by one or more nuclear genes with partially dominant interaction [41] or due to additive inheritance [42].

At the biochemical level, resistance to Alternaria pathogens is associated with high activity of phenolases (polyphenol oxidase, peroxidase, catalase), high sugar content in the leaves [43] and a thick epicuticular wax layer, which forms a hydrophobic coating that reduces the adhesion of water seed

and also limits the rate of spore germination. The presence of intense wax deposition on the leaves seems to correlate with the resistance shown by other plants of the cruciferous family.

It has been established that wild cruciferous plants secrete phytoalexins during inoculation. Among the species resistant to Alternaria, redhead stands out for its immunity against *A. brassicicola* infection, which is based on the plant's ability to synthesise camalexin, a compound with antibiotic properties, and thus prevent the pathogen from developing. Indeed, a camalexin-deficient Arabidopsis mutant, pad-3, has been shown to be more susceptible to *A. brassicicola* than wild-type plants [44].

Further evidence that camalexin plays an important role in resistance is the observation that different Arabidopsis ecotypes with different camalexin contents show correlated differential resistance [15]

Finally, the esa1 mutation affects resistance to *A. brassicicola* through a strong reduction in both camalexin production and jasmonate dehydrogenase gene induction, although the Esa-1 gene has not yet been cloned [18].

A direct method for determining resistance to Alternaria is phytopathological testing: field, greenhouse or phytotron. Field observations can be carried out during natural infection with the pathogen, or after controlled artificial inoculation with a fungal suspension. The advantages of greenhouse or phytotron tests are speed, reproducibility, and the ability to control the conditions. Phytopathological tests require conidia of Alternaria spp. collected directly from infected plant tissue or grown on artificial media. On the widely used artificial PDA media, fungal growth and efficient spontaneous sporulation occurs at a temperature of 25 ± 2ºC, in the dark. There is a choice of other methods for the growth and maintenance of Alternaria spp. *A. brassicicola* hyphae have been successfully cultured on V8A artificial medium (V8 juice – agar) at 25 ºC, which led to spontaneous sporulation under a 12-hour photoperiod [20].

Phytotests under controlled conditions are carried out on whole plants (in vivo) or on isolated leaves (in vitro) [45]. Plants are usually tested at the 3–6-week seedling stage, but phytotesting results for cotyledon leaves have also been published. The detached leaf method is one of the most common ways to assess the level of resistance to Alternaria spp. demonstrated by the plants under controlled conditions. However, there are differences in the method of inoculation and the conditions of the assay.

As described in several studies, an inoculum of 5 × 104 spores × ml^{-1} was placed on the upper (adaxial) side of the leaf, while other authors describe spraying the lower (abaxial) side of the leaf with an inoculum of 3 × 105 spores × ml^{-1} [17].

Others inoculated only the 4th and 5th leaves (45 days old seedlings). Wet swabs were used to remove the wax layers from both nerve sides on the adaxial surface of the leaf, so that the aqueous spore suspension was evenly distributed on the leaf surface, without the need for agar or adjuvants. Better adhesion of the aqueous suspension of spores to the waxed surface of cabbage leaves is ensured by the addition of agar [46] or tween. Small superficial incisions were made with a fine needle and a drop of inoculum (4 × 103 spores × ml^{-1}) was placed on them. Disease symptoms were assessed in 24-h increments at 3-days intervals. The assessment of the resistance of individual plants included three parameters: percentile of infected leaf surface (0–60 points), lesion size (0–30 points) and incubation time (0-10 points). Plants with maximum susceptibility received 100 points. Individual plants were grouped into resistance classes according to the scores: 0 – completely resistant; 1–15 points – moderately resistant; 16–25 points – susceptible; over 25 points – highly susceptible. As noted above, the optimal conditions for phytotesting are a temperature of about 20 °C, relative humidity of at least 90% for 6 hours or more, and an inoculation load of 6×104 spores×ml^{-1}.

Since resistance to Alternaria black spot is generally regulated by polygenes, breeding for resistance may involve pyramiding minor genes to provide additive/polygenic resistance. Rapid advances in tissue culture techniques, protoplast fusion, embryo rescue and genetic engineering have made it possible to transfer disease resistance traits across impenetrable incompatibility barriers that would otherwise be impossible. Disease-resistant transgenic plants that overexpress various antifungal compounds, such as pathogenesis-related proteins (PRs) (chitinase, glucanase, osmotin, etc.) and ribosome inhibitory proteins (RIPs) such as thionines, defensins and phytoalexins, to inhibit pathogen growth seem to be less effective. Somatic hybrids between *C. sativa* and *B. carinata* have been developed to introduce resistance to *A. brassicicola* derived from ryegrass into commercial varieties, but researchers have not been able to propagate the hybrids [47].

A similar strategy of fusion of *C. sativa* and *B. oleracea* protoplasts with subsequent regeneration of hybrids also failed [48]. Several research groups have attempted, but without success, to introduce black spot resistance derived from *E. sativa* into different species of cultivated cruciferous vegetables [49–51]. The first somatic hybrids obtained as a result of protoplast fusion were hybrids of *B. napus* (rapeseed) and *S. alba* [52]. None of the hybrids obtained in this way showed resistance to *A. brassicae* comparable to that of *S. alba*. Chevre et al. (1991) [53] used these species for interspecific crosses through somatic hybridisation and bidirectional crosses. Using the embryo rescue technique, the researchers were able to regenerate *B. napus* plants that carried 38 chromosomes characteristic of this species and demonstrated resistance to *A. brassicae* at a level close to that of *S. alba*, *B. oleracea* var. *botrytis* or *B. carinata* [54].

Seeds of the intertribal somatic hybrids between *B. napus* and *C. sativa* (using protoplast electrofusion) had an intermediate phenotype compared to the parental species. They also showed higher levels of linolenic and eicosanoic acids, but the hybrid plants are awaiting determination of their resistance to Alternaria [55]. In general, it has been suggested that the introduction of alternaria resistance genes into commercial cruciferous varieties depends on the accumulation of horizontal resistance genes. Therefore, it is crucial to identify the different sources of horizontal resistance among cruciferous plants and subsequently combine them to increase reliable protection against Alternaria. The strong cross incompatibility, polygenic origin of resistance (additive and dominant gene interactions), and differences in ploidy (different chromosome numbers) between the respective cruciferous species make it difficult to transfer resistance to Alternaria from wild species to cultivars. In addition, this is often associated with the use of modern in vitro hybridisation techniques, including somatic hybridisation, embryo and ovary preservation or protoplast fusion.

This has indeed been demonstrated in Colletotrichum and Magnaporthe, for which transcription factors involved in the regulation of melanin synthesis during development have been identified [56].

To date, there is not a single 100% resistant variety to Alternaria in various cruciferous species. Therefore, the use of resistance from wild species can be an effective breeding tool. Plant pathogens manage to infect different species, but cannot overcome host resistance [57]. Examples

of some non-host plants of *A. brassicae* include chickpea, lentil, wheat, sugarcane, barley, tomato, and potato.

Pre-infestation protection can include structural features of plants such as a large number of trichomes and chemical compounds that inhibit spore germination [58–60]. Previous studies have shown that spore germination occurs at the same rate on both host and non-host plants. Despite spot germination, pathogens may not reach stomata. Stomata in non-host plants may be misrecognised by the pathogen because the surface topography may differ significantly from that of the host leaf.

Another structural feature that can impede the penetration of Alternaria is the epicuticular wax [61–62]. Plants that are more resistant to damage may have more epicuticular wax than susceptible plants [63]. In addition, it was found that the non-native plant is able to induce stomatal closure, preventing the penetration of pathogens and creating an inducible chemical barrier that inhibits hyphal production and differentiation through the rapid formation of phytoalexins, antimicrobial compounds [64–66].

In a plant resistant to Alternaria, nutritional deficiencies and the presence of antimicrobial compounds in the apoplast can also prevent hyphae production into the mycelium. The pathogen also generates nonspecific or general toxins that can damage plant cells, ultimately leading to necrosis [67]. To avoid this, the plant is more resistant to damage – it can recognise these toxins and use defence mechanisms to detoxify them. Pathogenetically related genes PR-1, PR-2, PR-3 were highly expressed in Arabidopsis and *S. alba* after infection with Alternaria [68–70]. In addition, these two species have demonstrated resistance to *A. brassicicola*. Chitinase enzymes, which hydrolyse the fungal cell wall and release chitin fragments, are actively secreted by these two species [71–72]. The action of NHR involves stimulation of the signal transduction cascade by the plant cell after pathogen detection, which triggers the activation of protein kinases and mitogen-activated protein kinase (MAPK) members and, as a result, leads to the activation of defence genes in plants. The expression of MAPK was higher in S. alba and lower in *B. juncea*, indicating its possible role in resistance to Alternaria.

It was previously noted that during the interaction between the host and pathogen (Alternaria – crucifers), a number of biochemical changes occur in both the host and the pathogen. These biochemical changes lead to

the formation of various types of primary and secondary metabolites that affect the host defence system and the virulence of the pathogen. *Alternaria brassicicola* produces compounds such as the antitumour depudecin, the antibiotic complex brassicolin and the phytotoxic brassicins. Production of glucosinolates and phytoalexins correlates with host resistance [73].

Host resistance in cruciferous plants to Alternaria species has different components and is multilayered. The inheritance of resistance in inter- and intraspecific crosses of *B. juncea* and *B. carinata* with *A. brassicae* is regulated by additive genes, dominant genes, epistatic genes of additive x additive, additive x dominant and non-allelic interaction genes of dominant x dominant type. Crossing between resistant plants contributes to an increase in the level of resistance to A. brassicae due to the pyramiding of resistant genes. A high level of horizontal resistance in oilseed genotypes was recorded [74].

Epicuticular wax and a small number and narrow stomatal opening provide resistance to Alternaria infection in cruciferous species. Concentration of phenolic compounds, activation of polyphenol oxidase and catalase is higher in the tolerant mustard genotype [75].

The isolation and accumulation of phytoalexins in cruciferous plants after alternaria infection and their role in disease resistance have been demonstrated. The ability of *A. brassicae* to sequester calcium can be used to increase resistance to this pathogen in canola by applying calcium compounds to the soil or foliar application. Numerous sources of resistance to Alternaria species have been identified in different cruciferous species and their close and distant relatives, but very few have been used to develop resistant varieties. Despite several bottlenecks in the development of resistant varieties, various methods and technologies, including traditional as well as biotechnological approaches, are being used to incorporate desirable traits into cruciferous crops against *Alternaria disease* [76].

Alternaria species that are pathogenic to cruciferous plants produce host-specific and host-neutral toxins that contribute to their pathogenic process to become a successful pathogen. Prior to colonisation, necrotrophs must kill host cells by producing both toxins and lytic enzymes, often by triggering genetically programmed apoplastic pathways or by directly damaging cells, leading to necrosis. *Alternaria brassicae* and *A. brassicicola*, pathogenic to cruciferous plants, produce a number of toxins and metabolites belonging

to chemical groups containing terpenoids, pyranones, steroids and nitrogen. The effect of toxins on plants at the physiological, biochemical and molecular levels has been studied. The role of toxins in the process of infection, their biosynthesis, mode of action, chemical structure, role in host defence and transformation into phytoalexins have been determined [77–83].

Thus, common cultural practices such as the use of healthy and treated seeds of recommended varieties, long rotation crop rotation (3–4 years), sanitation, weed control, shallow sowing (2 cm depth) with proper sowing dates, use of balanced mineral nutrition, proper plant density, proper field drainage, management of plant residues, and use of tolerant (resistant) varieties should be recommended; the use of chemicals (bioagents) at appropriate times with adequate leaf coverage should be recommended for the management of Alternaria diseases of cruciferous crops. That is, the most appropriate is the integration of all control strategies, namely: cultural, chemical, biological, nutrient, biotechnology and genetic engineering.

Several biochemical components were found to confer resistance to *A. brassicae* in rapeseed and mustard. Total sugars, reducing sugars, flavonol and chlorophyll were present in high amounts in healthy leaves, while total phenol, o-dihydroxyphenol, carotenoids and protein increased with increasing *A. brassicae* infection [84–86].

However, total sugar, total phenol and ortho-dihydroxyphenol were higher in chlorotic areas than in necrotic areas of infected leaves. The content of flavonol and chlorophyll was lower in different infected parts of the leaves than in healthy ones, and significantly lower in necrotic areas than in chlorotic areas. The activity of some oxidative enzymes, namely peroxidase (PO) and polyphenol oxidase, increased in B. juncea leaves after infection [87]. The total phenol content and specific activity of phenylalanine ammonia kinase (PAK) and tyrosine ammonia kinase (TAK) were higher in leaves and pod walls infected with Alternaria compared to healthy leaves, indicating their possible involvement in plant defence against the disease [88]. Transpiration in oilseed rape decreases after infection with Alternaria species [89].

Several sources of tolerance to Alternaria have been reported among different Brassica species, with *B. juncea* and *B. rapa* being more susceptible than *B. carinata* and *B. napus*. Disease-resistant lines in B. juncea include PAB-9511, PAB-9534, JMM-915, EC-399296, EC-399301, EC-399299, EC-399313, PHR-1, PHR-2, Divya, PR-8988, PR-9024 and RN-490;

in B. carinata – HC-1, PBC-9221 (Kiran), NRCDR-515 and DLSC-1; in B. napus – PBN-9501, PBN-9502, PBN-2001 and PBN-2002 [90–91]. Sources of resistance to *A. brassicae* were found in wild cabbage species, namely: *Brassica alba*, *Camelina sativa, Capsella bursa-pastoris, Eruca sativa, Neslia paniculata, Brassica desnottesii, Coincya pseuderucastrum, Diplotaxis berthautii, Diplotaxis catholica, Diplotaxis cretacea, Diplotaxis erucoides ma Erucastrum gallicum*.

To genetically increase the level of resistance, was proposed [92] breeding programme using the number and size of lesions to identify differential responses of different genotypes to *Alternaria blight*. Resistance to Alternaria blight of mustard oilseed rape is associated with factors such as phenolic compounds, namely polyphenol oxidase, PO, catalase in leaves, higher sugar and nitrogen content, lower in resistant species, or inhibiting conidial retention on the plant surface, e.g., high epicuticular wax deposits, which form a physical barrier in the form of a hydrophobic coating that reduces the deposition of aqueous seed and also reduces the rate of conidial germination and germ tube formation. *B. napus* (Tower, HNS-3), *B. carinata* (HC-2) and *B. alba* have more wax on the plant surface compared to *B. rapa* (BSH-1, YSPB-24) and *B. juncea* (RH-30). Two phytoalexins, namely camalexin and brassinin, and two isothiocyanates (ITC), namely allyl and benzyl ITC, were reported to have antifungal activity at different stages of development of Alternaria pathogens, namely A. brassicae and A. brassicicola of cruciferous plants [93].

It was found that wild cruciferous plants produce phytoalexins during inoculation. Activity of some compounds related to camalexin ($C_{11}H_8N_2S$) and 6-methoxycamalexin ($C_{12}H_{10}N_2SO$), turned out to be the most toxic for *A. brassicae*.

The phytotoxin destruxin B induces a phytoalexin response in *B. alba* [94]. reported that destruxin B is not a selective host toxin and does not induce the availability of host plants to *A. brassicae*. Resistance to A. brassicae is multilayered and multicomponent, with sensitivity to the host-specific toxin destructin B, quantitative and qualitative elimination of phytoalexins, hypersensitive response and Ca sequestration determining the fate of the host-pathogen interaction.

Resistant cruciferous cultivars also produce some metabolites, namely sesquiterpenes, deoxyuvedin B, albrasitriol, isoalbrasitriol and brassicadiol [95].

As resistance to Alternaria is regulated by additive or polygenes, breeding for resistance to these diseases may include pyramiding of minor genes, introgression of genes from material found to be resistant, reciprocal re-selection or diallel selective crossing, extensive hybridisation (*B. alba*), molecular selection (e.g. from *C. sativa* by somatic hybridisation; transgenic expressing the endochitinase gene of *Trichoderma harzianum*), pollen culture and destructin B sensitivity testing.

Although some studies on the mechanism of resistance to Alternaria have pointed to the influence of additive genes or polygenic or cluster genes, with resistance controlled by nuclear partial dominance genes, it has also been found that resistance components are highly correlated with each other in terms of slow disease development, and dominance plays a predominant role in the genetic control of the timing of resistance emergence. Additive × dominance prevails for other factors of disease progression, namely, the area under the disease progression curve [96].

Idiotypic (morphological) signs of resistance of cruciferous plants to Alternaria were also established. Thus, variations in the number and size of stomata in resistant and susceptible varieties were recorded – the number of stomata was maximum in the susceptible variety. Stomatal aperture was also narrower in resistant varieties compared to susceptible varieties (Table 4.6). Significantly lower number of stomata per unit area and smaller stomatal aperture are important morphological resistance factors in reducing infection of cruciferous genotypes *A. brassicae*.

The structure of wax in cruciferous plants and its role in pathogen resistance has been studied by a number of researchers [97–102]. In the Candle, Tobin and Altex rape varieties, the wax is organised into an amorphous layer overlying a crystalline layer. The crystalline layer consists of lamellar crystals and a layer of upright weeping and rod-shaped crystals (Figs. 4.3–4.5) [103].

Cruciferous wax is complex both structurally and chemically [105]. Cruciferous waxes have the same nine main components (alkanes, esters, ketones, aldehydes, secondary alcohols, ketones, primary alcohols, triterpenols and fatty acids), but in different proportions [106].

In *B. napus* ssp. *oleifera*, the main wax constituents are C 29 alkanes, C 29 ketone, C 29 secondary alcohol and C 40 -C 48 esters [107].

Table 4.6

Correlation coefficients (R) between different components of Alternaria resistance and yield of mustard (*B. juncea*) genotypes [104]

Disease components and yields	The size of the stain	Disease index	Leaf defoli-ation	Spore-bearing	AUDPC	Contami-nation	Productivity
Number of spots	0.883**	0.897**	0.812**	0.923**	0.956**	0.864**	–0.788*
Size of spots	–	0.985**	0.934**	0.982**	0.956**	0.893**	–0.668*
Disease index	–	–	0.905**	0.974**	0.949**	0.876**	–0.684*
Defoliation of leaves	–	–	–	0.952**	0.884**	0.743*	–0.625 NS
Sporulation	–	–	–	–	0.973**	0.851**	–0.679*
AUDPC	–	–	–	–	–	0.903**	–0.790*
Infection rate	–	–	–	–	–	–	–0.770*

* Significant at the 5% level; ** significant at the 1% level; ns – not significant.

In providing host resistance against Alternaria spp. the wax appears to be a physical barrier without any direct chemical effect.

The wax forms a hydrophobic coating and reduces the deposition of the aqueous seed. The wax also reduces the germination rate of the conidia and the number of germ tubes formed by each conidium. The crystalline wax layer is made fluffy by nested air pockets, which may be responsible for the above two effects by impeding the movement of plant exudates.

B. napus ssp. oleifera plants are very waxy compared to *B. rapa* ssp. *oleifera* plants, which are more susceptible to *A. brassicae*. Leaves of *B. napus* cultivars resistant to Alternaria have a significant amount of epicuticular wax [108]. According to [109–110], Alternaria-resistant genotypes have more wax on the leaves at different growth stages compared to susceptible genotypes. Gomez-Campo and Prakash (1999) [111] identified three different epicuticular wax columns in Brassica species with chromosome number (n) = 9: long columns, short columns and reticulate columns. *B. napus* and *B. carinata* inherited the reticulated wax type present in *B. oleracea*. It was observed that intraspecific crosses

between *B. napus* and *B. juncea* had a high content of epicuticular wax (Table 4.7, Figs. 4.4–4.5).

It is noted that mutation selection may be one of the possible methods of developing pathogen-resistant varieties in the absence of a useful donor of pathogen resistance in the existing germplasm of crops. Some *B. napus* plants resistant to *A. brassicicola* were regenerated from selected and unselected calli after mutation using gamma rays (physical) and ethyl methane sulfonate (chemical) mutagens [112].

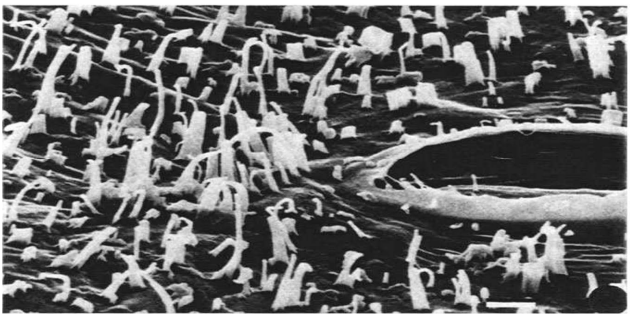

Figure 4.3 – Scanning electron micrograph of an air-dried, osmium vapour-fixed and gold-coated middle leaf of Brassica rapa, showing wax crystals (bar = 2 μm) [115]

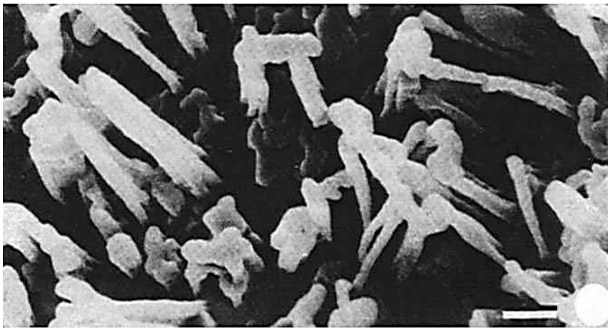

Figure 4.4 – Scanning electron micrograph of an air-dried, osmium vapour- and gold-coated Brassica rapa stem showing a gently sloping and vertical wax crystal (bar = 1 μm) [115]

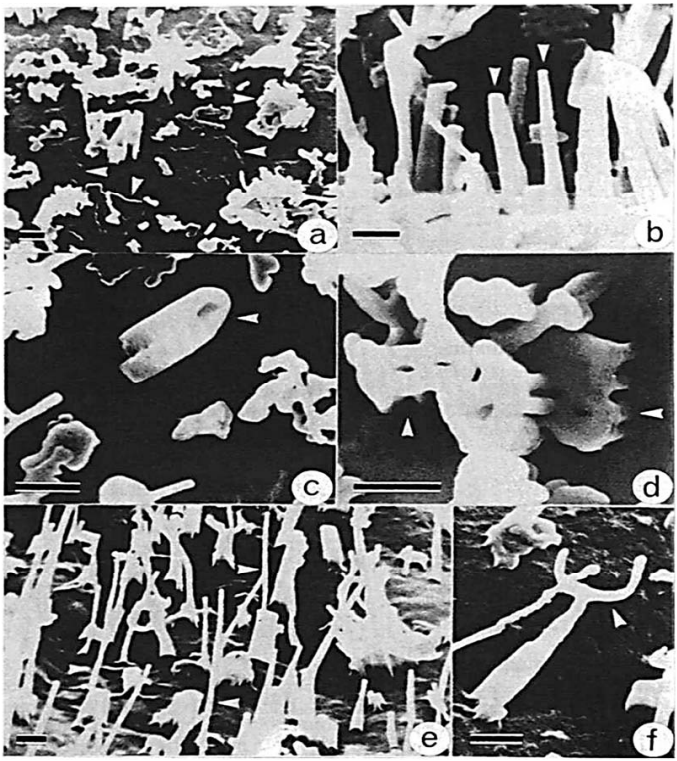

Figure 4.5 – (a) Adaxial surface of the upper leaf of Brassica napus cv. Altex, showing lamellar wax crystals (arrows); (b) stem surface of Altex from the middle of the plant, showing rods (arrows); (c) adaxial surface of the upper leaf of B. rapa cv. Tobin, showing fused rods (arrow); (d) adaxial surface of the upper leaf of *B. napus* cv. Westar, showing fused rods (arrows) and growth rings in wax crystals; (e) adaxial surface of the upper leaf showing small wax crystals (a); and (f) adaxial surface of the middle leaf showing a branched small wax crystal (arrow). The plant surfaces shown in Figures a-f were prepared for SEM by air drying (bar = 1 μm) [115]

Crop rotation is one of the easiest and most effective ways to control Alternaria in the field, as the main source of primary inoculum is infected plant residues in the soil. The minimum rotation duration is considered to be a three-year crop rotation with a non-cruciferous crop, which is necessary to avoid infection with a soil-borne pathogen [113–114].

For many producers, especially those with small acreages, it can be difficult to achieve a crop rotation in which host crops are adequately separated in both time and space due to the large number of host crops in the cruciferous family and their long overlapping growing seasons. In addition, studies of mortality of A. brassicicola and A. brassicae during overwintering have been conducted mainly in Europe, and it is possible that longer crop rotations may be required to break down lignin-rich stem tissue.

Cultural practices may also be important to minimise the secondary spread of the disease. Leaf and stem residues in the field containing infected plant parts can serve as a source of inoculum, as *A. brassicicola* and *A. brassicae* can continue to grow and reproduce as long as host tissue is present [116–117]. Therefore, it is important to manage crop residues in the piles, and cruciferous crops should be grown in fields that are as far away from these storage facilities as possible. Weed control is crucial in any system and can be an important component of an integrated approach to Alternaria management [118].

As mentioned earlier, fleas can transfer *A. brassicicola* spores from plant to plant within a field as well as from field to field, so controlling these insects can be an important part of an integrated disease management effort. Fleas are difficult to control and are a major limiting factor in organic production of vegetables and cabbage. They are controlled in these systems primarily by using floating covers to provide a physical barrier between the beetles and the plant leaves [119]. There are many insecticides available to conventional growers and those containing pyrethroids or carbamates that provide the best control, although fleas are still the main pest in cruciferous agrocenoses [120].

Biological control serves as the first line of defence against plant diseases in any production system, but in some cases it may be the only option available to reduce disease intensity in organic systems. Most biological control methods are aimed at reducing the amount of pathogen in the field, reducing plant-pathogen contact and creating an environment unfavourable

to disease development. Cultural practices that can be effective in reducing the damage caused by Alternaria leaf spot on cruciferous crops include the use of pathogen-free seeds, and maintaining crop rotations of at least three years, managing infected crop residues, reducing populations of quinoa weeds that can serve as alternative hosts, and controlling flea beetle (*Phyllotreta cruciferae*) populations as these insects can spread spores of the disease pathogen, *Alternaria brassicicola*.

Alternaria leaf blight spreads mainly through infected seeds and infected crop residues in the field. To prevent infection by soil-borne *A. brassicicola* spores, a three-year or longer crop rotation is recommended [121–122]. However, many farms, especially those with small areas, often find it difficult to maintain a crop rotation in which crops are adequately separated in time and space due to the large number of host crops of the Alternaria pathogen in the Brassicaceae family and their long growing season. Therefore, the use of mulch to create a physical barrier between the host plant tissue and overwintering *A. brassicicola* spores in the soil was investigated. Several mulch materials were tested to determine their effect on the growth of cruciferous crops from the perspective of alternaria infection. The management of Alternaria in organic systems depends on preventing the introduction of the pathogen into the field through infected seeds, as well as preventing infection of the crop by overwintering spores transported from the soil. Therefore, the hypothesis that mulch can reduce the incidence of Alternaria by creating a physical barrier between infected soil and susceptible plant tissues was tested. The effects of low-density film, Biotelo biodegradable plastic film and wheat straw on disease incidence and plant growth were measured and compared to the control without mulch [123].

All three mulches tested reduced the incidence of Alternaria, but only the straw mulch significantly reduced the incidence compared to the control without mulch. There may be several reasons for the differences in the effectiveness of the three mulch materials, but soil coverage at the base of the plants, leaf mulch breakdown during the growing season and surface moisture are likely to play an important role. In this regard, the physical barrier created by the straw mulch was probably much more complete than that of the plastic sheet mulch. In addition, sheet mulch can be torn or ripped by the user, animals or even the wind blowing over the field, creating more

exposed soil surface. This is especially true in the case of Biotelo mulch, which is quite fragile and was indeed torn during the mulch decomposition process and had many large tears by the end of the experiment. Incomplete soil coverage would likely have reduced the effectiveness of the mulch as a physical barrier to soil seed, and would have increased weed pressure, which would then have to be handled manually, which can be a time-consuming and therefore expensive task.

Another possible explanation for the difference in effectiveness between leaf and straw mulch is related to the moisture content of the soil surface. A. brassicicola spores can be spread across the field by wind, rain and rain splashes. Although conditions remained hot and dry for most of the growing season, temperatures dropped in September and October and rains became more frequent and heavy. During these wet periods, puddles of water could be seen on the surface of the LDPE mulch and Biotelo sheet mulch, while rainwater could seep through the straw mulch and no standing water accumulated on the soil surface. These puddles could have caused spores to be dispersed by spray or provided the free moisture and leaf moisture (sometimes low-hanging cabbage leaves were observed hanging in these puddles) needed for spores to germinate, cause infection and sporulation. It is possible that if a mechanical plastic layer had been used under the film to form raised beds, better soil-mulch contact would have been achieved (fewer air pockets that later became flooded areas) and water could have rolled off the film and been diverted away from the host crop. This was not done because the experimental plot was so small that randomisation of the mulch treatment would have been difficult to achieve with the tractor-mounted pile mulch spreading equipment.

Mulch can also serve as a soil barrier for the insect pest, the cruciferous flea beetle (*Phyllotreta cruciferae*). Adult flea beetles feed on the green tissue of host plants during the day and burrow under the soil at night [124]. Adult females lay their eggs in moist soil at the base of host plants, and when larvae emerge, they live in the soil where they feed on the roots of host plants until they pupate and become adults in about two to three weeks [125]. Although flea damage to plants was not measured in this study, plants in the control treatments had significantly more flea damage in the form of "through holes" than plants in the mulched treatments. Fleas may also be an important factor influencing the intensity of Alternaria outbreaks, as

these insects are able to physically carry A. brassicicola spores on their bodies and in their faeces, spreading the pathogen from plant to plant and field to field [126]. Thus, if mulch can reduce flea numbers in crops, it may also reduce the severity of Alternaria damage. There is also reason to believe that there may be differences in flea behaviour depending on the type of mulch, as it has been shown that *Phyllotreta pusilla* (western black flea) populations are affected by the colour and reflectivity of mulch [127]. Thus, this study demonstrated that mulch has the potential to reduce the incidence of Alternaria, possibly by reducing the initial infection of plants with overwintering *A. brassicicola* spores. Mulch also increased plant growth, and in a hot and dry year, straw mulch provided the greatest benefit to yield growth.

It is known that organic matter application causes changes in the density and composition of microbial communities, and thus can affect microbiologically mediated plant defence responses [128–131]. The biochar is the product of the thermal degradation of organic materials in the absence of air, a process known as pyrolysis, and is being studied extensively worldwide for its potential as an additive to soil organic matter to improve soil fertility, water and nutrient retention, and to sequester carbon and mitigate climate change. Although the biochar has been widely studied in agronomic settings, little is known about its impact on plant diseases. Several recent studies have reported that biosolids have been successfully used to reduce disease incidence in controlled environments and microplots, and while several mechanisms are likely responsible for the observed disease suppression, induced systemic resistance has been documented in several pathosystems [132–136]. Greenhouse study by Elad et al. in 2010 [137], showed a significant reduction in the intensity of the development of diseases caused by the pathogens Botrytis cinerea grey rot and powdery mildew Leveillula taurica on peppers and tomatoes when applying a biochar from citrus wood in concentrations of 3 and 5% to coconut fibre.

In a similar greenhouse study conducted by Harel et al. (2012) [138], A significant reduction in the severity of diseases caused by three strawberry leaf diseases (*Botrytis cinerea*, *Colletotrichum acutatum* and *Podosphaera apahanis*) was found when plants were grown in a medium with 3% (w/w) biochar. In addition, such "biochar", which is produced by burning plant or animal materials, is approved by the Organic Materials Review Institute and

is listed as a certified organic product for use as a soil fertiliser. Therefore, we investigated [139] The impact of biofuels on the severity of leaf spot by Alternaria. Biochar produced from lodgepole pine chips was used in greenhouse and field studies to investigate the sustainable management of Alternaria leaf spot in cruciferous vegetable crops. A detailed chemical analysis was carried out to determine the elemental composition and relevant physical and biochemical parameters of the biochar used in the greenhouse and field studies. The results showed a significant reduction in the prevalence of Alternaria and the degree of damage even under favourable conditions of pathogen development.

Treatment of seeds with hot water reduces the growth of Alternaria. However, the spores of these fungi can survive on leaf tissue for 8–12 weeks, and on stem tissue – up to 23 weeks. Therefore, in fields that are reseeded shortly after harvest, a large amount of seed is often available for rape-mustard disease, which is likely to affect the emergence of crop seedlings and early stages of growth. Thus, crop rotation with non-cruciferous crops and the eradication of cruciferous weeds can help control these pathogens.

Early sowing of well-preserved, clean, certified seeds after deep ploughing with 45 cm row spacing, deep tillage, timely weeding and maintaining an optimal plant population, avoiding irrigation during flowering and pod formation stages can help control the disease [140]. Sowing of seeds should not be carried out by the method of spreading, as this increases the intensity of the disease, which can be reduced on leaves and pods by applying 40 kg K/ha together with the recommended dose of nitrogen (N) or sulphur (40 kg/ha), or together with the recommended dose of NPK [141]. However, higher doses of N make crops more susceptible to disease. Soil application of K as the main fertiliser has been found to control mustard Alternaria disease. Sulphur, zinc and boron have been reported to reduce Alternaria development and increase mustard seed yields. The use of some trace elements, viz: B at a concentration of 1 g/l, Mo at a concentration of 1 g/l, S at a concentration of 2 g/l and Zn at a concentration of 2 g/l, in various combinations reduced Alternaria development and increased the yield of rapeseed and mustard.

Inorganic fertilisers, namely phosphorus (P) and potassium (K), also reduce the incidence, while higher rates of nitrogen increase it [142]. This is important at a time when growers are reporting an increase in the prevalence

of Alternaria and a decrease in control. The GR isolate of Trichoderma viride was on a par with manococcus in terms of efficacy when testing the intensity of damage to mustard leaves and pods. The conidial suspension of T. viride was more effective than the culture filtrate in reducing the intensity of the disease on leaves and pods [143].

The strain of *Bacillus subtilis* UK-9 isolated from reclaimed soil caused morphological changes in vegetative cells and spores by destroying and lysing the pathogen cell wall, which led to a decrease in the intensity of disease development and spore germination on leaves [144].

Treatment of seeds with bioagents led to an increase in the content of lipids (phospholipids, glycolipids and sterols) and proteins in the seeds of treated plants. However, seed treatment and foliar spraying of white mustard leaves with bioagents increased the content of dry matter, total phenol, orthohydroxyphenols, starch, total soluble sugars, reducing sugars total lipids and various membrane lipids in the leaves, but the total protein content decreased after treatment with biocontrol agents at 30 and 60 days after germination, which may be due to protective mechanisms and enhanced plant growth [145]. Extracts of several plants were evaluated against *A. brassicae* [146]. The level of effectiveness of *Azadirachta indica* extract increases with the number of sprayings [147]. Spraying of garlic bulbs and neem leaf extract at the flowering stage suppressed disease incidence and increased mustard yield [148]. Foliar spraying with *Calotropis procera* leaf extract, *A. indica* kernel and *A. sativum* bulbs can induce resistance against *A. brassicae* by increasing the content of soluble phenol, sugar and soluble proteins, namely polyphenol oxidase in mustard leaves [149]. Among the several essential oils evaluated, peppermint oil (*Mentha piperita*) provided complete inhibition of fungal growth at 2000 µg/ml, followed by cyperus oil (*Cyperus scariosus*).

Essential oil from radish roots (at a concentration of 1:2500) inhibits *A brassicae* [150]. Deproteinised leaf extracts *Acacia nilotica*, *Enicostema hyssopifolium*, *Mimosa hamata* and *Vitis vinifera* showed fungistatic activity against *A. brassicicola* [151]. Extracts obtained from the leaves *Lawsonia alba*, root of *Datura stramonium* and *Mentha piperita* inflorescences, have fungitoxic activity against *A brassicae* isolated from cabbage leaves. Extracts of the ferns *Adiantum caudatum*, *Diplazium esculentum* and *Pteris vittata* reduce the growth and germination of *A. brassicicola* [152–153].

The plant extracts of roots, leaves, stems, inflorescences and fruits of several species (Table 4.7) showed fungicidal activity in vitro and in vivo against the two main Alternaria species, namely *A. brassicae* and *A. brassicicola*, which cause Alternaria or black spot of cruciferous vegetables. In vitro, almost all plant extracts limit mycelial growth, sporulation and conidial germination. Some have shown efficacy in the field, limiting infection points, spot size and disease intensity.

Table 4.7

Plant extracts used against A lternaria spp. on cruciferous plants [154]

Plant species	Concentration (%)	Sources of the study
Acacia nilotica	–	[154]
Encostema hyssopifolium		
Mimosa hamata	–	
Vitis vinifera	–	
Datura stramonium	–	
Lawsonia alba	–	[155]
Mentha piperita	_	
Adiantum caudatum	–	[156]
Diplazium esculentum	–	
Pteris vittata	–	
Allium sativum	5	[154]
Azadirachta indica	10	[157]
Lawsonia inermis	5	[158]
Erythrina chiaposana	5	
Ricinus communis	5	
Zingiber offi cinale	5	
Euphobia pulchrima	5	[154]
Rumax dentatus	5	
Urtica dioica	5	
Eucalyptus globules	5	
Ocimum sanctum	5	[159]
Anagallis arvensis	5	
Solanum nigrum	5	
Rhus chinensis	–	[160]
Polygonum perfoliatum	1	
Agave americana	1	[161]
Solanum xanthocarpum	1	[162]
Lavandula pubescens, Calotropis procera	10	[163–164]

Eucalyptus spray gave significantly fewer spots per leaf (2.05), minimum spot size (1.28 mm), minimum spore intensity (1.22 x 105) and minimum disease index, followed by calotropis, ocimum and polyanthea extracts at 5% [165].

Mustard Alternaria can be controlled by spraying aqueous extracts of *Azadirachta indica*, *Allium sativum* and *Zingiber officinale* at concentrations of 5, 10, 15 and 20 %, which leads to higher yields. However, spraying with 15% *A. indica* extract gave the highest yield with the best cost-benefit ratio [166].

While, according to the [167–168], the use of *Allium sativum* onion extract in concentrations of 45 and 75 p.p. gave the highest yield of cruciferous seeds. *Allium sativum* extract is also the most effective in the fight against mustard fungi, which are transmitted with seeds [169].

Saprophytic phylloplanktonic fungi such as *Aureobasidium pullulans* and *Epicoccum nigru*m are pathogenic to *A. brassicicola*.

Verticillium state of Nectria inventa Pethybridge, a destructive myco-parasite, is one of the dominant phylloplane fungi of rapeseed seeds [170].

Among the leaf surface mycorrhizal fungi, the most antagonistic are *E. purpurascens*, *A. pullulans* and *Cladosporium cladosporioides* in the case of *A. brassicae*. The metabolites of Acremonium roseogriseum, *Aspergillus terreus* and *C. cladosporioides* inhibit *A. brassicae*. The most significant effects are observed when spraying with spores of surface fungi and their metabolites before inoculation of the pathogen on the leaves [171].

Pre-application of Streptomyces rochei spore suspension or its diffusate leads to a significant decrease in the intensity of *A. brassicae* and *A. brassicicola* leaf damage on *B. rapa* [172–173].

Jayant and Sinha (1981) reported that *S. hygroscopicus* is a strong antagonist of *A. brassicae* and *A. brassicicola*. When spraying the culture filtrate a week before or a week after spraying with a suspension of *A. brassicae* and *A. brassicicola* spores, germination and development of diseases are reduced.

The pigmented and xylose-utilising strain of *S. bobili* was found to be active against *A. brassicae*, *A. brassicicola* and *A. raphani* [174].

An isolate of Streptomyces spp. obtained from light *Finnish sphagnum* garden peat proved to be an effective biological agent for controlling plant pathogens [175].

Treatment of cauliflower seeds with isolates of *Trichoderma viride* and Streptomyces spp. inhibits or reduces desiccation caused by *A. brassicicola* [176–177].

Seed treatment with mycostop, a powdered preparation made from streptomycete spores and mycelium, was successful in controlling the drying out (80–90%) of seeds artificially infected with *A. brassicicola*. The seed treatment remains effective on seeds stored in dry conditions for 5-6 weeks, but its effectiveness slowly decreases thereafter. Streptomycetes treatment controls, as well as chemical thiram treatment, the prevention of desiccation caused by Alternaria fungi in seedlings grown from commercial seed lots of different origin [178].

It is reported [179], that Patostop, a biofungicide based on a selected isolate of S. griseoviridis from Finnish sphagnum peat, applied either by seed or soil treatment, controls *A. brassicae*.

Cruciferous seeds treated with Gliocladium virens-19, Trichoderma harzianum-22, T. harzianum-50, Penicillium corylophilum-36 and P oxalicum-76 gave a significantly higher yield of healthy seedlings. The hyphae of antagonist fungi were able to adhere to conidia or wrap around or penetrate germ tubes or hyphae.

It was found that *A. brassicicola* conidia shrivelled and plasmolysed in the presence of antagonistic fungi [180]. For the biological control of *A. raphani* and *A. brassicicola* of radish, which are transmitted by seeds, antagonists such as *Chaetomium globosum*, *T. harzianum*, *T. koningii* and Fusarium spp [181].

Wu i Lu (1984) Trichoderma, Gliocladium and Penicillium spp. were found to be parasitic on *A. brassicicola*. The use of *A. alternata* before inoculation with A. brassicae reduced the level of A. brassicae on rape by about 60 %, and after inoculation – by about 26% [182].

Spraying with *T. viride* conidial susceptibility inoculum reduces the damage to mustard by Alternaria on leaves (76%) and pods (68%), respectively. Bioagents survive on the leaves for up to 30 days at a relative humidity of 80–90% and a temperature of 20–35 °C [183]. У Польщі повідомлено про *Gonatobotrys simplex* як гіперпаразита *A. brassicae*.

Excellent control of *A. brassicae* in white cabbage and cauliflower seeds was obtained in Danish experiments by immersing them in water heated to 45 °C for 30 minutes, or for 20 minutes at 50 °C, or even 30 minutes at

40 °C. This treatment improves germination by up to 13% and also kills other fungi such as Penicillium and Mucor spp [184]. Treating seeds with hot water at 50 °C for 30 minutes controls cabbage diseases [185].

According to [186] treatment with hot water for 25 minutes at 50°C eliminates Alternaria infection from legume seeds. Treatment of seeds at 50 °C for 20 minutes is highly effective in controlling seed-borne fungi, including *A. brassicae* (B. juncea), without any significant effect on seed germination [187].

One of the most effective measures to control the disease caused by Alternaria is the effective use of fungicides.

Seed treatment is an effective measure in the control of Alternaria because it helps to reduce the number of primary inocula. Seed treatment with hot water at 50°C for 30 minutes to control Alternaria was recommended by Walker, while Ellis recommended the same temperature for 25 minutes to eliminate Alternaria infection from cabbage seeds. Seed treatment with thiram plus kaptan (1:1) 0,3% and four sprays with zineb (0,25%) proved to be quite effective in controlling the disease [188].

Chemical plant protection is known to be an integral part of integrated crop protection systems against pests. Winter rape seeds are a source of infection for many pathogens, including Alternaria and Fusarium, so seed treatment is an important element of preparing them for sowing. The treatment helps protect seeds and seedlings from damage in the early stages of plant ontogeny, which is the basis for healthy and friendly seedlings. The results of the phytosanitary examination of winter rape seeds indicate that the annual infection rate of fungi from the Alternaria genus ranges from 3 to 100% and Fusarium from 1.0 to 26.0%.

Infected seeds are the other main source of primary seed, and therefore the use of clean seeds and transplants is important to prevent the introduction of *A. brassicicola* and *A. brassicae* into clean fields. Treatment with hot water for 18 minutes at 50 °C resulted in a 98% reduction in disease incidence, but this method may be less effective in the presence of significant internal infection and seeds may lose viability. Hot water treatment is the only method currently available for seed disinfection in organic crop production systems.

In conventional systems, seeds can be treated with surface-active fungicides, but the best control is achieved with the locally applied fungicide

iprodione, which can also be absorbed by seed tissue to levels sufficient to kill established cotyledon infections, although further movement or toxicity is limited. Iprodione has been used for seed treatment since at least the 1970s and continues to be the main tool for controlling Alternaria worldwide [189]. Some biological control methods are known, especially in the form of seed inoculation, as discussed earlier. The effectiveness of several microbes isolated from broccoli seeds or from the rhizosphere of broccoli seedlings in reducing the incidence of seed blight has been investigated. The authors found that *Gliocladium roseum* and *Trichoderma harzianum* were effective in reducing seed infection, increasing germination and reducing leaf infection by *A. brassicicola*. An early study on the treatment of cabbage seeds infected with *A. brassicicola* with seed-borne antagonists showed that Periconia sp., Pencillium sp. and *Chaetomium globosum* strain Kunze increased the emergence of healthy seedlings equivalent to iprodione [190].

Although there is a great deal of interest in biocontrol during the seed stage of A. brassicicola and A. brassicae, very little is known about the effect of biocontrol organisms on the developmental stage of the pathogen on leaves. One study demonstrated the potential protection of rapeseed (*B. napus*) leaves against *A. brassicae* by seed treatment with *Bacillus amyloliquefaciens*, indicating that the induction of plant defence responses [191].

Induction of systemic defence reactions of plants by Trichoderma spp. was associated with the protection of tomatoes from *Alternaria solani*, which causes early blight of this crop [192], and may be useful for *A. brassicicola* research.

There are a number of biological control agents that are registered for foliar use in organic production and listed as control agents, but the effectiveness of these products in reducing disease intensity is not known and this area needs more attention in the future.

The strong cross incompatibility, polygenic background of resistance (additive and dominant gene interactions), and differences in ploidy between cruciferous species of interest make it difficult to transfer resistance to Alternaria from wild species to cultivars. In addition, this often involves the use of in vitro hybridisation techniques, including somatic hybridisation, embryo and ovary preservation or protoplast fusion of cruciferous species,

as the transgenic approach has been unsuccessful. Thanks to our growing understanding of pathogen-host interactions, identification of sources of resistance and evaluation of resistance trait inheritance, cruciferous crop breeding programmes for alternaria resistance mode of inheritance can be improved.

This is of particular importance, as in recent years there has been a dynamic development of ecological and integrated crop production with an emphasis on plant resistance to biotic stresses. highly resistant genetic resources have been reported among cultivated cruciferous species, although some varieties differ in terms of resistance and susceptibility.

This means a significant economic impact of the disease: In 2020, Polish production of cabbage and other cabbage crops ranked 7th, and cauliflower and broccoli 8th in the world (1141200 tonnes and 252325 tonnes, respectively) with a net production value of USD 171 million and USD 60,5 million, respectively (FAOSTAT: http://faostat.fao.org). Methods of preventing and controlling Alternaria include a combination of good agricultural practices and chemical protection. An important method of disease prevention is the production of healthy seeds obtained from crops with intensive fungicide protection. In a 2-year period of cruciferous seed production, fungicides containing iprodione as an active ingredient had a good effect of protection against Alternaria infections during the 1st year of growth [193]. In Poland, the only product containing it is the T 75DS WS Seed Treatment (Zaprawa Nasienna). As both pathogens survive on crop residues, seeds and in association with weeds[752], Crop residue management (e.g. through crop rotation and deep tillage), as well as the use of clean seeds and good weed control should reduce the disease. Once symptoms appear, infection can be limited by repeated spraying with fungicides containing strobilurins as active ingredients (Amistar 250 SC, Signum 33 WG, Zato 50 WG) and iprodione-based fungicides (Rovral FLO 255 SC) [194]. This method, however, is not economically viable and may not be effective under favourable weather conditions, especially on seed crops that favour the spread of pathogenic infection. An alternative method of protection is the use of antagonist fungi; the deployment of *Aureobasidium pullulans* and Epicoccum nigrum on cruciferous leaves reduced infection rates under controlled conditions [195].

It is noted that chemical control of Alternaria on seeds and in the field remains the most common method of controlling this disease worldwide.

Chlorothalonil, a broad-spectrum fungicide with multiple sites of action, has also been widely used as a foliar spray to control Alternaria [196], and there are several new fungicides that have become widely used. The most important of these new fungicides is azoxystrobin, a quinone external inhibitor with a very specific mode of action that exerts very high selection pressure on resistant isolates in pathogen populations.

At the same time, resistance of *A. brassicicola* to several major fungicides has been reported elsewhere and in other plant pathogenic Alternaria spp [197-198]. Field isolates of *A. brassicicola* with resistance to iprodione, the most widely used chemical for controlling late blight, were first identified in the mid-2000s. Cross-resistance to both dicarboximides (including iprodione) and phenylpyrrols was also present in these populations. Resistance to azoxystrobin has not been demonstrated for A. brassicicola or A. brassicae, but its development in other Alternaria species (as well as in many other plant pathogenic fungi) indicates that resistance management procedures should be carefully followed.

Research into the biological control of seed infection includes the use of antagonistic fungi and bacteria, most commonly *Nectria inventa* spp., *Trichoderma* spp., *Gliocladium* spp., *Penicillium* spp., *Periconia* spp., *Chaetomium globosum* i *Streptomyces griseoviridis* [199–200]. Although many of these biological control agents have been shown to be capable of controlling disease incidence, none of those studied to date have been as effective in controlling internal seed infections as fungicides. Many biological control antagonists also have less protective effect in the field due to narrow growth requirements or weak competition in the rhizosphere, and as a result, fungicides are still the most widely used control method worldwide.

Some studies have found that [201–202], that pre-sowing treatment of seeds with Protect, CS (3,5 l/t); Kruiser Rapeseed, SC (11.0 and 15.0 l/t); Modesto Plus, CS, (16.0 l/t) and Agrovital Plus, CS, (5.0 l/t) contributed to a reduction in seed infection by 84,5–100%, an increase in laboratory germination by 15.2–19.3%, field germination by 6,2–7,6% and inhibition of Alternaria development on leaves by 35.0–82.0%. On pods, the effect of the treatments on reducing the development of Alternaria ranged from 3.3 to 36.6%.

During the years of research [203] Kruiser Rapeseed, SC at a consumption rate of 1,5 l/t provided high laboratory germination rate of

92.0–99.0% and field germination rate of 72.7–75.0% compared to other treatments. Also in this variant, the effect of restraining the development of Alternaria on pods was noted – 14.7–36.6 %, which resulted in saving 3.3–6.2 centner/ha of yield. In general, seed treatment made it possible to save from 1.3 to 8.2 centner centner/ha, depending on the preparation and the year of research.

Studies have shown that the duration of the protective effect of seed treatment in inhibiting the development of Alternaria is limited. Therefore, to protect the crop in the second half of the growing season, fungicides are required. Out of 43 fungicides approved in different countries for use on winter rape, 32 products, or 74.0%, are 2-component.

The choice of preparations is determined by the active substances most often used to protect rapeseed from diseases – Mirador Forte, CE (azoxystrobin, 60 g/l + tebuconazole, 100 g/l) – 2,0 l/t and Custodia, KS (azoxystrobin, 120 g/l + tebuconazole, 200 g/l) – 1,2 l/t.

It is noted that long-term studies of the dynamics of the disease development indicate a variation in the degree of leaf damage within 1.2–16.2%, which led to the preservation and accumulation of infection to affect the pods. The surveys showed that the development of Alternaria on pods increases with the degree of leaf damage. It has been established that repeated use of the same products can lead to a decrease in the effectiveness of fungicides due to the emergence of highly resistant forms of pathogens in the population.

In the absence of resistant varieties, fungicides are the most reliable means of disease control [204]. In order to achieve economic yields and acceptable quality on infected crops, multiple applications of fungicides are required. Thus, Khan et al. in his research, he used the systemic fungicides Thiophanate methyl, Ridomil MZ (Mancozeb, 64% + Metalaxyl, 8%) and Carbendazim separately and in combination with four non-systemic fungicides Kaptan, Mancozeb, Zineb and Tiram at a rate of 0.2% a.i. in the field. Ridomil MZ was the most effective, followed by the combination of Carbendazim + Kaptan.

Reported [205], that three consecutive sprays of Mancozeb resulted in maximum control of leaf blight intensity, followed by two consecutive sprays of Mancozeb (0.2%) and the third spray of Rodomil MZ (0.25%). Foliar spraying with Mancozeb proved to be the most effective in controlling the disease [206–207].

It is effective to supplement fungicides with plant extracts to control Alternaria. The use of various plant extracts and natural products is encouraged as they do not pose a health hazard and do not pollute the environment. Extracts *Canna indica, Convolvulus arvensis, Ipomoea palmata, Cenchrus catharticus, Mentha piperita, Prosopsis spicigera, Allium cepa, A. sativum, Lawsonia inermis, Argemone mexicana, Datura stramonium* і *Clerodendron inerme* completely suppressed the germination of *A. brassicae* spores isolated from cauliflower leaves [208].

The use of eucalyptus leaf extracts significantly reduced the number of leaf spots, the minimum spot size, the minimum disease index and the highest yield, followed by spraying with calotropis, ocimum and polyanthesis extracts [209]. Foliar spraying with aqueous extracts of *Allium sativum* (garlic) and Eucalyptus globulus (eucalyptus) has been reported to be effective in controlling Alternaria on leaves and pods and may be an environmentally safe substitute for the chemical fungicide mancozeb in the control of mustard diseases [210].

Some research results indicate the possibility of biological control of Alternaria. Foliar application of *T. harzianum* and *P. fluorescens* isolates proved to be effective in controlling Alternaria [211].

Resistance of susceptible mustard cultivar PR-15 to highly and moderately virulent isolates of *A. brassicae* was induced using an avirulent isolate of A. brassicae. The induction of resistance by an avirulent isolate against a highly virulent and moderately virulent isolate of *A. brassicae* resulted in a significant reduction in disease severity.

Due to increased awareness of the risks associated with fungicide use, considerable attention is being paid to an integrated approach to pathogen management. Burning the previous year's crop residues, timely sowing, using healthy certified seeds, timely weeding, using balanced doses of nutrients, maintaining optimal plant numbers, and avoiding irrigation at sensitive stages of crop development (45 and 75 days after germination) can help minimise the incidence. Potassium application at a dose of 40 kg/ha [212–213], as well as the addition of minerals such as sulphur, borax, potassium and zinc to the soil have proven to be effective in the fight against mustard Alternaria. These minerals were found to increase plant resistance.

The disease was also found to develop at a minimum degree at a row spacing of 45 cm compared to the spread seeding method and in early crops with low weed levels.

Spraying with iprodione was effective in controlling the infection on pods caused by A. brassicae. Both a reduction in disease incidence and an increase in seed yield and weight were observed with the use of iprodione [214], and its residues in edible parts of plants were lower than the maximum residue level, which indicated the safety of this fungicide at the recommended rate. A higher number (3–4) of sprays with iprodione had a significant reduction effect on the number of spots on siliques. Currently, there is a need for new fungicide molecules to control this pathogen, given their fungicide resistance (Table 2.24). Mycelial growth, conidial germination and germ tube elongation revealed the existence of A. brassicicola isolates with high resistance (EC_{50} > 100 mg/l) to both dicarboxymides (e.g. iprodione and procyamidone) and phenylpyrroles (e.g. fludioxonil).

The use of fungicides on seeds reduced the content of two Alternaria toxins, namely Alternaria and Alternaria methyl ester [215]. Two consecutive foliar sprays with Mancozeb 75 WP (0.2%) followed by spraying with metalaxyl + Mancozeb (Ridomil MZ 72: 0.25%) provided high seed yield and 1000 seed weight [216].

Tiram (75%) was the most effective fungicide at 5000 ppm, while complete suppression of Alternaria was observed at 10.000 ppm in the case of Tiram (TMTD 80%) and Arasan 50% [217]. All fungicides showed significant efficacy in reducing disease severity and increasing seed yields. The time of the first spray, interval and number of sprays depended on the type of crop.

On *B. rapa* and *B. juncea* crops in India, significant disease control was achieved if the first spray was applied 60–75 days after sowing; 2–4 more sprays at 10–15 days intervals, depending on crop maturity, increased control [218–220].

It should also be noted that the literature contains information on the low fungicidal effect of azoxystrobin against fungi of the genus Alternaria, on the other hand, high efficiency is noted when it is used in field experiments. In this regard, studies were conducted to investigate the population structure of Alternaria spp. fungi isolated from leaves and pods of winter rape plants. The analyses showed that 32.8% of the fungal isolates on the leaves were *A. brassicicola*, 35.9% – *A. tenuissima*, 9,4% – *A. alternata*, 21.9% –

A. arborescens, and the share of *A. brassicicola* on the affected pods was 25,0%, *A. tenuissima* – 50.0%, *A. alternata* – 0.0% and *A. arborescens* – 25.0%.

To determine the susceptibility of Alternaria spp. fungi, a drug screening was performed. The fungi *A. alternata, A. tenuissima, A. brassicicola, A. arborescens* were included as test objects. It was found that [221], that the Alternaria spp. fungal population is heterogeneous in terms of susceptibility of isolates to fungicide active ingredients when evaluated in vitro. High susceptibility was observed to tebucanazole (EC_{50} less than 10 μg/ml) in *A. alternata, A. tenuissima* and *A. brassicicola*, and to azoxystrobin in *A. arborescens* and *A. brassicicola*. In the populations of these fungi, there are also isolates with medium sensitivity (EC_{50} from 10,1 to 40 μg/ml) and resistant, 60.0% of isolates of *A. alternata*, 10.0% of *A. tenuissima* and 20.0% of *A. brassicicola* to azoxysitrobin, and 10.0% of *A. arborescens* to tebucanazole. Therefore, in the case of dominance of *A. brassicicola* fungus on the leaves, the pathogenicity of which is 100%, the effectiveness of fungicides can be high, since 80.0% of isolates are sensitive to azoxystrobin and 90.0% to tebucanazole.

In the years of moderate and depressed development of Alternaria in field experiments [222] the effectiveness of Custodia, KS is higher in protecting the leaf than Mirador Forte, CE, while the effectiveness of pods is higher than Mirador Forte, CE. During the years of epiphytic development of the disease on leaves and pods, the effectiveness of the preparations is relatively the same, but in the protection of the leaf apparatus is higher – 83.7 and 80.8%, than in the protection of pods – 46.7–38.9%, which is due not only to the timing of the use of fungicides against Alternaria, but also to the structure of the fungi of the pathogenic complex. Fungicides were applied at the threshold of disease development, in these variants, 1.8–6.2 centner/ha were saved. Evaluation of the effectiveness of fungicides against Alternaria has been studied quite intensively and is still being studied in Ukraine. Thus, studies to determine the effectiveness of the use of disinfectants and fungicides for spraying during the growing season were conducted at the Agronomic Research Station of NUBIP of Ukraine, the Research Centre 'Experimental Field' of Lviv National Agrarian University and the experimental field of Bila Tserkva National Agrarian University [223] (Table 4.9–4.11).

The range of oilseed rape protectants includes 12 products, of which 6 are two-component, 5 are three-component and 1 is one-component.

The effectiveness of Cruiser OSR 322 FS t.c.s. (15 l/t), TMTD c.c.s. (5 kg/t), Vitavax 200 FF c.c.s. (Z kg/t), Maxim XL 035 FS t.c.s. (5 l/t) and the biological preparation Phytodoctor – Bacillus subtilis bacterium (2 g/kg) was studied on the Siesta F1 hybrid. All the studied preparations reduced the spread and development of Alternaria compared to the control variant (without treatment) (Table 4.9), but did not affect the yield of the variants.

The effectiveness of the use of fungicides Tilmor c.e. (0.6 l/ha), Faraday v.g. (0.5 kg/ha), and Pictor c.s. (0.5 l/ha) alone and with pre-treatment with the growth-regulating preparation Karamba v.r. (1 l/ha) was investigated. The survey carried out in the phase of economic ripeness of rapeseed showed that the spread of the disease in the variant without the use of fungicides in the conditions of Lviv region reached 90.3%, its development – 54.3%. Spraying the plants with the studied preparations made it possible to reduce these indicators to 45.7–50.3% of the disease spread and 10,6–21,6% of the disease development and provided an increase in the yield of fungicide-treated varieties from 0.27 to 0.42 t/ha.

Karamba is both a fungicide and a rapeseed growth regulator. Its regulatory effect is to strengthen the root system, increase branching, uniformity of flowering, stronger and shorter stems. In production, it is recommended to use the following spring rape protection system, which involves treatment with Karamba at a plant height of 20–25 cm and with Pictor fungicide during flowering.

This treatment scheme provided the most effective protection of plants – the development of the disease was 10.6% with 45.7% prevalence. Treatment with Pictor without preliminary application of Karamba was less effective – the development of Alternaria reached 12.7%, and the spread was 48.0%. The ability of plants to resist alternaria after spraying with Tilmore and Faraday was slightly lower compared to Karamba and Pictor, and significantly higher compared to the control variant (Table 4.11).

Based on the research, the authors concluded that varieties with high resistance to Alternaria can reduce the number of fungicide treatments, which helps to obtain environmentally friendly products. These varieties can be used in further breeding work as donors of resistance to Alternaria pathogen. At the same time, the use of plant protection products and growth regulators significantly reduces yield losses in the face of high infection rates and favourable conditions for the disease.

Table 4.8

Chemicals and fungicides tested against Alternaria species on cruciferous plant species [224]

Acetone	Phenyl acetate	
Actidion	Ferbam	Silite
Agrosan	Fermat	Tebuconazole
Alar	Folicur (tebuconazole)	Tetrahydropyrimidine
Anthracol	Folpet	Thiabendazole
Arasan	Flutriafol	Thiophanate-methyl
Azoxystrobin (Amistar)	Formaldehyde	Tiovit
Azadirachtin (Nimarin)	Granosan	Tiram
Baffin	Guazatin	Tilex
BAS 480 F	Halogen derivatives	Topsin M
Baykor	Imazalil	Triademephon
Bayleton	Indophyll M-45	Triapentanol
Bavistin	Indophyll Z-78	Triarymol
Benlate	Iprodion (Rovral)	Tri-basic copper sulphate
Benz (1,2) isoxadoles	White urea	Trisonic copper salts
Biokvin	Kavach	Tridemorph
Blitox	Lunasan	Trifloxystrobin
Bordeaux liquid	Malic acid	Trimiltox forte
Boric acid	Mancoceb	Vinclosoline (Ronilan)
Boscalid	Maneb	Water-soluble sulphur
Brassicol	Manzate	Zato 50 WG
Brestan	Merpan	Zincop
Bromosan	Metalaxyl	Cineb
Calixin	Metiram	Zinc sulphate
Kaptaf	Miltox	Ziram
Kaptafol	4-Nitrosopyrazole	Antibiotics
Kaptan	Nurimol	Griseofulvin
Carbendazim	Ozone	Mycostatin
Carboxyne (Vitavax)	Panogen	Mycotricin
Chlorothalonil (Daconil)	Penconazole (Topaz)	Polyoxine B and D
Copper oxychloride (Blitox)	Pentachlorophenol	Kipermethrin
Copper sulphate	Phygon	Deltamethrin
Kuman L	P-Methoxytetrachlorophenol	Dimecron
Cupravite	Profloraz	Fenvalerate
Copper acetate	Propiconazole	Flucitrinate
Cuprox	Propineb	Methoxytox
Cyclohexamide	Pyraclostrobin	Methyldemethon
Delan C	Pyrene compounds	Permethrin
Dichlorofuanide	z-Cunolate	Phosphomedon
Diphosphonates	Cunon	Rogar
Difenoconazole (Skor)	Ridomil MC	Humates
Dithane D-14	Ronilan	N, P, K, Ca, Cacl2
Dithane M-45 (Mancozeb)	Semesan	CuSO4, CO(NO3)2, Fe EDTA,
Dithane Z-78	Signum 334WG	Mn SO4, Na2 BO7, Zn SO4
Duter	Sistan	Thiourea
Edifenofos	Sodium fluoride	Borax
Euparen	Spergon	S, SO2
Fenarimol	C-triazine	Zn
Fenpropimorph	Sumilex (Procimidone)	

Table 4.9

Spread and development of Alternaria in spring oilseed rape variety Siesta F_1 under the use of seed treatment [223]

Варіант	LNAU				BNAU			
	Prevalence, %		Development, %		Prevalence, %		Development, %	
	Phase outlets	Ripeness	Phase outlets	Ripeness	Phase outlets	Ripeness	Phase outlets	Ripeness
Without dressing	4.7	90.5	1.1	19.8	4.3	77.5	0.8	15.4
Cruiser OSR 322 FS, hp	4.1	90.2	0.9	20.2	2.7	75.9	0.5	15.2
TMTD, in.s.c.	4.3	90.8	0.9	20.1	2.9	75.7	0.5	15.1
Vitavax 200 FF, b.s.c.	3.7	89.7	0.8	18.6	3.3	76.5	0.6	15.3
Maxim XL 035 FS, hp	3.9	91.1	0.8	19.4	3.0	77.1	0.6	15.4
Phyto doctor	4.3	90.6	0.9	20.1	3.1	76.4	0.6	15.3
SSD_{05}	0.33	1.1	0.1	1.6	0.5	1.5	0.2	0.4

Notes: LNAU – Lviv National Agrarian University, BNAU – Bila Tserkva National Agrarian University.

Table 4.10

Spread and development of Alternaria in the variety Siesta F_1 of spring rape under the use of different fungicides (LNAU) [223]

Variant	Disease prevalence, %	Disease progression, %	Yield, t/ha
Without spraying	90.3	54.3	2.00
Karamba, v.r. + Pictor, h.p.	45.7	10.6	2.42
Pictor, h.p.	48.0	12.7	2.40
Tilmore, k.e.	47.0	18.1	2.29
Faraday, v.g.	50.3	21.6	2.27
SSD_{05}	3.2	2.4	0.05

The use of alternaria-resistant varieties in production, combined with the application of rational protection systems, reduces the cost of production and helps to increase the profitability of production. Seed treatment helps to protect plants from pathogens that may be present in the seeds and the environment in the early stages of growth, but does not have a significant

impact on the susceptibility to Alternaria during the most dangerous period – pod formation and seed maturation.

Table 4.11

Spread and development of Alternaria on spring oilseed rape variety Kalinovsky under different fungicides (NUBIP) [223]

Variant	Disease prevalence, %	Disease progression, %	Yield, t/ha
Without spraying	81.3	16.1	2.46
Karamba, v.r.	64.6	14.5	2.58
Pictor, h.p.	54.2	10.9	2.63
Tilmore, k.e.	52.1	12.5	2.62
Faraday, v.g.	68.8	14.2	2.60
Ridomil Gold MC, v.d.g.	72.9	14.0	2.55
SSD_{05}	5.6	2.2	0.10

Thus, the fungicide Pictor is highly effective in controlling the spread and development of Alternaria pathogen on spring rape crops, while Tilmore, Faraday, and Ridomil Gold are somewhat less effective.

It should be borne in mind that an individual approach to the selection of a specific fungicide for controlling Alternaria is advisable, taking into account the soil and climatic characteristics of the region, varietal composition and prevalence of the pathogen itself.

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4.2. Integrated systems and methods for controlling sclerotinia in cruciferous crop agrocenoses

Controlling sclerotinia is challenging due to the wide range of hosts and the long survival of the pathogen. Since the disease is transmitted through sclerotia with crop residues, and plant waste stimulates the formation of sclerotia, it is advisable to collect and harvest all infected residues to destroy sclerotia. Clean seeds free of sclerotia should be used for sowing. Due to the airborne transmission of ascospores and the wide range of hosts (about 408 species), crop rotation seems to be a less successful method of controlling the disease. However, deep summer ploughing and crop rotation with non-susceptible hosts (rice, maize), using only recommended doses of nitrogen fertiliser, irrigation and maintaining plant populations within recommended rates, and flooding the soil if possible, will minimise the population of sclerotia in the soil, which may later prove useful in controlling soil inoculum disease [1]. Avoiding thickening in the row to minimise contact between plants through the roots and stem, to reduce the spread of the disease by mycelial pathways, is also an effective measure. Control of broadleaf weeds such as Chenopodium spp. is important in disease management.

The occurrence of sclerotinia can be reduced or avoided by sowing rapeseed late [2]. Late sowing can be beneficial as it shortens the period between phenological susceptibility and maximum ascospore load. Sowing dates had a significant impact on the incidence of sclerotinia rot and yield [3]. Correlation analysis showed that there is a significant positive correlation between maximum and minimum temperature on the occurrence of the disease. The data showed that stem rot infection was negatively and significantly affected by maximum temperature (r= -0.697*) and number of sunny hours (r= -0.855**), while maximum relative humidity (r= 0.883**) and minimum relative humidity (r= 0.871**) showed high reliability and positive correlation with Sclerotinia sclerotiorum infection.

Application of compost to the soil inhibited the carpogenic germination of S. sclerotiorum and reduced sclerotinia infection [4]. The extracts of five organic additives, namely sunflower cake, safflower cake, mustard cake, neem cake and manure, significantly reduced the growth of *S. sclerotiorum* mycelium [5].

The combined effect of trace elements, namely: B at a dose of 1 g/l, Mo at a dose of 1 g/l, S at a dose of 2 g/l and Zn at a dose of 2 g/l, on reducing the incidence of sclerotinia rot and increasing the yield of rapeseed [6].

Currently, there are a number of disease control measures aimed at different stages of the S. sclerotiorum infection cycle (Figure 4.13). Some of these are theoretical and have only been demonstrated experimentally, while others are already being applied by growers. The different types of control measures include cultural control, fungicides, biological control, selection for genetic resistance and genetic modification (which is currently theoretical).

Current methods of controlling the disease are based primarily on cultural control and fungicide use. Most cultural control methods are aimed at reducing the level of *S. sclerotiorum* inoculum in the soil or creating a local environment unfavourable for the pathogen.

Fungicides are commonly used to prevent the development of S. sclerotiorum embryos on rapeseed root tissue in order to break the disease cycle. However, the effectiveness of these fungicides depends on the ability to predict when the fungal ascospores first appear on rapeseed tissue. Failure to apply fungicides on time can lead to economic losses.

Cultural control methods contribute to the creation of local conditions unfavourable for the survival of pathogens and the development of diseases [7]. In order for cultural control methods to be effective, an understanding of the basic biology of the target pathogen is essential. The control of sclerotinia in cruciferous crops is largely dependent on cultural control practices (Figure 4.7).

Crop rotation is a popular way to control the number of sclerotia in oilseed rape fields. Crop rotation with crops that are not susceptible to *S. sclerotiorum* can disrupt the annual life cycle of *S. sclerotiorum*, reducing the annual number of sclerotia entering the soil 'sclerotia bank'.

Currently, canola producers are advised to rotate their crops with other crops such as wheat or barley once every 4 years [9]. However, this advice should only serve as a guide, as it has been suggested that individual *S. sclerotiorum* sclerotia can remain viable in the field for at least 7 years [10–11]. A study conducted in Canada showed that sclerotia isolated from a canola field that had been reseeded with barley for three consecutive years remained viable and were able to germinate and develop apothecia [12]. The accumulation of sclerotia in the soil is further enhanced when the

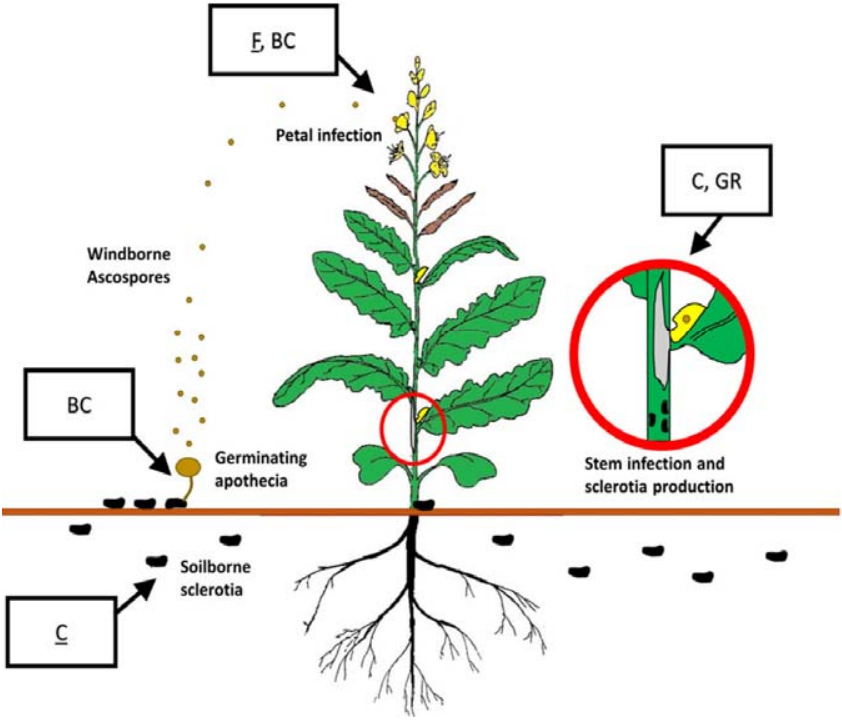

Figure 4.7 – The infection cycle of Sclerotinia sclerotiorum and potential points of intervention. Ascospores are released from the germinating apothecia and are carried by the wind to the aboveground tissues. The ascospores germinate and primarily infect the aging tissues of the petals. The infected petals fall off and lie in the leaf axils, allowing S. sclerotiorum to penetrate the stems and infect them, causing sclerotinia. After infection, sclerotia are formed and can persist in the soil for several years. At different stages of the infection cycle, different control measures can be used to combat this pathogen: cultural control (CC), biocontrol (BC), fungicides (F) and genetic resistance (GR) [8]

host crop is grown for several consecutive years without crop rotation. Crop rotation duration is a key component of cultural control that must be carefully considered when trying to limit the incidence of sclerotinia.

Crop rotation is only effective when the life cycle of the target pathogen is interrupted. One of the challenges associated with *S. sclerotiorum* is that it can complete its life cycle on more than 400 different host species, including common weeds such as wild radish (*Raphanus raphanistrum*), shepherd's purse (*Capsella bursa-pastoris*), field thistle (*Cirsium arvense*), yellow thistle (*Sonchus arvensis*) and medicinal dandelion (*Taraxacum officinale*) [13]. For crop rotation to be effective against S. sclerotiorum, it must be combined with an effective weed management programme that minimises the likelihood of a "green bridge" that allows S. sclerotiorum to persist in fields where oilseed rape is not grown in the rotation.

The impact of tillage on the survival of sclerotia in soil has been widely studied. Tillage practices reduce the ability of sclerotia to form apothecia by burying them in the soil.

Reported [14], that *S. sclerotiorum sclerotia* function only in the top 2–3 cm of soil, as the apothecia are unable to grow longer than 3 cm. It was confirmed that ploughing sclerotia to a depth of 6–15 cm reduces germination and the formation of apothecia the following year. However, the survival of *S. sclerotiorum sclerotia* increases when the sclerotia are buried deep into the soil [15]. Subsequent years of tillage will only bring the previously buried sclerotia back to the soil surface. Therefore, this method is more effective if the sclerotia are buried and remain embedded in the soil until the viability of the sclerotia is reduced.

Another method used to reduce the viability of sclerotia in the soil is to manipulate the water content of the soil. It has been shown that high soil moisture negatively affects the survival of sclerotia [16–17]. In extreme cases, when soaking lasted for more than 24 consecutive days, the viability of sclerotia was seriously reduced [18]. On the other hand, limiting the availability of water in the top 5 cm of soil can also affect the viability of sclerotia. Manipulation of soil water content to control sclerotinia will be limited to cultivation systems that use controlled irrigation schemes. In addition, these control methods will need to be applied between growing seasons, as the described water and soil environment is likely to have a negative impact on the viability of the crops themselves.

Chemical soil treatments have also been shown to be effective in reducing the carpogenic initiation of sclerotia. In particular, the commercially available fertiliser calcium cyanamide has been shown to significantly reduce the number of aptocia in four field trials – by up to 87% [19].

It is noted that the susceptibility of plants to sclerotinia rot was higher when using ammonium sulphate, while spraying with thiourea showed a lower intensity of the disease development [18].

Some cultural control methods focus on modulating the local field environment so that conditions are unfavourable for the development of sclerotinia. Relative humidity is considered to be a key factor influencing the epidemiology of *S. sclerotiorum* in *B. napus* crops. The analysis of data collected at local weather stations showed that relative humidity values exceeding 80% correlate well with the development of sclerotinia in culture [20].

High relative humidity is particularly problematic during flowering, as senescent flower petals are the main site of *S. sclerotiorum* ascospore accumulation. Relative humidity in crops can be reduced by using appropriate row spacing and seeding rates at sowing time to ensure air exchange between individual plants.

Few genetic sources of resistance to the pathogen are available to breeders, and this has led to fungicide applications becoming the main method of controlling sclerotinia. Among the fungicides that suppress sclerotinia are Benomyl, thiophanate-methyl, vinclozolin and tebuconazole. Ditan M-45 (Mancozeb), Ditan Z-78 (Zineb), Ziram, Difolatan-80, Blitox-50, Benlat; Iprodion, fenpropimorph; Tiram [21–23]. However, the number of flowers under the canopy and the density of plants prevent from achieving good spray coverage, and an effective forecasting tool is needed for timely fungicide spraying [24]. Even more importantly, the development of fungicide resistance threatens the continued effectiveness of this method of disease control. In addition to routine chemical control, various forecasting systems are used, including the petal test method for the prediction of cruciferous sclerotinia. This forecasting method was developed based on the relationship between disease incidence and the level of pathogen infection of petals at the beginning of flowering. A risk score table was developed, but the prediction based on the risk map was not as accurate for different fields. The use of both petal infestation and enzyme-linked immunosorbent assay

(ELISA) can reduce some of the shortcomings of each prediction method as tools for stem rot risk assessment in oilseed rape. Risk prediction maps for *S. sclerotiorum* in rapeseed are currently available [25].

Globally, several different classes of fungicides have proven effective against S. sclerotiorum, including anilinopyrimides, benzimidazoles, dicarboxamides [26], demethylation inhibitors [27], external quinone inhibitors (otherwise known as strobilurins) [28–29] and succinate dehydrogenase inhibitors [30–31]. Others have been tested in vitro for activity against *S. sclerotiorum*, but have not yet been used in the field, such as phenylpyrroles. These classes of fungicides demonstrate different modes of action: anilinopyrimidines inhibit methionine biosynthesis [32], and dicarboxamides are thought to inhibit osmotic signal transduction [33], although the exact molecular mechanisms of this activity are unknown. Benzimidazoles bind tubulin, which disrupts microtubule formation [34]. Finally, similar to dicarboxamides, phenylpyrroles inhibit osmotic signal transduction by inhibiting a specific protein kinase [35]. Thus, there is a wide range of fungicides that can be used to prevent sclerotinia in oilseed rape, although not all of them are registered for use in oilseed rape in all growing regions. As most of the above classes of fungicides are active only in certain areas, the likelihood of fungal resistance developing is relatively high. Indeed, for each of these classes of fungicides, resistant strains of pathogenic fungi are known [36–42], Thus, there is a wide range of fungicides that can be used to prevent sclerotinia in oilseed rape, although not all of them are registered for use in oilseed rape in all growing regions. As most of the above classes of fungicides are active only in certain areas, the likelihood of fungal resistance developing is relatively high. Indeed, for each of these classes of fungicides, resistant strains of pathogenic fungi are known [43–44]. However, resistance of *S. sclerotiorum* has been reported worldwide only to benzimidazoles and dicarboxamides [45–46], and in both cases, resistant strains emerged more than ten years after the introduction of these fungicides.

The reason for the low tendency of *S. sclerotiorum* to develop resistance to fungicides may be the monocyclic cycle of infection. By definition, this type of infection originates from a single source of inoculum during the growing season [47]. This effectively reduces the population size and genetic potential, as secondary spread of the disease occurs through the expansion

of multinucleate mycelium by mitotic division. Indeed, a predictive model has demonstrated that the strategy of monocyclic or polycyclic infection is an important determinant of the risk of fungicide resistance in plant pathogens [48]. This effectively reduces the population size and genetic potential, as secondary spread of the disease occurs through the expansion of multinucleate mycelium by mitotic division. Indeed, a predictive model has demonstrated that the strategy of monocyclic or polycyclic infection is an important determinant of the risk of fungicide resistance in plant pathogens [49].

In summary, the data suggest that fungicides are a useful long-term method of controlling S. sclerotiorum as it is unlikely to develop resistance quickly, especially if fungicides with different mechanisms of action are used. However, there is still a need to test and register a more diverse set of fungicides in regions where chemicals with a limited spectrum of action are used. This is because no matter how small the risk of resistance development, it still exists and can pose a potential threat to future crop yields if fungicides are not managed properly [50]. In addition, selective pressure caused by the overuse of a small number of registered fungicides on cruciferous crops can create resistance in other species that infect these crops, such as Alternaria brassicicola, which has already developed resistance to several classes of fungicides [51].

In addition, in some cases, unregistered fungicides have shown greater potential than those registered for sclerotinosis. One example is the phenylpyrrole compound fludioxonil, which has demonstrated greater activity against Chinese *S. sclerotiorum* isolates than iprodione, which is a widely used fungicide in China [52]. In the future, testing of alternative fungicides for the prevention of sclerotinia may be important for controlling the disease in regions where the availability of registered fungicides is limited.

Due to environmental constraints on fungal growth and plant infection, outbreaks of sclerotinia are difficult to predict. Consequently, deciding on the need and timing of fungicide spraying to control the disease is a difficult task. If fungicides are sprayed prophylactically, regardless of the potential outcome of the disease, years in which the incidence of sclerotoniosis would have been low or non-existent will suffer economic losses due to unnecessary fungicide consumption.

As a result, a large number of studies have been conducted to develop mathematical models and sampling methods that can be used to predict sclerotinia outbreaks. Numerous quantitative variables have been described that affect the degree of damage to different crops, including the number and spatial distribution of apothecia, the amount of airborne infection, the frequency of petal infection, soil moisture content and relative humidity [53–56]. These variables are inextricably linked to each other and to other qualitative variables such as weather forecasts and crop history. Several attempts have been made to use these variables individually or in combination to predict sclerotinia outbreaks in cruciferous oilseed rape.

A checklist has been developed to optimise fungicide spraying decisions in oilseed rape based on factors thought to influence the incidence of sclerotinia [57]. A forecasting scheme based on controlled germination of sclerotia was developed. It involved collecting sclerotia from infected rapeseed fields, then priming them for germination and sowing them in designated locations. The percentage of germinated sclerotia in a particular repository was then used to predict outbreaks of sclerotinia in rapeseed crops within a 15 km radius [58]. However, this approach has a number of drawbacks, including its insufficient predictive power for individual fields with different historical cultivation regimes and, consequently, sclerotial numbers, its inability to account for ascospore formation and dispersal, and its subjectivity to local environmental conditions. To improve the predictive power of this scheme, attempts have also been made to measure the release of ascospores from sclerotial depots [59].

Another approach is to use the number of infected rape petals to predict outbreaks of sclerotinia. To do this, rapeseed petals were incubated on agar to determine whether *S. sclerotiorum* would grow from them, which allowed us to indirectly assess the presence/absence of the disease. Using this method, we were able to show that the percentage of petals infected with S. sclerotiorum could be used to accurately predict the severity of sclerotinia in 74% of cases, based on the results of several consecutive field trials. It is likely that these studies led to the development of petal testing kits that became commercially available to Canadian canola growers. They consisted of plates containing agar medium suitable for *S. sclerotiorum* growth and instructions for use [60].

Similar petal testing kits have been commercialised in Australia, although they were sold with the caveat that they were only useful for determining the presence or absence of *S. sclerotiorum* in a canola crop, not for predicting disease severity.

Although petal testing has proved useful in predicting sclerotoniosis, it loses its predictive power when environmental conditions are not favourable for S. sclerotiorum infection. Attempts to counteract this have been made [61] based on the inclusion of environmental variables such as light, leaf area index and crop height in prediction systems based on petal infection. This study also showed that the amount of petal infection varied between early, full and late flowering, with a general trend of increasing infection as the flowers developed. However, the authors of the study raised questions about the ease of measuring environmental variables and the practicality for growers of continuously sampling petals covering different stages of flowering.

Another attempt to combine environmental variables with petal infection to predict sclerotinia was made [62]. A simpler prediction model has been developed that is based on both the level of petal population and relative soil moisture. However, another problem with the petal test method is that the assessment of the level of petal population may itself be dependent on environmental variables. For example, it has been shown that collecting wet petals or collecting petals just before heavy rain can lead to an underestimation of petal infestation [63], as well as picking petals in the morning rather than in the afternoon.

Perhaps because of their ease of implementation, models based on simpler factors such as crop history, disease incidence in previous years and weather forecasts are currently the most widely used by growers to make decisions about fungicide use against sclerotinia.

Developed [64] a forecasting model based on a risk score table using the factors "number of years since the last rapeseed sowing", "incidence of the last *S. sclerotiorum* host crop", "sowing density", "rain in the last 2 weeks before sowing", "weather forecast" and "regional risk of aphotic development". With a given threshold score, the model provided accurate spraying recommendations for 75% of the fields that needed fungicide application and 84% of the fields that did not.

Although oilseed rape growers have applied various S. sclerotiorum risk assessment schemes based on the information from the above studies,

a centralised assessment scheme for oilseed rape growers in a particular region was not developed until 2007 in Germany. This model, called SkleroPro, worked by creating a regional disease risk assessment based on environmental variables obtained from weather stations, such as relative humidity and rainfall, which could then be used to determine the risk for a particular field based on parameters such as cropping history, expected yield, product price and spraying cost. Spraying recommendations could be automatically determined by entering data on these parameters through an online platform. This model could provide accurate recommendations in 70-81% of cases, based on historical data and field trials. However, the authors acknowledged that the model does not take into account external levels of inoculation and is therefore most suitable for regions where *S. sclerotiorum* inoculation is consistently present at high levels.

An alternative to assessing petal infestation to predict the severity of oilseed rape sclerotinia is to assess inoculum levels detected in air samples adjacent to field areas, as previously done with Burkard spore traps. Traditional methods of quantification, i.e. microscopic analysis of trapped spores, have been replaced by PCR-based detection [65]. This method can be used to determine the presence of *S. sclerotiorum* DNA in a spore trap, which is used as an indirect measure of its presence/absence in the field. The method itself has been improved with the development of a quantitative real-time PCR-based assay [66]. This new method was sensitive enough to detect as little as 0,5 pg of *S. sclerotiorum* DNA, which is equivalent to approximately 1,5 ascospores. This is well suited for deploying widely scattered spore traps to detect *S. sclerotiorum* in large regions rather than in individual fields, which may be useful for more coordinated efforts to reduce the impact of the disease on cruciferous plant species.

An improvement on PCR-based detection systems is the SYield sensor system, commercially available from Syngenta. This system is able to automatically detect and quantify the amount of *S. sclerotiorum* inoculum in the air by monitoring the level of oxalic acid in the culture medium. Information from the spore traps can be transmitted wirelessly to alert farmers to high levels of infection, which can help in the timing of fungicide spraying [67–68]. The above models were developed in temperate regions.

The detection of the pathogen on mustard (*B. juncea*) plants affected by sclerotinia rot was made possible by the use of a remote sensing method

that can help in multi-stage disease tracking and forecasting [69–70]. Developed [71] a stepwise multiple linear regression model for sclerotinia rot of white mustard. A multiple linear regression model was described as part of an epidemiological study of sclerotinia rot and 10 independent weather variables. The equation of the fitted model is as follows: Incidence of sclerotinia rot = -11.2351 + 0.9529 x (Sum of temperatures) + 4.93924 x (Evenness of rainfall distribution) + 3.83308 x pH (Acidity) + 0.60885 x RF (Rainfall) – 0.406458 x RH1 (Relative humidity) + 0.524095 x RH2 (Soil moisture) + 0.17386 x Soil moisture (%) – 0.30461 x Tmax (Maximum temperature) – 0.677744 x Tmin (Minimum temperature) – 2.19556 x WS (Wind speed). The ScleroPro system is easy to use and fully computerised, and based on weather and field condition data, this programme has been available since 2006.

Biological control has also been explored over the past few decades due to growing concerns about the use of chemical pesticides [72]. Many biological agents are potential means of controlling this disease. The most studied biocontrol agents are mycoparasitic fungi, hypovirulent strains of *S. sclerotiorum*, bacteria and insects [73]. The use of organic and inorganic materials or developed compounds has also been shown to inhibit *S. Sclerotiorum* [74]. For biological control, it is recommended [75]; *Coniothyrium minitans* і *Talaromyces flavus* (Klocker) Stolk and Samson. The use of an actinomycete fungus was effective *Streptomyces arabicus* [76–77].

Over the past 20 years, significant efforts have been made to identify biological control agents (BCAs) for *S. sclerotiorum*. Despite the rapid rate of discovery of potential BCAs, only a small number of them have been commercialised [78]. Most of the reported BACs belong to the fungal and bacterial kingdoms, but it has recently been shown that viral particles can also be used to disrupt growth of *S. sclerotiorum* [79]. Many organisms identified as parasitic to S. sclerotiorum are also fungi. *Trichoderma harzianum* parasitises both the sclerotic and hyphal stages of growth *S. sclerotiorum* [80-81]. Analysis of gene expression during these parasitisation events indicates that *T. harzianum* actively produces enzymes that destroy the fungal cell wall. Functional studies have demonstrated the importance of the endogenous chitinase Chit42 in the destruction of the *T. harzianum* cell wall. Trichoderma harzianum isolates transformed with

a constitutively expressed Chit42 transgene had higher levels of chitinase activity than wild-type isolates, making them more capable of inhibiting the growth of *S. sclerotiorum* [82]. It was shown that the fungus Ulocladium atrum has an antagonistic effect on germinating ascospores of *S. sclerotiorum* [83]. Joint inoculation of rape petals with *U. atrum* and *S. sclerotiorum* reduced the amount of pathogen development compared to inoculation with *S. sclerotiorum* alone.

The most studied mycoparasite for biocontrol of *S. sclerotiorum* is *Coniothyrium minitans*. Like *T. harzianum*, *C. minitans* parasitises sclerotia and mycelium of *S. sclerotiorum* [84-86]. The key to the success of *C. minitans* as a BAC is its ability to persist and spread in the soil.

Coniothyrium minitans is relatively resistant to annual fluctuations in soil temperature and moisture. In non-irrigated soil with ambient temperatures ranging from 10 to 39 °C *C. minitans* was able to survive for 750 days [87]. Conidia of *C. minitans* can easily spread through the soil by free water. It has been shown that active spread of C. minitans at the stage of rapeseed seedlings can reduce the number of carpogenic germination of *S. sclerotiorum* later during the growing season [88]. The parasitisation of *C. minitans* by *S. sclerotiorum* is likely to be associated with the breakdown of oxalic acid, a known pathogenicity factor of *S. sclerotiorum*. Research [89] showed that *C. minitans* actively breaks down oxalic acid, which leads to local pH changes. It is assumed that the induced change in pH of the infected tissue stimulates the production of enzymes that destroy cell walls. The role of oxalic acid in the mycoparasitism of *C. minitans* on *S. sclerotiorum* was further confirmed by studying defective mutants of *C. minitans* oxalate decarboxylase that lost the ability to break down oxalic acid. When coincubated with *S. sclerotiorum*, the Cmoxdc1 mutant had a reduced ability to infect *S. sclerotiorum* mycelium compared to wild-type *C. minitans* [90]. In addition to its ability to break down oxalic acid, *C. minitans* is also thought to secrete antifungal compounds. It has been shown [91], that substances previously added to the culture filtrate of *C. minitans* were active against mycelial growth and germination of *S. sclerotiorum* ascospores.

In addition to parasitic fungi, many bacterial mycoparasites have been identified as potential enemies *S. sclerotiorum* – *Streptomyces platensis* [92], *Streptomyces lydicus*, *Bacillus subtilis* [93–99], *Bacillus*

amyloliq-uefaciens [100], *Bacillus megaterium*, *Pseudomonas fluorescens* [101–102], *Pseudomonas chlororaphis* [103–105] and *Serratia plymuthica* [106]. Unlike the fungal BACs described above, most of the bacterial mycoparasites described above target ascospores and growing hyphae *S. sclerotiorum* [107]. Usually, broth cultures or cell suspensions of potential bacterial BAC are applied to the aerial parts of rapeseed plants by spray inoculation.

Scanning electron microscopy (SEM) images of rapeseed leaves pre-inoculated with *S. sclerotiorum* and *B. subtilis* EDR4, showed *S. sclerotiorum* hyphae with abnormal growth, cytoplasmic leakage and fewer infection cushions compared to the negative control. It was also shown that the mycelia of *Sclerotinia sclerotiorum* acquire an irregular shape when incubated with *P. fluorescens*. As a result, the growth of *S. sclerotiorum* was reduced by 84,4% [108].

It is reported [109], that *T. harzianum* and *P. fluorescens* did not differ significantly in terms of pathogen control efficiency. Similar results were obtained with the use of garlic bulb extract, *T. harzianum* as a seed treatment in combination with *P. fluorescens* spraying significantly outperformed chemical fungicides in the control of sclerotinia rot. Foliar spraying with garlic bulb extract significantly increased seed yield compared to the control. It was reported that the combination used in this study significantly reduced the incidence of sclerotinia rot and was as effective as the combination of seed treatment with *Trichoderma harzianum* and foliar spraying with *Pseudomonas fluorescens* and *T. harzianum*. The economic profitability was higher when using biological products (*A. sativum, T. harzianum, P fluorescens* bulb extract) compared to chemical fungicides.

Combination of seed treatment with T. harzianum and its further use in the form of foliar spraying [110], as well as a similar combination of seed treatment and foliar spraying with bulb extract of *A. sativum* [111], has led to a higher profit-to-cost ratio.

They found [112], that isolates Trichoderma harzianum-3 and T. Harzianum-4 were significantly better and most potent in reducing the growth of *S. sclerotiorum*. Similarly, the antagonists T. Harzianum-4, T. Harzianum-3 and T. virens antagonists reduced the formation of sclerotia.

It is reported [113], that the tested fungicides and garlic extract significantly reduced the incidence of sclerotinia, and [114] reported that

preventive foliar spraying with carbendazim twice at 45 and 60 days after sowing was the most effective for controlling white mustard stem rot in the field.

Trichoderma harzianum was tested against *Sclerotinia sclerotiorum*. The highest reduction of sclerotinia rot (69,0%) was achieved by *T. harzianum* GR isolate compared to the control, followed by soil application of *T. harzianum* SI-02 isolate with manure (60.8%) and foliar spraying with aqueous garlic extract (60,8%). Independent studies on spray inoculation with *B. amyloliquefaciens* [115] and *B. subtilis* Em^7 [116] led to a decrease in the incidence of sclerotoniosis by 83.3% and 50–70%, respectively. The levels of *S. sclerotiorum* control achieved in these experiments are comparable to those achieved with synthetic fungicides [117].

As an alternative to spraying methods, *S. sclerotiorum* bacterial ABA can also be applied as seed treatment granules. These protective structures increase the viability of the BAC over time and may also facilitate colonisation of roots and the rhizosphere [118]. Some of the bacterial ABAs used for seed treatment had the additional effect of increasing plant growth and yield. *Bacillus megaterium* A6, *B. subtilis* Tu-100 and *P. fluorescens* PS demonstrate plant growth stimulation effects combined with the ability to reduce the incidence of sclerotinia [119–121].

Three of the above-mentioned biological control agents have been commercialised for use against *S. sclerotiorum*. The fungal preparations *C. minitans* and *T. harzianum* were developed for sclerotia control, while the bacterial preparation *B. subtilis* was developed for controlling fungal growth in the phyllosphere [122].

A study comparing the ability of each of the three commercially available ABAs to inhibit *S. sclerotiorum* germination showed that C. minitans was the most effective, reducing the viability of S. sclerotiorum in soil by 95.3% and reducing the overall disease severity by 68.5%. In an independent study, the use of Contans WG in field trials on rapeseed resulted in a significant reduction in the incidence of slough disease compared to untreated controls [123]. At the same time, the ability of the spraying equipment to maintain effective concentration on the field is often questionable and largely depends on environmental conditions.

However, BACs are often seen as environmentally friendly alternatives to conventional fungicides [124]. Contans WG is considered to be relatively

cheap compared to other biological control agents and remains the most promising non-cultivated control option for the eradication of *Sclerotium sclerotiorum*.

Integration of seed treatment with foliar sprays contributed to better disease reduction [125–126]. *Trichoderma atroviride* demonstrated the formation and penetration of pathogen hyphae [127]. Soil application of *T. harzianum* at a dose of 15 g/kg soil at the same time or 7 days before the pathogen emergence resulted in low intensity of the disease development [128]. It is reported [129], that the W-1 strain of Caseobacter spp. can control the pathogen.

Carpogenic germination of pathogenic sclerotia can be reduced with a bioagent *Gliocladium virens* [130].

It was observed [131] antifungal activity of strain 11-3-1 of *Streptomyces longisporoflavus npomu S. sclerotiorum.*

Pseudomonas fluorescens P13, released from the soil of a rapeseed field produced hydrogen cyanide [132] and *Pseudomonas chlororaphis* PA-23 induced rapeseed plants to produce more hydrolytic enzymes, namely chitinase and beta-1,3-glucanase [133], in response to *S. sclerotiorum* infection, thus being effective against the pathogen. However, the control of the pathogen by Psuedomonas DF41 strain depends on the production of lipopeptides and the presence of a functional Gac system in the bioagent [134]. The chitinase activity of different *B. napus* genotypes significantly correlates with the sclerotinia rot damage, suggesting that chitinase can be used in breeding programmes to increase the disease resistance of rapeseed.

Treatment of seeds with a bacterial strain, namely Mesorhizobium loti MP6, isolated from the root nodules of Mimosa pudica, led to improved seed germination, early vegetative growth and seed yield with a sharp decrease in the incidence of sclerotinia rot [135]. Strains Y1 [136], NJ-18 [137], YS45 [138], Tu-100 [139–140] та EDR2 [141] *B. subtilis* and BS6 *Bacillus amyloliquefaciens* [142] have shown promise against this disease in oilseed rape. A new antifungal protein produced by Bacillus licheniformis W10 could be used as a biofungicide to combat this disease [143].

Bioagent, namely Coniothyrium minitans, which destroys hyphae [144] and sclerotia [145–146] *S. sclerotiorum*, was used to control the disease. This bioagent decomposes oxalic acid, negating its pH effect. In addition, it can stimulate the production of beta-1,3-glucanase by the bioagent and

can improve the mycoparasitism of the agent on *S. sclerotiorum*, which will lead to the protection of plants from infection by the pathogen [147].

Water application of C. minitans during rapeseed sowing was effective in suppressing carpogenic germination of the pathogen [148]. Soil treatment with this bioagent proved to be effective in reducing the production of ascospores by the pathogen [149]. To increase long-term effectiveness, infested areas can be regularly inoculated with deep soil spores of *C. minitans* before or after sowing crops. Reported [150], that the aerial application of this bioagent is an effective method of inhibiting the growth of pathogen mycelium on petals. Tautomycin, produced by Streptomyces spiroverticillatus, and other related compounds, namely 2,3-dimethylmaleic anhydride, diphenylmaleic anhydride and dimethylmaleate, have significant potential against the pathogen [151].

P. fluorescens PS1 biological product based on sawdust caused morphological changes by perforating hyphae, which allowed to control the disease [152].

The use of microviruses to control *S. sclerotiorum* is an exciting new development in biological control research [153]. It has been demonstrated that viral particles of the hypovirulent DNA virus *Sclerotinia sclerotiorum*-1 (SsHADV-1) are able to limit the growth of *S. sclerotiorum* when applied to infected plants of Arabidopsis thaliana. In addition, when a fragmented suspension of virus-infected *S. sclerotiorum* hyphae was applied to the aerial parts of B. napus, the incidence and severity of sclerotoniosis were increased. Despite the limitations on the spread of these viral particles through host cells, the data indicate that they can be transmitted between fungi regardless of vegetative compatibility.

The suitability of these viruses as potential BACs is also supported by the fact that they have a limited host range [154]. For example, SsHADV-1 can infect species in the genus Sclerotinia, but is unable to infect Botrytis cinerea, a close relative of the Sclerotiniaceae. The advent of high-throughput sequencing has facilitated virus detection and contributed to the discovery of additional hypovirulent S. sclerotiorum viruses that could be developed as potential BACs [155–156]. Although the cost-effectiveness of viral BACs has not yet been determined, they open up new possibilities for the future control of rape sclerotinia. Thus, there are a number of potential and already commercialised options for biocontrol of sclerotinia

in oilseed rape. Reported [157], that *C. minitans* reduces the number of sclerotia in the soil by 95.3%, in a similar study by the same authors [158] *C. minitans* to reduce the number of sclerotia by only 50%. It has also been shown that different strains of *S. sclerotiorum*, which produce different amounts of oxalate, are differently sensitive to *C. minitans*. In addition, the study [159] application of *T. harzianum* did not inhibit germination of sclerotia compared to untreated controls, despite several reports of its effectiveness [160].

Another factor influencing the potential use of BACs for disease control is their cost-benefit ratio compared to traditional methods. For products such as Contans WG, which may require multiple seasonal applications to achieve full effect, it is likely that their use by growers is strongly influenced by this factor [161]. Despite these obstacles, the fact that several biocontrol agents exist and are registered for plant protection in different countries suggests that there is at least a limited level of use by producers.

Overexpression of proteins involved in plant defence mechanisms against diseases is one of the strategies proposed to increase plant resistance to fungal pathogens. A hybrid endochitinase gene under a constitutive promoter was introduced by Agrobacterium-mediated transformation into an inbred line of winter rape (*B. napus* var. *oleifera*). When the progeny of transformed plants are exposed to pathogens, the plants show increased disease tolerance compared to non-transgenic parental plants [162].

It is noted that the control of cruciferous sclerotinia by means of cultural and chemical control is often very tedious and not very effective due to its complex mode of infection and its long survival (up to 10 years in the soil in the absence of a host) in the form of a dormant structure called a sclerotium [163]. In addition, the use of fungicides poses a serious threat to the climate and increases the cost of growing crops. Therefore, genetic host resistance is the most convenient, economical and environmentally friendly approach to effectively control this devastating pathogen [164-165]. Previous attempts to identify sources of resistance to this disease in white mustard have been complicated because all tested genotypes of *B. juncea* were susceptible to sclerotinia stem rot, and all identified sources of resistance belonged to other cruciferous crops and their wild relatives, such as *Brassica napus*, *B. fruticulosa*, *B. rupestris*, *B. incana*, *B. insularis, B. villosa, Erucastrum cardaminoides, E. abyssinicum, Sinapis alba* та *Diplotaxis tenuisiliqua*

[166–178] However, there were no reports of resistance in B. juncea, which is an important oil cruciferous crop. However, in the last few years, more and more attention has been paid to this issue, which eventually led to the identification of several mustard genotypes resistant to this pathogen [179–180].

Heritability of sclerotinia resistance in *B. napus* is high, controlled by nuclear genes and is not associated with the low erucic acid content trait. The petal mutant of *B. napus* is almost free from stem rot compared to the normal petal mutant [181].

Inheritance of resistance to *S. sclerotiorum* in *B. napus* is partially dominant [182]. Genetic analysis of resistance to *S. sclerotiorum* in *B. napus* 15 days after inoculation on petals is controlled by major genes with additive dominant epistatic effects and polygenes with additive dominant epistatic effects [183].

Genetic analysis of resistance to *S. sclerotiorum* in *B. napus* 15 days after inoculation on petals is controlled by major genes with additive dominant epistatic effects and polygenes with additive dominant epistatic effects (Figs. 4.8–4.9).

In India, rapeseed genotypes Cutlon, ZYR-6, PSM 169, PDM 169, Wester, PYM 7, Parland, Tobin, PCR 10, Candle, Wester, Cutlass and Torch and mustard genotypes PCR 10, RW 8410, RW 9401, Hyola 401,

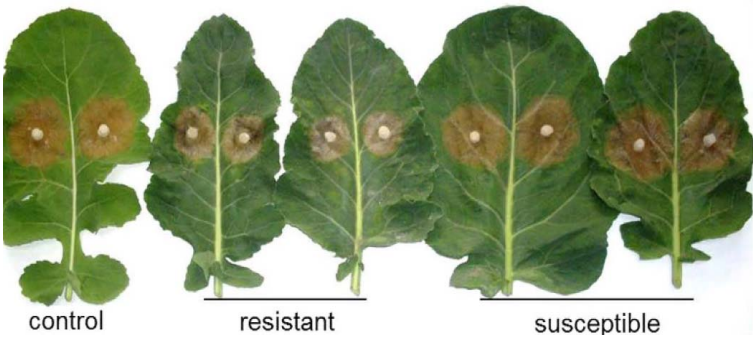

Figure 4.8 – Appearance of *Brassica oleracea* leaves infected with Sclerotinia sclerotiorum. (A) Symptoms of resistant and susceptible *Brassica oleracea* plants 3 days after inoculation with *S. sclerotiorum*

PBN 9501, PWR 9541, Kiran, RH 9401, RH 492, RW 8410, PAB 9511 and RGN 8006 were found to be resistant to S. sclerotiorum. In Japan, the rapeseed varieties Koganenatane, Aburamasari and Kizakinonatane have low incidence rates [185].

Notified [186], that the oilseed rape lines OKEG 8, 94, POH 285 and H 243/33 are the most resistant to *S. sclerotiorum*. In Poland, the winter rape (B. napus) varieties BOH 2600, BOH 1592, BOH 1693, MAH 1391 and MAH 1592, Bermuda, Capio and Mohllan are resistant to Sclerotinia. The strains PNG 2170, MA 1615-1, MZL 236, BK 2466/93, MA 1649-1 are the most resistant. A high degree of resistance was observed in the Isuzu rapeseed variety.

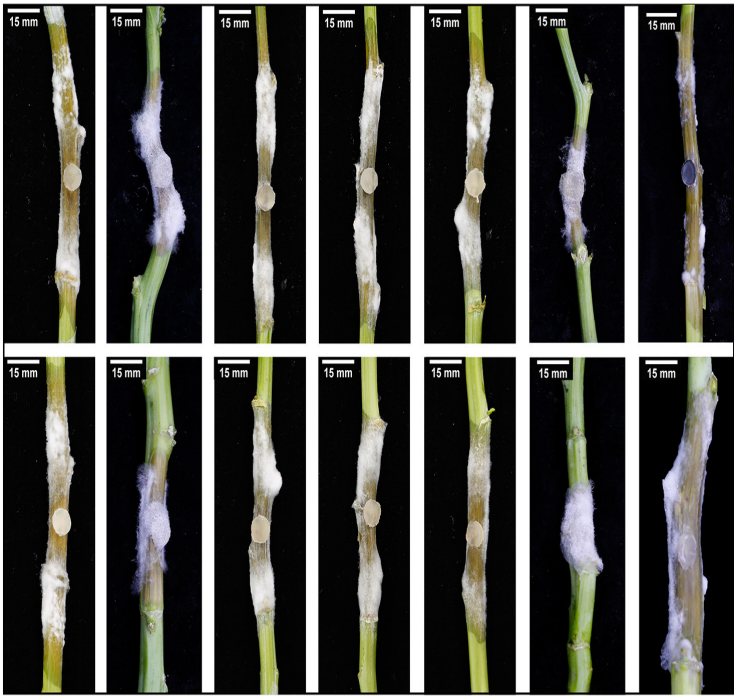

Figure 4.9 – Stems of rape varieties and lines with different resistance to *S. sclerotiorum* 120 h after inoculation with *S. sclerotiorum.* Scale bar 15 mm [184]

Due to the wide range of hosts and the lack of tissue specificity, the development of sclerotinia-resistant varieties has been less successful. However, differences in the general growth pattern and morphological traits of plants may be important characteristics for disease tolerance. Another trait, i.e. plant stem diameter, may be a useful parameter for pathogen tolerance. It has also been reported that lines with high glucosinolate content are more susceptible to *S. sclerotiorum* than lines with low glucosinolate content [187]. Several genotypes of mustard oilseed rape have been tested for sclerotinia rot caused by *S. sclerotiorum* using different methods under natural and artificial conditions [188–189]. The response of some genotypes was relatively consistent, regardless of the pathogen isolates, while some other genotypes showed highly variable responses to the same isolates. Although complete resistance was not found in rapeseed, partial field resistance to sclerotinia rot was found in Chinese cultivars Zhongyou 821 [190] and Zhongshuang № 9 [191].

Four B. napus cultivars, namely BOH 2600, Bermuda, Capio and Mohican, were found to be resistant to *S. sclerotiorum* after a 3-year study. During three consecutive growing seasons, eight genotypes, viz: Hyola-401, PBN-9501, PWR-9541, Kiran, RH-9401, RH-492, RW-8410 and PAB-9511, were found to be resistant to S. sclerotiorum.

In India, white rot of mustard can be effectively controlled by three foliar sprays of benomyl at 0.025% followed by zirram (0.156%). Significant reductions in disease development and lesion size were observed with benlate and topsin-M sprays on B. juncea. In Europe, spraying with prothioconazole 250 EC (Proline) at 175 g a.i./ha controls *S. sclerotiorum* in spring and winter oilseed rape [192].

In Canada, a single spray of Benomyl is available at the early flowering stage in disease-prone regions. The simultaneous use of Benomyl and vinclozolin fungicides effectively controls rape stem sclerotinia when applied at 25% flowering stage. Control is less stable when using Iprodion. Application of Benomyl at a dose of 1.0 kg and Iprodione at a dose of 0.5 kg e.i./ha by air in large-scale trials provides control equivalent to comparable treatments in small-scale trials [193].

Aerial application of benomyl to Altex and Kendle rape seeds reduces the level of sclerotinia stem rot from 44 to 8% with an increase in yield, and

this application is economically feasible when the yield increases by at least 180 kg/ha [194].

In Canada and the United States, for effective control of *S. sclerotiorum*, it is recommended to spray canola with protioconazole 480 EC at a rate of 150–200 g a.i./ha. It is also recommended [195], that such fungicides as azoxystrobin, benomyl, boscalid, iprodione, protioconazole, tebuconazole, thiophanate-methyl, trifloxystrobin and vinclozolin consistently reduce the incidence of sclerotinia stem rot in rapeseed.

In Poland, Contans WG (*C. minitans*) applied before sowing and Alert 375 SC (flusilazole + carbendazim) applied during flowering of rapeseed reduced S. sclerotiorum infection and increased yields [196].

The use of vinclozolin at a rate of 1.5 kg/ha at the stage of full flowering proved to be very effective in controlling white rot of the rapeseed stem with an increase in yield of up to 8% [197].

Suggested [198] use spore traps to optimise the timing of vinclozolin application to achieve maximum disease control.

The use of Iprodion, Prochloraz + carbendazim and tebuconazole (Flikur) on rapeseed gives good disease control with increased yields [199]. The optimal period for chemical control of rape sclerotinia is from 100% flowering stems to 80% flowering branches. The second spraying should be carried out five to seven days after the first, when all branches are in bloom [200].

In France, the fungicides Benomil (1000 g a.i./ha), Procimidone, Winclozolin, Iprodion WP and Iprodion Flow at 750 g a.i./ha were found to be effective against rape sclerotinia. However, the most effective were vinclozolin and procyamidone [201].

Flutriafol (117.5 g a.i./ha) + carbendazim (250 g a.i./ha) provides good control of rape stem rot with yield increases in the UK and France [202]. However, they found [203], that guazathine is an effective fungicide against *S. sclerotiorum* in oilseed rape. Among all five fungicides, it was found that carbendazim completely (100%) inhibited the growth of the pathogen mycelium [204].

In Switzerland, the best control of *S. sclerotiorum* is achieved by fungicide spraying during full flowering. The germination of sclerotia is reduced by calcium cyanamide, which is applied in early spring when new shoots are 5–10 cm long. Preventive measures include the use of

less susceptible crops in crop rotation, careful ploughing of affected plant residues, control of cabbage stem weevil, control of intercrops of rape and cruciferous crops, and cruciferous weeds, including shepherd's purse and field mustard [205].

In China, the agricultural antibiotic 2–16 (in 100-fold and 150-fold dilution) reduces the level of sclerotinia rot in rapeseed by 82.6 and 78.1 per cent, respectively [206].

The list of fungicides recommended in the world practice of cruciferous sclerotinia control is given in Table 4.12.

For most fungicides, the recommended application period is between 20 and 50 per cent flowering, and the optimal time is usually around 30 per cent flowering. To estimate the flowering stage, take a few plants in the field and count the number of open flowers. One method is to identify the main stem, remove the secondary branches, and count only the open flowers on the main stem. Generally, it takes two to four days from the first flower to 10 per cent flowering (Figure 4.35).

The purpose of applying fungicide is to cover as many petals as possible, while ensuring that a certain amount of chemicals also penetrate the canopy to protect potential infection sites (e.g. axils and leaf bases). However, the fungicide only works on the petals present at the time of spraying and does not protect petals that appear after spraying. Most fungicides are contact fungicides with limited systemic function. In addition, the therapeutic properties of most fungicides are limited on existing sclerotinia stem rot lesions, especially those that are large or have penetrated the stem tissue. Therefore, it is important to apply the fungicide before significant petal drop when environmental conditions are favourable for sclerotinia infection.

Seeding density can influence the risk of sclerotinia under favourable environmental conditions The density of the agrocenosis can be changed by seeding rate, row spacing and fertility, which is the main factor that influences the sowing density.

Generally, high numbers of fast-growing plants result in faster canopy closure and the formation of a thick, dense canopy. While these dense agrocenoses often have the highest yield potential, they tend to maintain high soil moisture levels in the stem, which increases sclerotia germination. Soil moisture for approximately 10 days or more encourages sclerotia to form apothecia and subsequently release spores. Wet conditions in the

lower part of the stem also increase the likelihood of infection when petals carrying spores fall on the lower leaves or in the leaf axils. In growing areas with a short season, *B. rapa* cultivars tend to have a lighter top cover and generally lower infection rates.

There are currently two biological products available for the control of sclerotinia stem rot: Contance and Serenade OPTI [207]. Kontans is a biological control agent registered for use in oilseed rape, soybean, dry edible beans, sunflower and safflower. The active ingredient is Coniothyrium minitans, a fungus that colonises and slowly destroys sclerotia on contact with them. The product is a pre-emergence biofungicide that takes several months for the fungus to destroy the viability of sclerotia.

Table 4.12

List of fungicides recommended for control in cruciferous crops [206]

Product	Company	Active ingredient	Rate per acre	Phase of application
1	2	3	4	5
Acapela	Corteva Agriscience	250 g/l picoxystrobin	325–485 ml	20–50% of flowering plants
Azoshy250 SC	Sharda Crop Chem Canada	250 g/l azoxystrobin	280–400 ml	up to 30% flowering
Contans WG	Bayer	5.0% strain Coniothyrium minitans	400–800 g	Pre-sowing and post-harvest processing
Cotegra	BASF Canada	250 g/l boscalid and 150 g/l prothioconazole	240–280 ml	20–50% of flowering
Dyax	BASF Canada	250 g/l of fluxapiroxide and 250 g/l of pyraclostrobin	120–160 ml	20–50% of flowering
Evito 480	UPL AgroSolutions Canada Inc.	480 g/l of fluoxastrobin	59–118 ml	20–50% of flowering
Holdfast	WinField United	480 g/l of prothioconazole	125–150 ml	20–50% of flowering
Lance AG	BASF Canada	70% boscalide; 250 g/l pyraclostrobin	132 ml; 140 g	20–50% of flowering

(End of Table 4.12)

1	2	3	4	5
Lance WDG	BASF Canada	70% boscalide; 250 g/l pyraclostrobin	140 g	20–50% of flowering
Miravis Bold	Syngenta Canada Inc.	200 g/l podiflumethophen	405 ml	20–50% of flowering
Overall 240SC	ADAMA	240 g/l of iprodione	0,85–1,25 ml	20–50% of flowering
Priaxor	BASF Canada	167 g/l of fluxapiroxide and 333 g/l of pyraclostrobin	180 ml	20–50% of flowering
Prodex	Sharda Crop Chem	240 g/l of iprodione	0.85–1.25 ml	20–50% of flowering
Proline 480 SC	Bayer	480 g/l of prothioconazole	125–150 ml	20–50% of flowering
Proline Gold	Bayer	200 g/l fluopyram and 200 g/l prothioconazole	253 ml	20–50% of flowering
Quadris	Syngenta Canada	250 g/l azoxystrobin	280–400 ml	20–30% of flowering
Quash	Valent Canada distributed by Nufarm Agriculture Inc.	50,0% metronazole	57–115 g	20–50% of flowering
Quash SC	Valent Canada.	480 g/l metronazole	59–118 ml	20–50% of flowering
Quasi	AgraCity Crop & Nutrition Ltd.	250 g/l azoxystrobin	280–400 ml	20–50% of flowering
Rovral Flo	FMC Corporation	240 g/l of iprodione	0.85–1.25 ml	20–50% of flowering
Serenade OPTI	Bayer	1,31 x 10 x 10 CFU/g Bacillus subtilis (strain QST 713)	0,1–0,4 кг	20–50% of flowering
Serenade SOIL	Bayer	1.31 x 10 x 10 CFU/g Bacillus subtilis (strain QST 713)	0,4–1,6 ml	Start applying at 20–30% of flowering
Soratel	ADAMA	250 g/l prothioconazole	240–280 ml	20–50% of flowering

Serenade OPTI is a bacterial preparation based on *Bacillus subtillis* that is applied foliarly at the 20 to 30 per cent flowering stage of rapeseed, similar to how fungicides are applied. *B. subtillis* is an antagonist of fragile ascospores and developing hyphae.

Crop rotation is not always effective in controlling sclerotinia stem rot, as *S. sclerotiorum* can be a host on many plants (including many popular crops) [208]. In addition, ascospores can be transported by air from neighbouring fields, where they are released by apothecia germinating from sclerotia left over from previous broadleaf crops. Nevertheless, the likelihood of high levels of sclerotinia stem rot increases with successive broadleaf crops due to the increased potential for spore formation within the field.

Cereals and grasses are not susceptible to the pathogen and may contribute to the reduction of viable sclerotia in the soil through decay and germination in the absence of susceptible hosts. Therefore, it is best to avoid sowing rape next to a field that was heavily infested the previous year. Controlling susceptible weeds and reservoir plants in cereal crops also helps to avoid replenishing the level of viable sclerotia.

It is recommended to use clean varietal seeds free of sclerotia. Since sowing density is an important factor, the recommended sowing rates should be observed. Studies conducted at the University of Manitoba have shown that increasing the seeding rate by two to three times the normal seeding rate can lead to lodging, which can increase sclerotinia infection [209].

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Unfortunately, this disease can progress rapidly in the swath in wet years, especially in winter oilseed rape (*B. napus*) varieties. It is recommended not to swath rapeseed crops with a high infection rate if rain is forecast, especially if the crop is immature (green) at the time of mowing. In wet, compacted swaths, especially on corners, sclerotinia rot can progress rapidly. The disease can be detected by the smell of rotten eggs coming from the swaths. Obviously, this problem is more prevalent in humid regions. The heavier and more compact the swath, the more likely it is that sclerotinia will rot in the swath before it is threshed.

In addition to seed infestation, viable sclerotinia pose a potential quarantine risk when exporting seed. Viable sclerotia in infected cruciferous seeds can be destroyed by fumigation. In order to check the secondary spread of the disease, the possibility of controlling the disease by foliar spraying with chemicals has been investigated. Some chemicals, such as quintosene, phenyl acetate and calcium cyanamide, have been found to be effective in inhibiting apothecial development of the fungus. Ridomil MZ (mancoceb + metalaxyl) as a seed treatment provided the highest germination and post-emergence mortality of *S. sclerotiorum* [211].

Seed treatment at sowing and foliar spraying at first budding-flowering with 0.2% benomyl proved to be the best option. The use of carbendazim at 0.25% w/w for foliar spraying can be effective in controlling this disease.

Application of fungicides in the full flowering phase [212] using venturi nozzle technology was effective in reducing pathogen infection. Foliar spraying with zinc pyrithione inhibited the development of the pathogen.

As noted earlier, no single method can effectively control *S. sclerotiorum*, and the best approach to controlling the pathogen is to integrate various environmentally sound measures. In recent years, the growing awareness of pesticide pollution and the development of fungicide-resistant strains of *S. sclerotiorum* [213] encourages plant pathologists to search for environmentally friendly means to combat sclerotinia rot.

Boscalid (trade name Cantus in China) is a new broad-spectrum fungicide belonging to the carboxamide class. It inhibits the enzyme succinate ubiquinone reductase (Complex II), also known as succinate dehydrogenase, in the mitochondrial electron transport chain [214–215].

A new fungicide, namely manganese prochloride chloride, proved to be effective in delaying both mycelial and carpogenic germination of *S. sclerotiorum*; thus, it has both a protective and therapeutic effect on the disease [216].

A combination of cultural and chemical means can be used to control S. sclerotiorum. Once again, crop rotation is an important practice to reduce the sclerotia population in the soil. Due to the long survival of sclerotia, the use of deep ploughing is questionable. It has also been found that drip irrigation can dramatically reduce the incidence of sclerotinia.

It should be noted that the degree of stem rot damage in cruciferous crops is assessed on a scale of 0–4 as follows [217]:

0 = No visible lesion;
1 = 0.1–2 cm lesions on the stem;
2 = 2.1–4 cm lesions on the stem;
3 = 4.1–6 cm lesion length on the stem and
4 = > 6 cm lesion length on the stem (completely dried plant).

Inoculum of S. *sclerotiorum* can be detected in field air samples (using the Burkard spore trap) and on petals by PCR analysis of nuclear ribosomal sequences.

The presence of S. sclerotiorum on plants can be detected by an immunological detection method, namely, dimeric single-chain variable fragments (scFv) of antibodies with affinity for the pathogen [218] and enzyme-linked immunosorbent assay based on polyclonal antibodies [219].

S. sclerotiorum infestation of petals can be rapidly detected using real-time and nested PCR methods [220]. Although the detection of *S. sclerotiorum* ascospores can be performed using a passive trap, bulk trapping and PCR methods can also be used to quantify ascospores [221–223].

Resistant cultivars with combined resistance to different isolates of white rust can be potential donors for further improvement programmes in oilseed rape [224]. Transfer of resistance to white rust in oilseed rape and mustard from *B. carinata* to *B. juncea* may be partially successful by growing disease-free plants under high disease pressure and then re-crossing them with *B. juncea* [225]. White rust resistance in oilseed rape and mustard is dominant, controlled by one or two genes with dominant-recessive epistasis or complete dominance in both gene pairs, but either gene, when dominant, is epistatic to the other. These genes can be located at

the same locus or at different loci [226]. Disease resistance at the true leaf stage and susceptibility at the cotyledonous leaf stage of the same genotype of *B. juncea* genotype appear to be regulated by two independent genes. Therefore, screening for white rust resistance at the cotyledon leaf stage is possible. Interspecific crosses between *B. juncea* and *B. napus* showed that resistance to *A. candida* is controlled by a single dominant gene.

In research [227] for of three interspecific crosses between *B. juncea* and *B. napus* revealed a digeneic control with epistatic interaction for white rust resistance trait and a close association between parental species and different degrees of leaf coverage.

Using diallel crosses between two white rust-resistant Canadian *B. juncea* cvs. Domo and Cutlass and two susceptible Indian *B. juncea* cvs. Kranti and Varuna, reported that the F_1 hybrids, except for susceptible × susceptible, were resistant; segregation for resistance in F_2 and test crosses was controlled by a single dominant gene in Domo and Cutlass, and that a recessive susceptibility gene was present in Kranti and Varuna.

Reported [228] on monogenic inheritance, which showed complete dominance in four crosses and no dominance in seven crosses between *B. juncea* and resistance sources from different species. Resistance was reported to be dominant in all crosses except susceptible × susceptible, where it was recessive. Under controlled conditions, inoculation with three different races of *A. candida* of the F_2 population from resistant × resistant crosses showed that resistance genes can be located at the same locus or at different loci. The partial resistance of *B. napus* to *A. candida* is controlled by a single recessive gene, designated wpr, with variable expression [229].

Resistance to white rust in *B. juncea* [230–232] is controlled by a single dominant gene. These studies have shown that only one resistance allele is sufficient to cause an incompatible response in this pathosystem.

Resistance genes were mapped and identified on *B. juncea* chromosomes, namely:Acr [233], AC-21 [234], AC-2, ACB1-A4.1 та ACB1-a5.1 [235]; *B. rapa*, namely ACA1 [236]; *B. napus*, namely ACA1 [237] та AC 2V1; та *A. thaliana*, namely RAC-1, RAC-2, RAC-3 та RAC-4 [238], effective against one or more than one race *A. candida.* One gene (Acr) responsible for resistance to *A. candida* was identified in a densely populated population of *B. juncea*.

Two closely related RFLP markers (X42 and X83) were identified at a distance of 2.3 and 4 cM from the Acr locus, respectively. To date, the following have been processed [239] linkage mapping of genes controlling white rust resistance in B. napus. A polymerase chain reaction (PCR)-based split amplified polymorphic sequence (CAPS) marker was developed for the tightly linked randomly amplified polymorphic DNA (RAPD) marker OPB061000.

The data obtained from 94 recombinant inbred lines showed that the CAPS marker for OPBO61000 and the AFLP marker E-AAC/M-CAA350 flank the Ac2(t) gene at a distance of 3.8 and 6.7 cM, respectively. Validation of the CAPS marker in two different F_2 populations of Varuna × BEC-144 and Varuna × BEC-286 crosses showed its usefulness in marker assisted selection for white rust resistance.

Crop rotation helps to manage this pathogen. Disposal of plant residues affected by the disease, especially carrion, helps to minimise the accumulation of the inoculum in the soil. Excessive irrigation of crops should be avoided, which helps to reduce the damage. Clean, healthy and certified seeds should be used to avoid seed-borne white rust disease.

Since *A. candida* spores require free water to germinate, not just high humidity, minimising the appearance and duration of leaf wetness, as the use of a drip irrigation system can reduce infections.

As the disease is more prevalent in areas with high humidity or in moderately humid climates, planting crops during dry seasons can reduce infection and the spread of the pathogen.

Removing symptomatic weeds of disease reservoirs can also help control the prevalence of the pathogen, as the pathogen infects more than 240 different plant species [240].

The application of K to the soil as the main fertiliser at a dose of 40 kg/ha resulted in a significant ($P < 0.05$) reduction in the amount of white rust on leaves and pods. Early sowing dates can help reduce the prevalence of the disease and increase seed yields [241–243]. An appropriate sowing date must be determined based on location and other epidemiological considerations to ensure that disease can be avoided in different locations.

In recent years, the growing awareness of the problem of environmental pollution by pesticides and the development of fungicide-resistant

strains of plant pathogens has prompted plant pathologists to search for environmentally friendly tools in disease control.

Aqueous extract of *A. sativum* bulbs 1% (w/v), isolate of *T. viride* as a seed treatment and in combination with appropriate foliar sprayers was statistically not inferior to manoczeb, combination of metalaxyl 35 ES 6 ml/kg seed treatment + 0.2 g/l spray of combination metalaxyl + manoczeb in terms of the degree of rust development on leaves and the amount of pathogen on the plant [244].

The inhibition of oospore development in *A. candida* by the natural bioagent *Psuedomonas syringe* in the field has been reported. Spraying with leaf extract of Eucalyptus spp. [245] can also effectively control the disease.

The first work on chemical control of white rust focused on the use of copper-based fungicides to control the developmental stage of the disease on leaves. In this case, it is reported [246–247], that this cruciferous disease can be controlled by frequent spraying with copper-based fungicides.

It is recommended to use Bordeaux mixture or Perox to control white rust of cabbage and other diseases. With the development of dithiocarbamate, control of white rust was achieved by repeated applications of protective fungicides. However, these fungicides did not provide sufficient protection against the sporulation phase of the disease. Acylalanines, which are specifically active against peronosporous fungi, now allow for control of both the leaf and cotyledon stages of white rust by seed treatment or soil impregnation and fewer foliar sprays. Three sprays of Polyram M 0.2% at 15-day intervals were most effective in controlling white rust of B. campestris in Pakistan.

Many fungicides have been evaluated for their effectiveness against white rust of cruciferous crops in India. Benlat 0.1%, Calixin 0.1%, Difolatan 0.2%, Dithan Z-78 0.2%, Miltox 0.3%, Tiovit 0.3%, Mancozeb 0.2%, Mancozeb + Metalaxyl (Ridomil MZ 0.05%) and Ridomil 0.2% were effective in controlling both foliar and heading stages of the disease and increasing crop yields [249–255]. Application of Metalaxyl, metalaxyl + manoczeb (ridomil MZ) [256–258], aluminium tris, and the combination of metalaxyl 35 ES 6 ml/kg seed treatment + 0.2 g/l spray of metalaxyl + mancozeb combination are reported to be able to control the disease. Three foliar treatments with the fungicide at an interval of 15 days after the disease emergence or on the 40-45th day of crop growth provide effective and cost-

efficient disease control [259]. For maximum disease control and high seed yield, it is recommended to treat seeds with metalaxyl (6 g Apron 35 SD/kg of seeds) followed by three sprayings with Ditan M-45 or metalaxyl [260].

Table 4.13

Effective fungicides used worldwide against white rust in cruciferous vegetables [248]

Name of the fungicide	Active ingredient	Pharmace-utical form	Crops for which it is recommended for use
Ridomil Gold® SL	Metalaxyl-M	Emulsion concentrate	All types of cruciferous plants
Serenade® MAX	*Bacillus subtilis* strain QST 713	Water-soluble powder	All types of cruciferous plants in organic cultivation systems
Abound® FF	Azoxystrobin	Emulsion concentrate	All types of cruciferous plants
Чемпіон® WG	Copper hydroxide	Wetting powder	All types of cruciferous plants
Earth-tone® GF	Copper salts	The solution is ready to use	All types of cruciferous plants
Regalia® BC (organic)	*Reynoutria sachalinensis*	Emulsion concentrate	All types of cruciferous plants in organic cultivation systems

Seed treatment with Apron 35 SD protects the crop from white rust for at least 60 days [261]. To control the phase of entering the tube, foliar spraying with Mancozeb, Metalaxyl or a mixture of Mancozeb + Metalaxyl is necessary [262]. Adequate leaf cover and a single spray coinciding with the start of flowering are essential to prevent secondary spread of the disease and infection of flower buds.

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4.3. Integrated systems and methods for downy mildew and powdery mildew control in cruciferous crops

There is no single method or approach to control downy mildew in cruciferous crops that is appropriate, effective, environmentally friendly and cost-effective. It is always necessary to integrate available disease management methods.

The cultural control of downy mildew in cruciferous vegetables is largely a matter of sanitation and manipulation of the environment to the benefit of the host and the detriment of the pathogen. Since the pathogen survives as oospores in the tissues of the host plant, it has been suggested that infected plant residues should be removed, destroyed and burned together with weeds to limit the source of the primary inoculum.

In addition, the use of clean, well-drained soils with a two-year crop rotation using non-cruciferous crops is recommended. Measures to reduce the relative humidity around the plants through adequate aeration and avoiding dense sowing and weed control also contributed to the reduction of the disease incidence. Avoiding continuous rapeseed crops in the same field or next to a field sown with rapeseed in the previous year also helped to reduce *P. parasitica* infection. Widespread cultivation of one or only a few varieties of the same species can contribute to the spread of the disease.

In India, late crops of canola and mustard were reported to have a higher incidence of downy mildew than early or timely crops [1]. Fungicide seed treatment followed by foliar spraying is a common practice for the control of downy mildew in cruciferous vegetables.

In the period from the mid-1940s to the mid-1990s, downy mildew control in cruciferous crops was based on the frequent use of sprays or fungicides such as chloranil (spergon), copper-based products and cyneb. These products were subsequently replaced by other non-systemic fungicides such as captafol, daconil, dichlorofluanide, propineb, Bordeaux mixture, copper oxychloride, mancozeb, ziram, chlorothalonil and fentin hydroxide. Captafol, mancozeb, difolate, copper oxychloride, dichlorofluanide, propineb and metalaxyl were better than other fungicides on large numbers of cruciferous plants in several locations. The timing of fungicide applications, number and interval of sprays depend on the duration and type of crop grown.

Biological control. Garlic juice or aqueous extracts of garlic have been reported to be toxic to *P. parasitica*, which causes downy mildew of radish [2].

Lepidium graminifolium – bacteria that have been observed on the mycelium, conidia and conidia of P. parasitica to reduce conidial germination. Many sources of resistance to downy mildew in cruciferous plants have been identified in major host species from different parts of the world. Information is also available on the genetic interaction between the parasite and the host. Efforts are underway to develop downy mildew-resistant varieties of various cruciferous crops using traditional and biotechnological methods.

In the quadrangle of integrated management (chemical-cultural-biological-host resistance) of downy mildew in cruciferous vegetables, biological control has not been used in the field Breeding for resistance has been successful for only some cruciferous vegetables. Chemical control of this disease may not always be reliable, as P. parasitica has developed resistance to metalaxyl, which at one stage proved to be extremely effective in controlling downy mildew [3].

Thus, there is a clear need to develop sources of resistance that can withstand pathogenic variation. It is also possible that differentiated sources of host resistance may be useful in integrated control programmes if used in conjunction with fungicides; this would potentially prolong the effectiveness of both control procedures [4]. Other methods include sanitation, field practices such as sowing time, plant density, and judicious use of nutrition and irrigation to prevent inoculum levels from building up [3].

Figure 4.10 – Monitoring signs of downy mildew in winter oilseed rape [5

The level of infection with downy mildew depends on the resistance of varieties and hybrids, the amount of infection in the field and protection systems. An additional incentive for the spread of the disease is the fact that recently a lot of agricultural land has been planted with rapeseed. The difficulty of controlling downy mildew is due to its biological characteristics. The use of ineffective products leads to the accumulation of pathogens in the soil. Peronosporosis is difficult to control because it is a fake fungus, and most of the products on the market are designed to control real fungi.

As a result, the main measures for controlling downy mildew on cruciferous crops are:

1. Growing resistant varieties and hybrids.
2. Sowing with treated seeds.
3. Destruction of carrion, which is a reservoir of infection. Complete clearing of the field from the residues of the previous harvest
4. Observance of crop rotation with the return of cruciferous crops to the same field no more than once every 3–4 years.
5. Adhere to agrotechnology, especially in the context of thickened crops.
6. Maintain spatial isolation (at least 1 km) of cruciferous crops from the fields where they were grown in previous years.
7. Use of balanced mineral nutrition of the crop. Magnesium and Boron increase the resistance of plants to downy mildew.
8. Use of fungicides during the growing season according to the "List of Pesticides and Agrochemicals Permitted for Use in Ukraine" based on active substances such as carbendazim, azoxystrobin, cymoxanil, etc.

Preparations based on a mixture of carboxyl substances with thiram or the active ingredient carbendazim are also effective. Preparations based on iprodione or potassium dithiocarbamate and a mixture of fludioxanil and metalaxyl will also be effective. The first spraying should be done after the vegetation has resumed on winter cruciferous crops before the branching phase on spring and winter forms, and the second spraying should be done before the budding and flowering phase.

Application of fungicides at the end of flowering and on pods – systemic fungicide Arbalet, CS – 0.6–1.0 l/ha or systemic and contact fungicide Junker, WP – 2,5 kg/ha. Defined [6] controlling powdery mildew through exclusion, eradication, protection, immunisation and therapy. Of these methods, chemicals and genetic manipulation are probably the most

important at the moment, given the nature and mechanisms by which the pathogen reaches epidemic levels within a very short period of time after disease onset. Future projections of climate change worldwide, with rising temperatures and dry periods, may make the situation worse for powdery mildew to develop into epidemic forms. Under such conditions, chemical control is the best option to combat the disease from the initial stage. However, the cultivation of resistant varieties is prioritised wherever they are developed or available to protect against environmental contamination and to save cultivation costs that may be imposed in the form of chemical and labour costs. Limited sources of powdery mildew resistance have been identified in *B. alba, B. alboglabra, B. rapa* var. *brown sarson*, *B. chinensis, B. japonica* and *E. sativa.* Transgenic *B. napus* plants expressing bacterial catalase in the chloroplast can inhibit the growth of E. cruciferarum. These plants showed constitutive expression of catalase and polyphenol oxidase enzymes and high levels of free polyamines such as putrescine, spermidine and spermine [7]. Alternatives, such as cultural control based on the time of sowing to avoid a favourable period for the pathogen to multiply, have also been recommended and effective. Certain micronutrients and biological control agents also help to control cruciferous powdery mildew. Selecting appropriate sowing dates according to the area is a promising method of controlling the disease. Scheduling irrigation only at the 50% stem branching stage in cruciferous crops can control the disease [8].

Powdery mildew hyperparasites can be used as a means of biological control. Cultural practices such as mixed cropping and intercropping can also be useful in application. Several chemicals have been tested against cruciferous powdery mildew. Some of them have been shown to be effective in controlling cruciferous disease and preserving crop yields. For effective control of the disease, fungicides should be applied immediately after the disease appears, as it spreads very quickly after its occurrence. The effective active ingredients of fungicides studied are presented in the table below 4.14–4.18.

General cultural practices, such as the use of healthy seeds of improved varieties, weed and crop residue control, sowing at the recommended time, long crop rotation, maintaining optimal plant density, and a rational fertilisation system are effective in controlling the development of powdery mildew in cruciferous crops by preventing primary sources of inoculum and secondary spread of the disease in the field.

Table 4.14

Fungicides and chemical compounds tested for effectiveness against powdery mildew [8]

Fungicide, chemical compound*	Reference to the source of study
1	2
Acrix	[7]
Actidion	[9]
Ammonium copper carbonate	[10]
Ammonium sulphide	[11]
Eipron 35 SD	[12]
Arsenat	[13]
Bavistin	[14]
Bakor Bayleton Baytan Benomil Blitox-50	[15]
Boora	[16]
Bordeaux liquid	[17]
Burgundy liquid	[18]
$CaCo_3$	[19]
Calixin	[20–25]
Carbendazim	[26]
Chloranil	[27]
Chlorothalonil	[28]
Copper-lime dust	
Copper sulphate	[29]
Cycloheximide	
Dichloronaphthoquinone	[30]
Diphenoconazole	[31]
Dinitrocapril phenyl crotonate	
Dinocap	[32–34]
Elgethol	[35]
Elosal	
Fermat	[36]
Flusilazole	
Formalin	[37]
Hexaconazole	

(End of Table 4.14)

1	2
Iprodion	[38]
Karatan	[39–41]
Liquid lime sulphur	[42–43]
Lithium carbonate	[44-45]
Malachite green	[46]
Mancozeb	
Maneb	[47]
Manzat	[48]
Metalaxyl	
Morestan	[49]
Morosid	
Nimbicidin	[50]
Penconazole	[51]
Potassium permanganate	[52]
Propiconazole (tilt)	
Ridomil MS-72	[53-54]
Rizoleks	
Salicylic acid	[55]
Sodium bicarbonate	[56]
Sodium chloride	[57]
Sodium thiosulfate	[58]
Spergen	[59]
Sulfex	[60-62]
Sulphuric acid	[63]
Sulphur dust	[64]
Colloidal sulphur	[65–69]
Tebuconazole (Folicur 48 EC)	
Tiovit	
Topsin	[70–72]
Triadimephon	[73–74]
Tridemorph	[75]
Vegetable oils	[76]
Vulcanised rubber	[77]
Zinc sulphate	[78]

*The name of the chemical corresponds to the original publication.

Plant extracts and some biological control agents of fungal and bacterial origin have been shown to have antagonistic effects against powdery mildew of cruciferous plants (Tables 4.19–4.20).

Breeding resistant cruciferous varieties is also important in terms of pathogen control. Sources of resistance to the main host genes were identified in *B. juncea, B. rapa, B. napus, B. carinata, B. alba, A. thaliana* and *R. sativus* from different countries.

Table 4.15

Effect of time and number of fungicide sprays on the development of mustard powdery mildew [77]

Fungicide	Concentration (%)	Disease intensity (%) (T_1)	Reduction in morbidity (%)	Disease intensity (%) (T_1)	Reduction in morbidity (%)	Disease intensity (%) (T_1)	Reduction in morbidity (%)
Sufflex	0.20	32.0	65.2	70.0	30.0	7.5	92.5
	0.30	30.0	67.3	70.0	30.0	5.2	94.8
Topsin M	0.05	63.0	31.5	82.0	18.0	14.5	85.5
	0.10	62.5	32.0	80.5	19.5	12.5	87.5
Karatane	0.05	26.6	71.0	63.4	36.6	6.2	93.8
	0.10	24.7	73.1	60.2	39.8	4.3	95.7
Calixin	0.05	36.1	60.7	72.3	27.7	8.4	91.6
	0.10	35.0	61.9	70.4	39.6	5.2	94.8

T1 = One spray at the time of disease onset; T2 = One spray 10 days after disease onset; T3 = Two sprays, the first at the time of disease onset and the second 10 days after the first.

These sources are used for breeding varieties resistant to powdery mildew using conventional and biotechnological methods. It is emphasised [79] that, that the most effective, cost-efficient and environmentally friendly management of powdery mildew disease can be achieved through the use of resistant varieties that can be easily developed using resistance sources by transferring cloned resistant R genes into agronomically susceptible varieties (Figure 4.11).

Table 4.16

Influence of variants of powdery mildew control agents application on the formation of white mustard seed quality indicators [79]

Variant of the active substance	Concentration (%)	PDI	Number of abnormal seeds per 100 seeds	Percentage reduction to control	Seed germination (%)	Length of seedling, cm	Growth strength index
Hexanazole	0.05	35.00	18.66	45.65	92.75	12.86	1192.8
Colloidal sulphur	0.20	38.67	18.33	46.61	91.75	12.53	1149.6
Tebuconazole	0.05	35.33	19.00	44.65	90.75	12.74	1156.2
Tridemorph	0.04	23.33	18.00	47.57	92.75	12.81	1188.1
Diphenoconazole	0.05	51.67	19.66	42.73	90.50	12.70	1149.4
Onion extract *(Allium cepa* L.)	5.00	78.33	32.66	4.86	86.00	12.50	1075.0
Neem leaf extract *(Azadirachta indica* A.)	5.00	74.00	30.66	10.69	85.25	11.99	1022.1
Eucalyptus leaf extract *(Eucalyptus globulus* L.)	5.00	74.67	29.00	15.53	85.75	12.36	1059.9
Karan leaf extract *(Nerium indicum* L.)	5.00	73.33	30.00	12.61	86.00	12.25	1053.5
Karanja leaf extract *(Pongamia pinnata* L.)	5.00	76.33	33.00	3.87	84.75	12.45	1055.1
Culture of *Trichoderma viride*	3.00	65.67	23.33	32.04	87.75	12.51	1097.8

Table 4.17

Effect of different fungicides on the development of powdery mildew on white mustard [77–79]

Variant	Concentration, %.	Percentage of damage (%)	Technical efficacy of the product (%)
Galixin	0,2	33,4	62,88
Hexanazole	0,2	30,6	66,0
Bovistin	0,1	46,5	48,3
Colloidal sulphur	0,2	40,3	55,2
Topsin M	0,2	63,7	29,2
Blitox-50	0,2	49,9	44,5

Table 4.18

Effect of different treatments on the development of powdery mildew on white mustard [77–79]

Variant	Pathogen infestation after application (%)
Garlic extract	50.6
Apron 35 SD	22.0
Carbendazim	16.0
Apron 35 SD + Carbendazim	13.0
Apron 35 SD + Ridomil MC	29.0
Mankotseb	59.6
Carbendazim + Ridomil MC	34.0

Table 4.19

Bio-agents tested against powdery mildew of cruciferous plants

Bioagents	References
Allium sativum (bulb extract, 1%)	[81–82]
Azadirachta indica (leaf extract, 2%)	[83]
Datura stramonium (leaf extract, 2%)	
Eucalyptus (leaf extract, 2%)	[84]
Trichoderma harzianum (10 g/kg)	[85]
Trichoderma harzianum (10^8CFU/кг)	[86]
T. viride (suspension)	
Ampelomyces quisqualis (10^8CFU/ml)	[87]
Nerium indicum L. (Karan) (leaf extract, 5%)	
Pseudomonas fluorescens (oil (10 g/l water))	[88]
Pongamia pinnata L. (Karanj) (leaf extract, 5%)	
Pseudomonas fluorescens (10^8 cells/ml)	[89]

Plants have developed a well-organised defence system against fungal attack by the powdery mildew pathogen. For example, cuticle wax acts as an important physical barrier to prevent fungi from entering the host cell [90], особливо для патогена, який росте поверхнево на рослинах [91]. Moreover, the host organism demonstrates a number of immune responses, including the accumulation of reactive reactions (Figs. 4.13–4.17).

Figure 4.11 – Rapeseed pods and stems infected with Erysiphe cruciferarum in fungicide-treated plants (left) and untreated plants (right) [79]

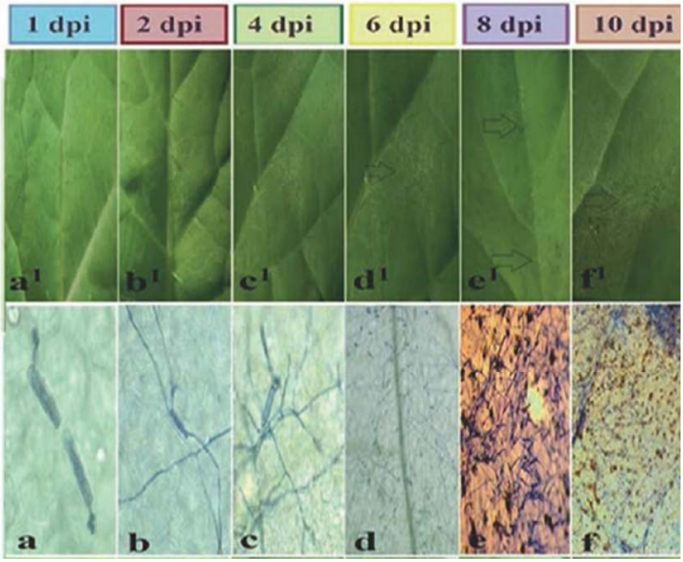

Figure 4.12 – Symptoms of *Erysiphe cruciferarum* on leaves infected with *B. napus* (pathogen resistant form) at six time points of recording. Symptom images were (a1, b1, c1, d1, e1, f1) and light micrographs were (a, b, c, d, e, f) at 1, 2, 4, 6, 8 and 10 days (dpi) after infection, respectively. Scale bars for light micrographs are 25 μm [89]

Some cruciferous species, such as S. *alba, E. sativa* and *R. sativus*, showed complete resistance to powdery mildew in both years of research. Varietal resistance provides an opportunity for effective management of powdery mildew in oilseed rape [92]. Since host resistance plays an important role in the spread of the disease, genetic engineering is a promising tool for reducing infection rates. There are promising results of increased resistance to *E. cruciferarum* in transgenic lines of *B. juncea*. The content of glucosinolates or the release of their volatile metabolites or other nitrogen- and sulphur-containing phytochemicals, such as phytoalexins and glutathione, which are synthesised after pathogen damage, may be one of the reasons for the different stress resistance of cruciferous plants [93–95]. In addition, daily temperature and light intensity, not to mention soil pH, influence stress tolerance, as the combined effect of UV-B radiation intensity and temperature was probably the reason why *B. juncea, B. napus* and *E. sativa* grown in the field contained four times more glucosinolates than those grown in the greenhouse [96]. Finally, the higher resistance of *S. alba, R. sativus* and *E. sativa* to powdery mildew compared to *B. juncea, B. napus* and *B. nigra* may also be related to morphological features of the plants, such as the density of non-glandular trichomes on the plants [97]. For example, a sparse distribution of trichomes is characteristic of *B. napus* leaves, while *B. villosa* leaves are much more densely and evenly covered with trichomes [98].

In general, a large number of non-glandular trichomes increases the reflectivity of the leaf surface and thus increases the resistance of plants to drought stress [99]. However, they also capture airborne particles, including fungal spores, and thus a higher density of trichomes can increase the risk of fungal infections [100]. Non-glandular trichomes are an excellent habitat for pathogens if they do not contain an antifungal hydrolase, which inhibits or reduces fungal infection by hydrolysing the fungal cell walls. Thus, based on the knowledge of glucosinolates and trichomes, attempts have been made to increase stress tolerance in, for example, B. napus through genetic engineering by transferring the tissue-specific lipid transfer protein from B. rapa to B. napus to increase the number of trichomes and glucosinolates in the leaves of plants [101].

Currently, there is a limited range of alternative cruciferous and non-cruciferous oilseeds for cultivation in the northern regions, and there

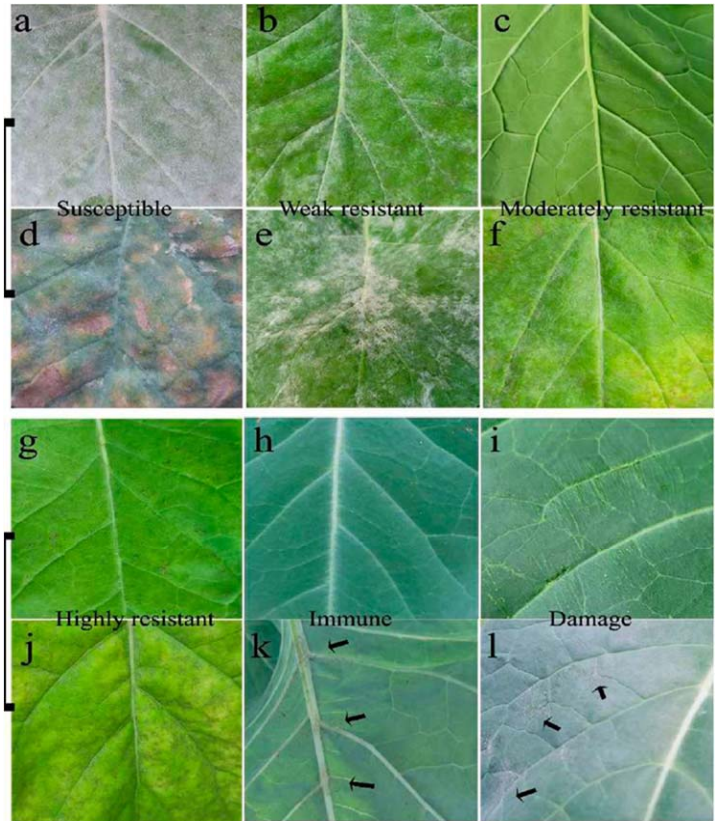

Figure 4.13 – Phenotypic differences in leaves of different plant samples after inoculation with powdery mildew pathogen. The susceptible variety (a) and the low-resistant plant (b) showed more hyphae and mycelium than the medium-resistant plant (c) and the highly resistant plant (g). Necrotic lesions on old leaves (d-f, j) of the above plants. No hyphae were found on the leaves of the immune plant (h), but several brown dots were observed on the old leaf (k, arrows). Spores failed to penetrate the leaves of the immune plant where surface damage was caused by sandpaper friction (i), but light infection (l, arrows) was observed on unhealthy plants with lateral damage [102]

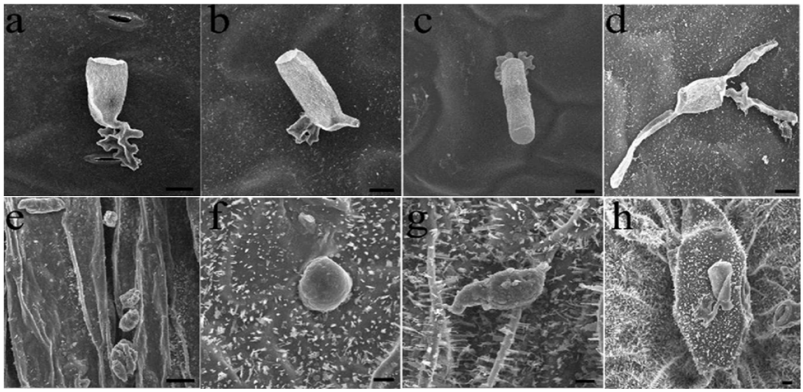

Figure 4.14 – Scanning electron micrographs of *E. cruciferarum* developing on rapeseed leaves (top row, non-susceptible plant, bottom row, resistant plant). Penetration into the host cell and formation of an appressoria on the stomatal cell (a), stomatal cell (b) or furrow between cells (c). Secondary hyphal growth after cell penetration (d). Dead cones on the leaf epidermis of a moderately resistant plant (e), a high-temperature resistant plant (f) and a pathogen-penetrating plant (g) after powdery mildew infection. Scabs formed as a result of shrinkage and condensation of tissue around the infection site (h). Scale bar 50 µm [99]

is a significant demand for new oilseeds from local producers [103]. Alternative oilseeds, such as *S. alba*, *E. sativa* and *R. sativus*, even under favourable conditions for powdery mildew infection, have great potential for chemical-free cultivation in different parts of the world. Since powdery mildew is a significant threat to oilseeds, it is essential to use available resistant species and resistant varieties, especially in organic farming systems. This knowledge is also important for the production of cover crops and green manure to suppress pathogens [104–105], and therefore for the selection of species and varieties that are less susceptible to the spread of the disease. White mustard (*S. alba*) may be particularly interesting as it is very suitable as a cover crop due to its rapid initial growth, high glucosinolate levels and low maintenance [106–107] (Table 4.20).

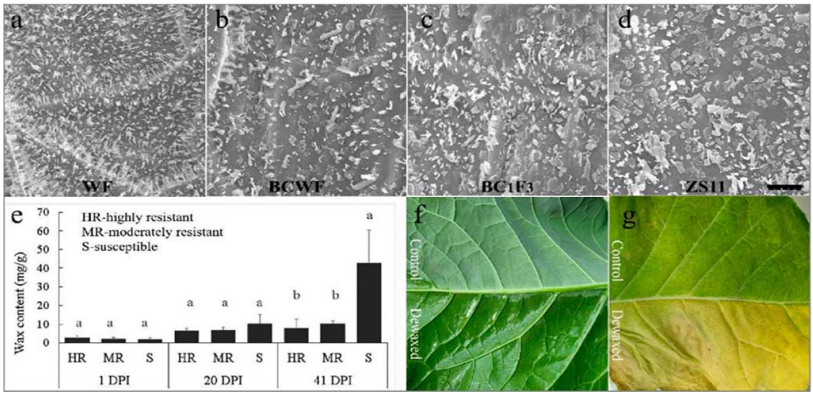

Figure 4.15 – Comparison of the shape and content of wax plaque on different plants and the effect of partial washing of surface wax. Samples in (a-d) are a resistant 'WF' and a moderately resistant 'BCWF' plant in the BC1F3 and 'ZS11' populations, respectively. The cuticle wax of 'BCWF' and 'WF' is needle-shaped. The wax crystals of the resistant 'WF' and 'BCWF' plants are tubular or short and tubular, whereas those of 'ZS11' are mostly flaky. Cuticle wax content in leaves of plants with different levels of resistance (e). Different letters indicate significant differences ($p < 0.05$). Removal of surface wax from half of the blade of a young leaf of 'WF' (f) leads to early senescence but not to changes in powdery mildew susceptibility (g) [99]

Table 4.20

Priorities for cruciferous powdery mildew management strategies [107]

Priorities	Order of importance
Resistant varieties	1
Application of fungicides	2
Seed production	3
Sanitation	4
Crop rotation	5
Mixed crops	6
Density of standing	7
Date of sowing	2
Balanced nutrition	4

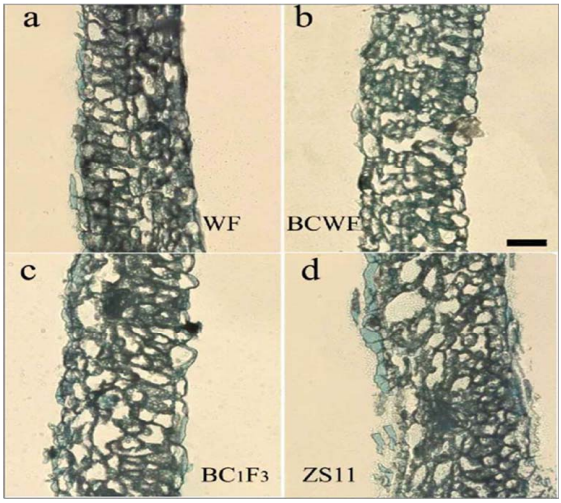

Figure 4.16 – Cross-sections of leaves of four plant samples: 'WF' (a), 'BCWF' (b), 'BC1F3' (c) and 'ZS11' (d). Images have the same magnification and scale bar = 100 µm3068 (resistant 'WF' and moderately resistant 'BCWF' forms to powdery mildew)

It is noted that [107] the need to prioritise powdery mildew control strategies according to the emergence of the disease in an area and the extent and intensity of the disease. The order of prioritisation in the table can be manipulated depending on the timing of disease emergence by using different combinations of control strategies for which the underlying pathogenicity data will be useful in making the appropriate technological decision.

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4.4. Integrated systems and methods for phomosis control in cruciferous crop agrocenoses

Global rapeseed crop losses from phomosis are estimated at more than $900 million per growing season [1–2].

Phomosis is one of the most damaging diseases of rapeseed *Brassica napus* L. ssp. *oleifera* (Metzger) Sinsk. The growing risk of epiphytic development of this disease is associated with the expansion of the area under rapeseed, shorter terms of returning the crop to its original place, low genetic diversity of varieties, a relatively wide range of pathogens, and increased marketing exchange of seeds between countries. The disease is of great economic importance in the main rapeseed growing areas [3]. Yield losses are usually at least 10%, but in some years with high intensity of the disease, they can reach 30–50% [4–6]. (рис. 4.17–4.19).

Phomosis is a very significant problem – the shortfall in rapeseed production due to this disease is 5–20% [7], 50% [8–11] and 75–90% [12–14].

Phomosis is an oilseed disease of international importance. In areas where cruciferous oilseeds are grown (especially in Australia, North America and Europe), this disease can cause significant yield losses [15]. The disease is associated with two closely related fungi, *Plenodomus lingam* and *P. Biglobosus* [16]. These fungi have been classified as Leptosphaeria, but recent studies have shown that they should be classified as Plenodomus [17–18]. The coexistence of these two pathogens has been reported in various European countries, including Poland and Ukraine [19], Lithuania [20] and the Czech Republic [21].

The name ‘rapeseed phomosis’ covers not one, but at least four different diseases, each with its own unique characteristics. The most common causative agent of phomosis in Ukraine is the fungus *Phoma lingam* (Tode: Fr.) Desm. (marsupial stage of *Leptosphaeria maculans* (Desm.) Ces. et De Not.). Due to its ability to produce the nonspecific toxin sirodesmin PL, this fungus causes the greatest damage to rapeseed plants.

The pathogen causes the appearance of large (up to 3 cm in diameter) necrotic spots on the leaves and stem, as well as in the root collar area. The density of the affected tissues gradually decreases, cancerous ulcers and signs of dry rot are observed. During strong gusts of wind, the stems can break. Numerous black fungal pycnidia with conidia are formed on

necrotic rapeseed organs, which contribute to the spread of the disease during the growing season. The marsupial sporulation formed on overwintered plant residues is one of the main sources of infection in spring. Rapeseed disease caused by the fungus *Leptosphaeria macu*lans is often referred to in the old phytopathological literature as A-form of phomosis. Another causative agent of phomosis is the fungus *Leptosphaeria biglobosa* Shoemaker et H. Brun.

The main difference between this species and the previous one is the inability to produce the toxin syrodesmin PL, so the signs of phomosis during the development of this pathogen are not so pronounced.

Necrotic spots on leaves and stems are much smaller (1–3 mm) and dark in colour. The number of pycnidia with conidia on the plants is also significantly lower. This manifestation of phomosis is known as B-form of phomosis.

This form dominates in Asian countries, is quite common in France and the Netherlands, and is probably present in Ukraine. However, its role in the occurrence of rapeseed phomosis in our country remains unexplored. The third pathogen is the fungus *Phoma sublingam* Boerema with the pouch stage of *Leptosphaeria submaculans* L. Holm. This species is distributed only in European countries and has not yet been recorded in other regions of the world. *Leptosphaeria submaculans* can infect various

Figure 4.17 – Leaf spot of phomosis, (upper position – the beginning of infection, lower position – partial death of leaves at the later stages of pathogenesis [22]

Figure 4.18 – Phomosis development in a pathogen-resistant winter oilseed rape variety

Figure 4.19 – Classic symptoms of stem canker are a sign of phomosis infection in rapeseed [23–25]

members of the cruciferous family, so rapeseed is not the main substrate of this species. It is usually found in large numbers on weeds such as dry ribweed (Sisymbrium), hiccup (Berteroa) and yellow brome (Erysimum). The intensive development of this form of phomosis is observed in the case of weed infestation of fields and roadsides. The fourth causative agent is the fungus *Didymella macropodii* Petr., which parasitises plants in the asexual sporulation stage of *Phoma nigrificans* (P. Karst.) Boerema, Loer. et Wittern. An important ecological feature of *Phoma nigrificans* is its high tolerance

to cold. It develops massively during the cold season, so its substrates are mainly perennial or winter cabbage plants: horseradish (*Armoracia rusticana* Gaertn., Mey et Scherb.), winter rape (*Brassica napus* L. var. *oleifera* Metzger), and sometimes field thistle (*Thlapsi arvense* L.). Until recently, this species was recorded only in Northern Europe, but now it is known in Ukraine. This form of phomosis can infect various plant organs, but the most dangerous is root collar rot in winter rape crops.

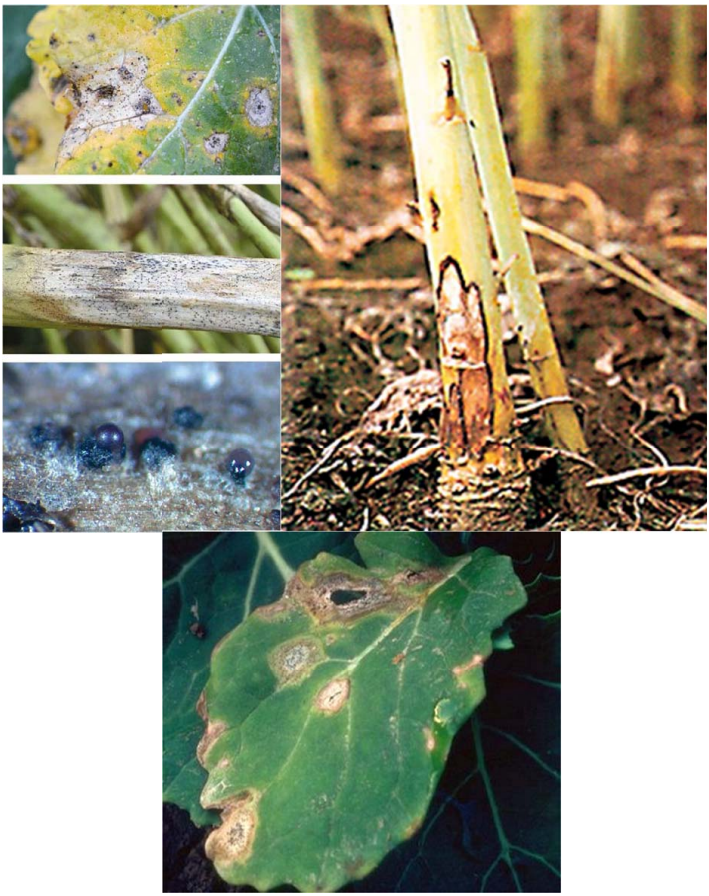

Figure 4.20 – Signs of rape phomosis [26–29]

Figure 4.21 – Both photos show phomosis damage to rapeseed leaves. Note the dead area in the centre, surrounded by a yellow zone. The small black dots in the centre of the lesion are asexual fruiting bodies of the fungus. Spores are formed inside the fruiting bodies and can be spread by rain and spray [30]

A number of studies have additionally reported that Leptosphaeria maculans (Desm.) Ces. & De Not. (anamorphic stage of Phoma lingam (Tode: Fr.) Desm.) and *Leptosphaeria biglobosa* R.A. Shoemaker & H. Brun are the causative agents of rape phomosis. Until recently, *L. maculans* was considered a complex species, within which two groups of isolates were distinguished. These groups were named by different researchers as highly virulent (HV) and weakly virulent (WV) [31], virulent and avirulent [32], aggressive and non-aggressive [33], Tox+ i Tox^0, pathotypes A and NA [35], Group A and Group B [36]. Groups differ in the morphology of colonies on nutrient media [37]. The significant difference between isolates of groups A and B in a number of features allowed us to hypothesise that they are different species [38] (Figs. 4.22–4.23).

They found [41] also morphological differences in the structure of pseudothecia of isolates of these groups and isolates of group B into an independent species Leptosphaeria biglobosa. In the life cycle of rapeseed phomosis pathogens, there are marsupial and conidial stages. Pycnidia develop on spots on leaves, stems and pods, as well as on dead

Figure 4.22 – Cotyledons of winter rape infected with: left: *Plenodomus lingam* and right: *Plenodomus biglobosus* [39]

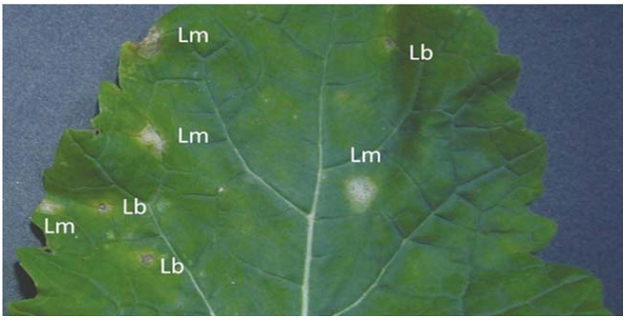

Figure 4.23 – Two closely related pathogens, *Leptosphaeria maculans* (Lm) and *L. biglobosa* (Lb), cause phomose leaf spot and stem cancer [40]

plant parts (Figs. 4.24–4.26). Pseudothecia are formed on dead lignified parts of infected plants. Pycnidia of both species practically do not differ in morphology. The pseudothecia of *L. biglobosa* differ from those of *L. maculans* by the presence of proboscis swollen at the top [42–45]. They are thought to have evolved from a common ancestor, with L. biglobosa being the older species [46–47].

*L. maculans (*anamorpha *Phoma lingam* (Tode: Fr.) Desm.) is an economically important pathogen because it causes stem cancer [48].

The causative agent of phomosis was first described by Tode [49] in 1791. The pathogen has a wide range of host plants within the Brassicaceae family, including wild and cultivated species, including the model species for genetics, *Arabidopsis thaliana* (L.) Heynh [50]. In 2001, weakly virulent isolates of this species were assigned to the species *L. biglobosa* [51].

It is believed that the prevalence of *L. maculans* and *L. biglobosa* in different countries of the world is due to seed transmission of *B. oleracea* L., *B. napus* L., *B. rapa* L. and other Brassica [53]. Previously, only *L. biglobosa* was found in North America and Eastern Europe, but then *L. maculans* was discovered [54]. Until the mid-1990s, the incidence of phomosis in Poland was usually also associated with *L. biglobosa* [55–56].

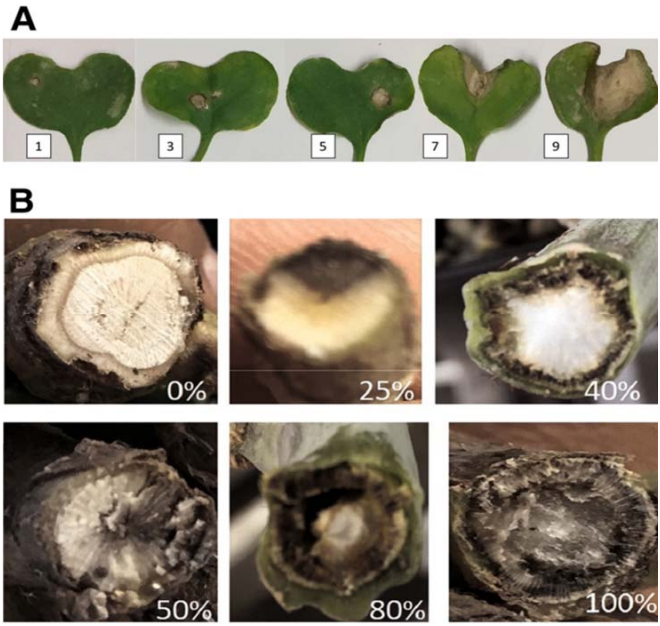

Figure 4.24 – Phomosis severity scale (black leg) used to assess damage (A) at the seedling stage on cotyledon leaves and (B) at the adult stage in percentage of internal tissues in the stem apex area of spring and winter rape, mustard species [50]

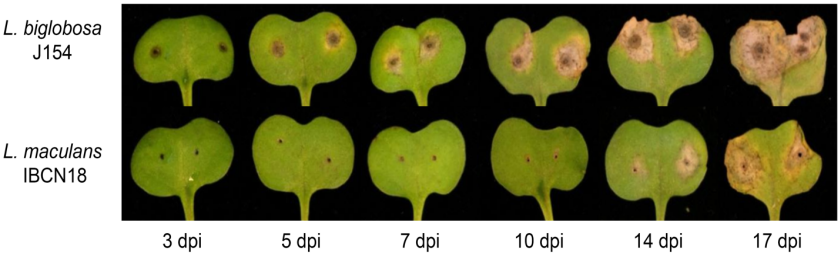

Figure 4.25 – Symptoms on cotyledons of *B. napus* cv. Westar infected with L. maculans brassicae or *L. biglobosa canadensis*. Cotyledons of *B. napus* cv. Westar were wounded and inoculated with spores of *L. maculans brassicae* or *L. biglobosa* canadensis. The disease developed within 17 days after inoculation (dpi). Cotyledons were harvested and photographed at 3, 5, 7, 10, 14 and 17 days (dpi) after inoculation to monitor the development of the lesion by the two pathogens [52]

A recent study of Leptosphaeria spp. on rapeseed leaves in Poland showed an increase in the number of L. maculans isolates compared to their prevalence ten years ago [57]. Changes in the relative frequency of these two pathogens were also found in the Czech Republic and Hungary [58]. The study of the distribution of species in Lithuania showed a variation in their proportion depending on environmental conditions, but in general, 70.3% of *L. maculans* and 29.7% of *L. biglobosa* isolates were detected [59]. These results indicate a west-to-east spread of *L. maculans* in Europe. Currently, *L. maculans* is a threat to rapeseed in Asia. *L. maculans* is present in many countries (except China) where cruciferous crops are widely grown [60]. In China, only *L. biglobosa* was found on rapeseed [61]. In Europe, yield losses are not attributed to *L. biglobosa*, as the pathogen, which affects leaves and the upper part of the stem, usually does not lead to plant death [62].

However, in countries with high summer temperatures, such as Poland and Ukraine, this species can cause significant losses in rapeseed yields [63].

It was believed that the dominance of *L. maculans* over *L. biglobosa* was due to the low aggressiveness of the latter, as *L. biglobosa* develops

only on aging plants at the end of the season and does not lead to significant phomosis damage. However, recently it has been found that this pathogen can cause significant damage not only to the upper part of the stem, but also to its base, leading to large yield losses. Under conditions of high relative humidity, *L. biglobosa* isolates become highly aggressive in cotyledon damage, as less lignin accumulates in the plant cell walls [64].

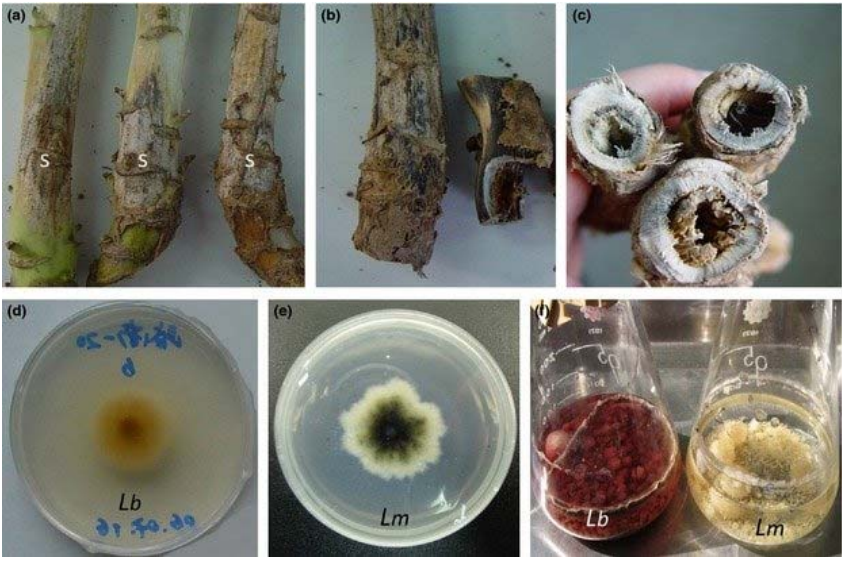

Figure 4.26 – Phomosis stem blight in oilseed rape and identification of Leptosphaeria species causing it. External cancer symptoms (s) observed on the upper stems (a) and stem bases (b) of winter oilseed rape sampled before harvest (black dots are *Leptosphaeria biglobosa* pycnidia), with cross sections showing internal necrosis (c). Potato dextrose agar tests showing the presence of *L. biglobosa* (Lb) (d) but not *Leptosphaeria maculans* (Lm) (e), and Chapeka-Dox broth tests (f) showing the presence of *L. biglobosa* but not *L. maculans* were used to confirm the presence of *L. maculans* or *L. biglobosa* in seeds imported from Canada, Australia and Ukraine [64]

Both pathogens are hemibiotrophs and have a complex life cycle. The fungus can survive as a saprophyte on stem and stubble residues for many years. Once it gets on the leaves, it becomes a necrotroph, producing spots on the leaves. Then, as a biotroph, the pathogen colonises the intercellular spaces, while the endophytic latent stage, where the fungus lives dormant, is asymptomatic. After colonising the intercellular spaces, L. maculans reaches the vascular system of winter rape and spreads down the xylem to the base of the stem within 9 months (in Europe). As a result, the stem bark is destroyed and stem cancer develops [65], that is, the second necrotrophic stage begins at the end of the plant growing season.

The life cycle of the fungus occurs over a wide temperature range. It takes 5 days at 20 °C and 2 weeks at 8 °C for lesions to appear on leaves inoculated with ascospores [66], and the time between the manifestation of lesions on the leaves and their manifestation on the stems is 77 days at 18 °C and 175 days at 3 °C [67].

At high temperatures, the severity of symptoms on cotyledons, leaves and stems increases, so the threat of phomosis increases with climate warming. It was noted that incompatible reactions (small necrotic lesions) on cotyledons introduced at 18 °C by avirulent isolates change to fully compatible reactions at 27 °C [68], which indicates the temperature sensitivity of resistance genes, so, for example, the disease develops faster at 24 °C than at 14 °C. High summer temperatures can lead to serious phomosis epidemics. Pseudothecia ripening depends on humidity and temperature (optimum 14–15 °C) [69].

Pseudothecia usually form on the stubble 9–10 months after harvesting, as temperatures below 0 °C in winter delay their maturation [70]. Залежно від умов навколишнього середовища період вивільнення аскоспор може тривати 3–4 місяці і більше, а пік спостерігається зазвичай через 1–2 місяці після його початку [71]. For germination of ascospores after their release, at least 8 hours of humidity at 4–28 °C (optimum 15–20 °C and 48 hours of humidity) are required [72]. The survival of *L. maculans* on stubble plays an important role in the epidemic, as ascospores and pycnidiospora from infected residues can serve as primary inoculum for infection of rapeseed in spring. The preservation of the fungus on infected residues is influenced by weather conditions and agricultural practices. The rate of degradation of residues depends on soil moisture and temperature,

and dry summers and cold winters are favourable for the pathogen's survival. In Western Canada, for example, ascospores are released from phomosis-infected stubble on the soil surface within 3–5 years because winters are very cold and summers are dry and hot [73].

Survival of the fungus on rapeseed stubble for 3–5 years exceeds the duration of the crop rotation (3 years on average). In Western Australia, L. maculans can survive for up to 4 years because infected canola residues do not decompose in hot, dry summers [74]. In the UK, where the climate is mild and humid, oilseed rape residues take 2 years to decompose. Therefore, proper crop rotation and stubble removal are effective farming practices for controlling phomosis, as this reduces the amount of inoculum available for overwintering [75].

In the generative stage (teleomorphs of *L. maculans, L. biglobosa*), the fungus sexually forms asci with ascospores developing in pseudothecia on lignified remnants of rapeseed roots or stems. In the vegetative stage (anamorph of *Ph. lingam*), the fungus forms almost superficial spherical black pycnidia with a thick sclerotial membrane, which produce colourless pycnidiospora. With sufficient moisture, pink-purple mucus containing vegetative spores is released from the pycnidia. Phomosis pathogens overwinter in the form of pycnidia and pseudothecia on stubble [76] in the form of mycelium in infected plants of winter rape and on the affected residues of cruciferous crops, in the form of mycelium or pycnidia on the seed coat [77–78]. The disease development cycle begins with the airborne spread of ascospores, which are released from pseudothecia (in Europe, for example, both in autumn and spring) and, when germinating, inoculate plants through stomata or in wounds (primary infection) [79]. Ascospores from the primary source of infection can be transported 1–2 km, up to a maximum distance of 10 km [80]. Recently, it was reported that in Canada, the potential for windborne ascospores of the pathogen is 17 km per year, and in China, 47 km per year in spring rapeseed and 70 km per year in winter rapeseed [81]. Shortly after leaf infection, pycnidia with pycnidiospora form on the leaves, which are carried by rain over short distances of up to 1 m and usually cause a less severe secondary infection. However, it has been noted that, for example, in Western Canada, pycnidiospora can also cause primary infection. Secondary cycles produced on affected plants by pycnidiospora do not lead to significant yield reduction, so the pathogen is considered a monocyclic pathogen [82–83].

Symptoms of the disease are observed on the hypocotyl and cotyledons, leaves, stems, pods and roots [84–86]. When infected seeds are sown, watery spots of various shapes appear on the hypocotyl and cotyledons of young plants, which, when dry, become grey with black dots (pycnidia) on the surface. Later on, rounded or elongated, slightly depressed light brown or greyish spots or ulcers covered with black pycnidia appear on the stems near the petioles of the lower leaves. As they grow, the spots and sores cover the stem all around. This form of the disease is called stem cancer. When the base of the stem is affected (root neck cancer, neck necrosis), *L. maculans* often spreads to the root system, causing dry root rot, which leads to lodging and death of plants. Sometimes phomosis is observed in the form of necrotic grey spots with dark pycnidia on the internodes. On the leaves and pods, the disease manifests itself in the form of grey, dry oval spots with concentric zonation and pycnidia. Affected pods crack and have small, wrinkled, tentacled seeds. In Australia, a close correlation was found between the frequency of cotyledon damage and the subsequent development of stem cancer [87]. In winter oilseed rape, the most damaging damage to the stem base is usually associated with phomose leaf spot if it has developed before the rapid elongation of the stem.

The global spread of rapeseed phomosis can cause serious yield losses in Europe, Australia and North America [88–89]. The harmfulness of phomosis is manifested in a decrease in germination of infected seeds, death of young affected shoots in autumn, loss of diseased plants during wintering, death of adult plants due to cancer of the stem base, reduction of the assimilation surface due to premature death of affected leaves, reduction of fodder qualities of green mass, significant reduction in the weight of 1000 seeds, deterioration of technological properties of seeds.

Certain differences in the morphometry of both types of phomosis pathogens of cruciferous plant species were also determined [89]

*Leptosphaeria maculans (*Desm.) Ces & De: Pseudothecia on stems initially recessed, then superficial, scattered, globose to pear-shaped, flattened at the base, 300–400 (500) μ in diameter, firm, smooth, glabrous or with few brown mycelial strands; when artificially inoculated with numerous smoky brown, septate, curved hyphae, 2–3 μ wide, sometimes covered with dark brown globules. Proboscis central, truncate-conical, papillary 90(100)×100 μ with 5–8 layers of scleroplectenchymal cells

3–5(10) μ in diameter. Stomata 60-100 μ wide, initially filled with hyaline pseudoparenchymal cells 8-10 μ in diameter, later open. The surface of the pseudothecia is globular to prismatic in texture, built of brown thick-walled cells, 8–12 μ in diameter. Lateral wall 30–70–100–150 μ thick, 3 zones are distinguished in it: outer zone consists of 2–3 (5) layers of isodiameter brown, scleroplectenchymal cells, 4–7 μ in diameter, central zone consists of 4–6 layers of prismatic brown scleroplectenchymal cells, 8–15 × 4–6 μ, inner zone consists of 2–7 layers of prismatic hyaline to yellowish pseudoparenchymal cells, 8–15 × 4–9 μ. Pseudoparaphyses numerous, 2–3 μ wide, septate, with anastomoses. Pouches numerous, bitunicate, cylindrical, to almost club-shaped, rounded at the top, on short stalks, 100–120(150) × 12(18)–21(22) μ with 8 ascospores. Ascospores rolling, elongate spindle-shaped, straight or slightly curved, (45)50–60(68) × 6–7 μ, with 5 septa, central cells largest, yellowish, with 1–2 drops per cell, smooth, with conoid to globose terminal appendages, 5–6 μ in diameter [90].

Leptosphaeria biglobosa R.A.Shoemaker & H.Brun: Pseudothecia on stems scattered, subepidermal, later breaking through, globose to pear-shaped, flattened at the base, 280–350 μ in diameter, hard, brittle, smooth, covered with a layer of loose hyaline mycelium. Upper part of the pseudothecia and proboscis with numerous smoky-brown septate, curved hyphae, 2–3 (5) μ wide; hyphae sometimes bearing dark brown globules. Proboscis central, almost cylindrical, pear-shaped in reverse, 200–400 μ long, 200–300 μ wide, with 8–10 (15) layers of polygonal scleroplectenchymal cells, 5–8 μ in diameter, with occasional scattered large cells 25–30 μ in diameter. Stomata 60–100 μ wide, filled with pseudoparenchymal cells 8–10 μ in diameter, sometimes with hyaline periphyses, 10–20 × 5–6 μ. Swelling of the proboscis in the upper part is often noted. The surface of the pseudothecium shell has a globular texture, composed of thick-walled brownish cells 8–10 μ in diameter. The wall of the pseudothecium in the lateral part is 50–75 (100) μ wide, consisting of 4–7 (10) layers of prismatic to isodiameter cells 10–15 × 8–12 μ. The outer several layers are dark brown, scleroplectenchymous, the inner layers are pale brown, scleroplectenchymous at the base of the proboscis and in its wall, the main cells are thin-walled. The innermost layers are composed of spherical, hyaline cells. Pseudoparaphyses are numerous, 2 μ wide,

20–25 μ long, septate, with droplets. Bags few, in the basal hymenium, bitunicate, rounded at the top, cylindrical to almost club-shaped, on a short stem, 100–140 × 12–16 (20) μ with 8 ascospores. Ascospores rolling, elongate spindle-shaped, straight to slightly curved, 42–48 (60) × 6–7 μ, with 3–5 septa; central cells largest, yellowish, with 1–2 drops per cell, smooth, with conoid to globose terminal appendages, 5–6 μ in diameter. Pycnidia scattered, spherical, up to 200–700 μ, smooth, glabrous, with a central cylindrical straight papilla, 150–200 × 100 μ, papilla wall 15–20 μ thick, with 6–8 layers of hyaline (except for the outermost brownish layer) polygonal cells, 2–4 μ in diameter. Stomata oblong, 80 μ. Pycnidial wall 18–24 μ thick, consisting of 3–5 layers of polygonal pseudoparenchymal cells, 4–6 μ in diameter. Conidia are unicellular, cylindrical, straight, 4–5 × 1.5–2 μ, hyaline, with 1 drop at each end, smooth. In pycnidia on lignified stems, the walls become scleroplectenchymous [90].

The host range of L. maculans is limited to species of the family Brassicaceae. The micromycete has been recorded on Brassica, Raphanus, *Sinapis alba*, *Tlaspi arvense, Camelina sativa* [91–92]. The source of infection is infected plant residues of rapeseed and other cruciferous plants, as well as infected seeds [93]. Airborne ascospores are the primary inoculum for infection of rape seedlings [94–95]. Airborne ascospores are the primary inoculum for infection of rape seedlings [96] or abundant dew [97].

Typically, spots begin to appear on infected leaves after at least 20 days of rain in August and early September. Each of the pathogens that cause phoma has its own characteristic leaf spot symptoms.

L. maculans: Usually brown spots with dark specks (asexual fruiting bodies – pycnidia)

L. biglobosa: Usually dark spots with a small number of dark specks (pycnidia).

The spots develop on the upper side of the leaf, the underside is free of fungal growth (in contrast to the white fungal growth associated with downy mildew). Some spots may have a yellow halo and cause browning of the leaf veins.

Leaf spot has a minimal impact on crop growth and yield, except when severe cotyledon infection leads to seedling death.

From the leaf, the pathogen grows along the petiole to the stem, penetrating and killing plant tissue cells. The classic symptoms of cancer

often form around the leaves at the base of the stem. They develop further and wrap around the stem, restricting the transport of water and nutrients. This can lead to premature aging. In extreme cases, the stem can break, the crop can lie down and the plants can die. The earliest infections are associated with the most dangerous consequences.

L. maculans: Usually causes relatively severe phomosis of the stem base

L. biglobosa: Usually causes damage to the upper part of the stem.

Symptoms of infection can also occur on flowers, buds and pods. The latter may show brown pod lesions with pycnidia and a black edge.

After harvest, the pathogen continues to develop on the stubble. However, the symptoms gradually disappear as the fungus enters the sexual stage on the stems and roots.

Leaf spot infestation can start from September when the seedlings emerge. The initial symptoms are white or fawn round lesions that become dotted with small black fruiting bodies. These leaf lesions are green underneath. They sometimes cause partial leaf death before winter, but usually have minimal effect on growth until spring. These large leaf lesions are caused by *Leptosphaeria maculans* (Phoma A). The second species, *Leptosphaeria biglobosa* (Phoma B), causes small, dark lesions with few fruiting bodies. L. biglobosa can spread to the stems, but has less impact on yield than *L. maculans*.

Over time, the fungus grows from a leaf spot to the stem through the petiole. The rate of this growth varies widely: from 5 mm per day at 20°C to 1 mm per day at 5°C. In summer, these stem cankers cause lodging and premature ripening. Symptoms of deep brown stem canker appear about six months after the initial infection. They gradually increase, encircle the stem and weaken it, which leads to premature ripening, lodging and death of the plant. The disease can spread to the pods, which develop brown lesions with a black border, potentially leading to premature maturation and infection of seeds, which can be a secondary source of infection to new crops.

At a temperature of 15–20°C, the first signs of the disease will be observed in 3–4 days. The presence of wounds (pest damage) greatly facilitates the process of infection of plants with phomosis.

The period of ascospore emergence depends on climatic conditions and is usually timed to coincide with the presence of young, sensitive rapeseed plants. For example, in Australia, ascospore emergence begins in May after

winter rains, which are essential for seedling development [98]. In Canada (Ontario), ascospores begin to emerge in September-November, which is the time when they can infect winter rape seedlings [99]. In western Canada, ascospores emerge from May to August and infect the leaves of young spring rape plants [100]. In Western Europe, ascospores emerge from the end of September during the autumn-winter period, with the time of maximum ascospore flight varying from year to year [101–102]. In Eastern Europe, ascospores emerge in September-November and spring [103]. Ascospores can remain viable for up to 6 weeks and can be spread by wind for several kilometres [104–106].

Ascospores and conidia germinate in a moist environment as infectious hyphae. The infectious hyphae enter the plant through stomata and wounds [107–108]. The minimum dew period required for infection of rapeseed plants by ascospores of both species is 8 hours. The maximum number of leaf lesions is observed after a 48-hour dew period at 20°C. For *L. maculans* isolates, the incubation period is 5 days at 20°C and 13 days at 8°C; for *L. biglobosa* isolates, respectively, 2 and 7 days [109].

The incubation period varies depending on the variety and age of the leaves [110]. The first six leaves of rapeseed plants were found to be more susceptible to infection caused by *L. maculans* isolates.

Inoculation of plants after the formation of six leaves leads to too late development of stem canker, which does not cause significant yield losses [111]. Proved [112] that symptoms develop faster on the sixth leaf than on the second or fourth leaf. However, when the pathogen was isolated from leaves without symptoms, the fungus was isolated from the second leaf 2 days after inoculation, from the fourth leaf 6 days later and from the sixth leaf 14 days later. Symptoms of the disease caused by *L. biglobosa* were more severe on senescent tissues. In order to initiate the development of damage at optimum temperature and humidity, 1–2 ascospores are sufficient [113]. Conidia can infect only damaged leaves, stems and petioles. It was noted [114] that the conidia could only cause infection of intact leaves if very high concentrations of inoculum were used to infect old leaves.

Conidia emerge from the pycnidia immersed in a sticky matrix and are carried by rain drops to other leaves and plants. Conidia spread more successfully in light rains with wind. Secondary infection caused by conidia is rare in Europe and Canada, but is more common in western Australia,

although it has little impact on yield. Symptoms of the disease caused by isolates of the two species are quite similar, although there are some differences. Damage caused by *L. maculans* on leaves initially appears as pale green spots that increase to 1–2 cm in diameter, often turning pale brown with numerous black pycnidia. Sometimes the centre of the spot may crack and fall out. *L. biglobosa* causes smaller brown spots with fewer or no pycnidia [115].

Despite these differences, changes in the nature of spots with age make it difficult or impossible to visually identify these species in the field [116]. The fungus grows from leaf and cotyledon spots biotrophically in the leaf blade and leaf petiole and penetrates the hypocotyl and stem [117].

Defined [118] that the natural infection goes through 5 phases: latent leaf infection, symptoms on the leaves, asymptomatic growth in the petiole, latent stem infection, and development of symptoms on the stem. After colonising the intercellular space in the spongy mesophyll of the leaf blade, the fungus reaches the vascular system and spreads down the petiole, mainly through xylem vessels or intercellular spaces of the xylem, parenchyma and cortex. During this phase, the fungus is biotrophic.

Direct infection of petioles and stems is possible only if they are damaged. In case of hypocotyl infection, symptoms similar to blackleg develop. Above the soil level and below the level of the first pair of leaves, watery spots form, which then dry up and turn grey, often with a stretch mark at the site of the lesion. Pycnidia develop on the affected tissue. This form of the disease is harmful in Australia and Canada [119]. The death of seedlings from the black leg in some fields can reach 70% [120]. In older plants, elongated, oval, depressed, beige spots are formed at the base of the stem, often surrounded by a clear dark brown or purple border, with numerous pycnidia in the centre of the spot. This type of damage is caused by the spread of pathogen hyphae from leaf spots that developed early in the growing season (e.g. in Europe in autumn). During pod development and seed ripening, these spots can enlarge and merge, completely covering the stem, dry rot develops in the root part of the stem, the stem is often bent, and the plant gradually dries up. Stem bases may break at the site of damage. This stage of the disease is called root neck cancer and is the most harmful. Stem damage at the soil level often spreads to the root system, causing root ulcers and root dry rot [121]. From foliage infected later in the season

(e.g. late winter or spring in Europe), the pathogen spreads along the petiole and produces oval, beige spots with a dark brown or purple border in the upper (> 5 cm from the root collar) part of the stem. This damage occurs at relatively early stages of development, such as during flowering, and can cause yield losses, Canada [122] and Europe. Damage to the stem in the upper part, as well as at its base, can increase in size, encircling the stem, and cause premature pod ripening due to impaired water transport in the plant [123]. In severe cases, the stems break. Leptosphaeria species differ in pathogenicity. *L. maculans* isolates are highly aggressive and usually cause symptoms of stem base canker. *L. biglobosa* is considered to be less aggressive and is mainly associated with damage to the upper part of the stem [124]. *L. biglobosa* isolates penetrate the stem core and can cause browning (which is only detected when the stem is cut longitudinally), but rarely lead to external symptoms [125]. However, as the stems age, isolates of both species develop numerous pycnidia on their surface.

The spots on the pods are elongated, slightly depressed, brown or grey, sometimes with a dark brown border. The pods are infected by conidia developing in pycnidia on spots of leaves and twigs. Pods are rarely affected, but can cause premature ripening and cracking [126]. The infection from the flaps can spread to the seeds, which become shrivelled and dull [127]. The pathogen is found in seeds as a dormant mycelium in the seed coat or cotyledons, and rarely in the embryo. The frequency of occurrence of rapeseed infected with the phomosis pathogen is low, for example, in Canada – about 5% [128], in Western Australia – 0.1–0.2%. Seed infection can be important for the spread of the disease to new areas. Infected seeds of other cruciferous plants, such as mustard, can contribute to the spread of the disease [129]. After harvesting, the aging stem tissue is rapidly colonised by pathogens that form numerous pycnidia. Conidia can colonise plant residues saprotrophically, which can increase the level of inoculum and, consequently, the number of pseudothecia. Pseudothecia are formed on plant debris. The maturation of pseudothecia depends on temperature and humidity, with an optimum at 14–15°C [130]. In Western Australia, pseudothecia ripen in the autumn and winter, as their maturation is slowed by hot, dry summer weather. In North America and Europe, pseudothecia are formed by harvest time, although due to dry weather in summer, their maturation may be delayed [131]. In Canada (Ontario), pseudothecia form

in September, and ascospores begin to emerge by the end of September. In western Canada, pseudothecia form within 9–10 months after harvest [132]; Ascospores emerge from pseudothecia that developed on plant debris from the previous year in late June and August, when plants are in flowering or at later stages of development. The following year, mature pseudothecia may release ascospores earlier (in May-June), which can lead to severe damage to seedlings.

The intensity of disease development on cotyledons, leaves and stems increases at higher temperatures. On plants inoculated at the cotyledon stage, stem base cancer was more intense at temperatures above 12°C [133–134]. The resistance genes of young plants can be heat-sensitive, which determines the intensive development of the disease at 24°C than at 14°C [135]. On plants inoculated at the bud stage, the intensity of disease development was higher on stems at 18°C than at 12°C. The most severe epidemics are associated with climatic conditions, for which temperatures of 25–30°C are typical during the development of stem canker. Such epidemics can also occur in Canada and Eastern Europe, where summer temperatures are high. In China, despite the high temperatures, epidemics of this magnitude are not typical, which is determined by the absence of group A isolates [136]. The quantitative ratio of rapeseed phomosis pathogen isolates is an important factor that determines the disease severity in different regions. In most rapeseed growing areas of the world, *L. maculans* isolates are considered economically important. In most countries, where epidemics are often very severe, populations are represented by this species [137].

The ratio between *L. maculans* and *L. biglobosa* isolates changes during the growing season. In the UK, pseudothecia develop earlier at the base of the stem and ascospores mature earlier in them than in pseudothecia on lesions of the upper part of the stem. Studies conducted in France, the UK and Germany have shown that isolates of L. maculans are isolated from the base of the stem, and isolates of both species are isolated from the upper part of the stem in equal proportions [138]. Differences in the maturation of pseudothecia determine the following facts: 95% of ascospores in early spring in Canada belong to *L. maculans*. In the UK, leaf lesions caused by *L. biglobosa* isolates appear later than those caused by L. maculans isolates; in infected seeds from the UK, the proportion of *L. biglobosa* isolates infecting seeds later in the season is higher [139].

As seed infection is dominated by *L. biglobosa, L. maculans* is less likely to be introduced into new areas. As the upper parts of the stalks, which have a higher proportion of *L. biglobosa*, are harvested at harvest time, the proportion of *L. maculans* increases during this period [140].

Two different forms of growth of the phomosis pathogen on agarified media were found. In culture, colony types were identified that differ in morphology, growth rate, spore production, degree of medium pigmentation, and toxin excretion into the liquid medium [141].

L. maculans grows slowly on nutrient media – on plum-lactose-yeast agar, the growth rate is 0.4-1.5 mm/day, forms irregular (with unevenly lobed edges), colonies that age rapidly (after 21 days, growth almost stops, and colonies rarely reach the edge of the cup).

Isolates of *L. biglobosa* grow rapidly (1.9–3.1 mm/day) and usually reach the rim of the cup by day 14. Saltants (in the form of sectors with pycnidia of different sizes) are often found in cultures. Sometimes isolates of L. biglobosa also grow slowly (growth rate of 0.7 mm/day), but in this case the colony edge is flat and no rapid aging is observed. Conidia of L. biglobosa form longer and more branched growth tubes during incubation on water agar for 40–44 hours than conidia of *L. maculans* [142]. This method allows for visual identification of the species of isolates without measuring the length of the growth tubes, and it allows conidia to be used directly from the pycnidia without isolating the pathogen into pure culture.

The external manifestations of phomosis can be very diverse: stem and root collar cancer, dry rot, leaf spot, and fruit damage. In the case of fruit damage by phomosis, seeds can form sick, weakened seedlings (black leg) or even completely lose germination.

In Ukraine, the main source of initial infection is airborne ascospores from stubble or residues of previous rapeseed crops near the new crop during warm, humid weather. They are dispersed by air currents and land on the leaves and sometimes on the root collar of young plants, where the disease develops. Early epidemics are associated with above-average rainfall in August and September. If cotyledons are infected, seedlings can die in autumn. The causative agents of cruciferous phomosis have several alternative sources of infection, which makes the disease difficult to control. During the growing season, the fungus spreads mainly by asexual spores – conidia, which are formed in necrotic areas of rapeseed and other plant

species from the cruciferous family. Under favourable conditions, several generations of conidia are formed, which are found mainly in the mucilage and are usually spread by rain over a short distance. The fungus overwinters in the form of mycelium in unmineralised plant debris and in affected seeds. The first mature ascospores are formed on the remains of winter rape in autumn, but the most massive sporulation usually begins in spring. The period of ascospore formation is quite long and reaches several months. Ascospores are spread by air currents and, unlike conidia, can travel long distances. Affected seeds produce affected seedlings. It is important that even a slight infestation of seeds with phomosis (< 0.1%) in the absence of control measures can initiate a significant outbreak of the disease in the field. For successful infection of plants with spores, drip moisture is required (at least 4 hours). The temperature requirements of different types of phomosis pathogens vary significantly, with Phoma nigrificans being the most cold-tolerant. At low temperatures (5–10°C), phomosis pathogens develop asymptomatically for a long period (up to 2 weeks).

Phomosis is one of the most dangerous diseases of rapeseed. At one time, it was phomosis in the form of rapeseed root collar cancer that severely limited the spread of this crop. And the fact that rapeseed is now grown on 6.5 million hectares in Europe was a significant impetus for the fact that breeders defeated this disease. New hybrids are usually relatively resistant to phomosis, but over time, new, more aggressive races of its pathogens appear, so successful rapeseed cultivation is impossible without the use of fungicides.

Control measures:

– Strict observance of crop rotation. Spatial isolation of rapeseed and other Brassica crops.
– Accelerate mineralisation of plant residues (shredding, ploughing, etc.).
– Control of weeds from the Cabbage family. Destruction of carrion.
– Seed quality control. Use of effective disinfectants.
– Timely use of fungicides during the growing season.
– Pest control (rapeseed flea beetle, covert borer, etc.).
– Selecting more resistant varieties and hybrids.
– Phomosis is a widespread disease of rapeseed worldwide.

The disease has become increasingly important due to the intensification of rapeseed production and climate warming. Effective phomosis control includes both agronomic practices and genetic protection of varieties.

In recent years, phomosis incidence has increased due to intensification of rapeseed production, climate warming and lack of phomosis management strategies. This has led to an urgent need for effective control of the disease, where both agronomic practices and the use of genetic resistance play an important role.

To control this disease, agronomic practices are used: crop rotation, soil cultivation, optimal sowing dates, seeding rates, fertiliser doses, and pesticide treatment. Depending on the conditions in the growing areas, it is recommended to return this crop to the same field in 3–5 years, and in Ukraine – in 4–5 years.

The spread of the disease can be contained by quarantine measures. For example, in Alberta (Canada) in 1984 (a year after phomosis was detected in the area), sowing and transporting infected seeds was banned, and farmers were also prohibited from sowing rapeseed for 4 years in fields where the disease was detected. Although the disease has now spread to most of the province, its spread has been significantly slowed.

Crop rotation is one of the oldest and most effective control strategies, which reduces fungal populations to a level where they are not economically important if the crop is re-seeded. The principle of crop rotation is to plan the order of placement of crops on the same field in such a way that the infected stubble decomposes. In this case, the ability of the pathogen to produce inoculum as a source of disease is reduced [143]. A 3–5 year crop rotation is recommended for rapeseed. Ploughing increases soil aeration and temperature, which leads to rapid decomposition of stubble, which is the source of primary infection, so ploughing crop residues into the autumn is a good way to control phomosis [144]. No tillage, for example, in Western Canada, leads to the persistence of infection on infected crop residues.

A good method of controlling phomosis is to plough the crop residues into the ground until autumn. In China and India, whole plants are harvested from the field (for use as fuel) and then flooded for rice, which in warm climates leads to rapid destruction of the inoculum.

The possibility of using the fungi Cyathus striatus and C. olla, which usually live in bird nests, to accelerate the destruction of rapeseed residues is being studied [145].

Minimal tillage is practiced, which in a hot, dry climate contributes to the accumulation of infected residues on the soil surface and their preservation

as a source of inoculum for 4 years. The increase in acreage in Australia has led to a reduction in the time it takes for canola to return to the same site, which also increases the amount of inoculum. Cold winters and dry, hot summers help to preserve plant residues for several years [146].

Moderate, humid climates cause rapid decomposition of residues within 2 years (Europe, south-eastern Australia), and deep ploughing accelerates the process of decomposition.

Phomosis is favoured by early sowing of winter rape and late sowing of spring rape [147]. Thickened rapeseed crops with thin stems are more severely affected. The severity of phomosis increases as a result of mechanical damage to plants by insects (cruciferous flea beetle, rapeseed flower beetle, etc.), as well as during plant care measures using machinery.

In France, with early sowing, rapeseed has time to develop a sufficient number of leaves before ascospores fly, which allows it to avoid infection at the most susceptible stages [148].

To reduce the infection of phomosis pathogens, optimal seeding rates and sowing dates are also important, taking into account environmental factors [149].

As for the influence of the fertilisation system, the effect of different fertiliser rates on the development of phomosis was investigated. The most effective of all studied variants of fertiliser rates was $N_{60}P_{60}K_{60}$, which reduced the spread of phomosis compared to the control by 32%, and the development by 9.3%. In terms of seed yield, this variant exceeded the control by 1.5 t/ha (Table 4.21).

As *Leptosphaeria maculans* overcomes major resistance genes, the disease can be controlled by diversifying cultivars in terms of resistance genes and their placement. Rotation of varieties containing different genes or combinations of resistance genes is recommended every four years. Regular monitoring of virulent gene frequencies is important to determine the effectiveness of known major resistance genes. One strategy to increase resistance to forms of phomosis is to use individual core genes or different combinations of genes in a genetic background with non-specific resistance. Long-term resistance can be increased by using a combination of species or varieties with different resistance genes in the same field and inter-field diversification. It is also necessary to protect rapeseed from *L. biglobosa*, which can cause significant damage, especially to varieties with effective core resistance genes for *L. maculans*.

Table 4.21

Effect of mineral fertilisers on spring rape resistance to phomosis [150]

Fertiliser rates	Phomosis infestation, %					
	2010		2011		Average value	
	Distribution	Development	Distribution	Development	Distribution	Development
Control	64	12.8	56	11.8	60	12.3
$N_{30}P_{60}K_{60}$	53	7.7	47	8.5	50	8.1
$N_{60}P_{60}K_{60}$	33	3.7	23	2.3	28	3.0
$N_{90}P_{60}K_{60}$	60	10.6	52	9.8	56	10.2
$N_{120}P_{60}K_{60}$	71	13.6	59	12.4	65	13
SSD_{05}	1.3	2.2	3.5	2.8		

Thus, the best way to manage phomosis is to grow resistant varieties [151]. At the same time, it is important to regularly monitor the frequency of virulence genes to determine the effectiveness of known major resistance genes. One strategy to increase the duration of resistance to phomosis is to use single major genes or their various combinations in a genetic background with non-specific resistance. The duration of resistance can be increased by using mixtures of varieties or species with different resistance genes in the same field and inter-field diversification. It is also necessary to protect rapeseed from *L. biglobosa*, which can cause significant damage, especially to varieties with effective main resistance genes against *L. maculans*. In addition, chemical protection of rapeseed against L. biglobosa requires higher doses of triazoles than for control of *L. maculans*, so there is a great need for breeding resistant rapeseed varieties to both *L. maculans* and *L. biglobosa*.

Avirulence genetics of *Leptosphaeria maculans* (*L. maculans*) is a haploid fungus with a small genome size of 45.12 Mb, encoding probably 10,000–13,000 genes within 17–18 chromosomes (some chromosomes are optional, i.e. B-type), the genome of *L. biglobosa* is smaller (30–40 Mb) [152].

The genome was created in 2004 by Genoscope (CEA) (http://www.genoscope.cns.fr), and in 2011 the sequencing of the *L. maculans* genome was completed. The genome sequence is publicly available (http://urgi.versailles.inra.fr/index.php/urgi/Species/Leptosphaeria) [153].

The genetic diversity of the *L. manculans* population is mainly due to sexual recombination, mutation, large population size and high gene flow due to large-scale distribution of ascospores. Sequencing of the *L. maculans* genome revealed the presence of many transposons (about 30% of the genome) [154]. This degenerate, retrotransposon-rich part of the genome is thought to contribute to the rapid evolution of virulence in *L. maculans* isolates through multiple whole-gene deletions, mutations, and re-induced point mutations in avirulence alleles (AvrLm) [155–157]. Probably, due to RIP mutations and localisation of Avr genes within repetitive regions, the fungus adapts under the pressure of selection by resistance genes [158].

In L. maculans, 14 avirulence genes were identified, and 8 of them are genetically clustered in two different regions. The first cluster contains AvrLm^{1}, AvrLm^{2}, AvrLm^{6} [159], the second – AvrLm^{3}, AvrLm^{4}, AvrLm^{7}, AvrLm^{9} and AvrLepR1 [160–162]. These clusters can be hundreds of kilobases in size due to the absence of meiotic recombination in such regions. To date, 7 avirulence genes of L. maculans have been cloned – AvrLm^{1} [163], AvrLm^{2} [164], AvrLm^{3} [165], AvrLm^{4}-7, AvrLm^{6}, AvrLm11 [166], AvrLmJ1 [167]. All of the activity genes, with the exception of AvrLm^{1}, which is localised to the heterochromatin region, encode small, cysteine-rich, secreted proteins that are highly expressed in the early stages of pathogenesis [168]. The AvrLm^{4}-7 gene encodes a protein of 143 amino acid residues. A single base mutation leading to the replacement of glycine with arginine results in the loss of the ability to recognise the Rlm^{4} gene, while recognition of Rlm^{7} is preserved (AvrLm^{7} specificity is not changed). The point mutation is the main event leading to the loss of Rlm^{4}-mediated resistance. After cloning AvrLm^{7}, it was found that AvrLm^{4} and AvrLm^{7} are two different alleles of the same gene (renamed AvrLm^{4}-7).

Investigation of the population structure of *L. maculans* on the basis of avirulence (virulence) in Poland, Sweden, Germany, England and France [169] showed a high frequency of the virulence genes avrLm^{2}, avrLm^{3}, avrLm^{9} and avrLm^{5}. The avrLml and avrLm^{4} genes were detected in a small number of isolates (less than 10%). In England, in 2012–2013, single isolates with avrLm^{7} were detected, and all of them had avrLm^{4} [170]. In Canada, less than 5% of isolates with AvrLml and AvrLm^{3} genes were detected in 2012 [171]. However, according to the [172], in 2012, in Canada (Manitoba), 22.0% of isolates with AvrLml were found in the fungus

population, 2.7% with AvrLm^3, 3.3% with AvrLm^9, 10.7% with AvrLepR2, 39.1% with AvrLepR1, 64.3% with AvrLm^2, 65.3% with AvrLm11, and 66.0% with AvrLm^6. The proportion of isolates with the avirulence genes AvrLm^4, AvrLm^5 and AvrLm^7 was high – 77.1, 80.7 and 89.2%, respectively. In Germany, an analysis of fungal populations in 2011–2014 revealed a high frequency of virulence genes for the resistance genes Rlm^1, Rlm^2, Rlm^3, Rlm^4 and Rlm^9 (more than 80% of isolates) and a low frequency for the Rlm^7 gene (less than 5%) [173].

Two types of disease resistance have been identified in species of the genus Brassica, including rapeseed: qualitative (race-specific, juvenile, mono- and oligogenic) and quantitative (non-race-specific, age-specific, usually polygenic) [174–183]. Juvenile resistance, which is expressed from the seedling (cotyledon) stage, depends on the presence of the R-gene for resistance in the plant genotype and the presence of the corresponding Avr-gene in the pathogen isolate. This is a very effective resistance, which works through the activity of the R-gene – the pathogen enters the cotyledons or leaves, resulting in a hypersensitivity reaction that prevents the further spread of *L. maculans* infection to the entire plant, although the impact of the pathogen can continue throughout the growing season [184]. That is, effective master genes of race-specific resistance to L. maculans act when ascospores or pycnidiospora infect cotyledons or leaves, preventing further spread of infection to the stem [185]. On the contrary, polygenic resistance is a partial resistance, and the small genes that cause it interact with each other in a complex way to form the plant's response to the pathogen. Each of these genes usually does not have a large phenotypic effect, so there is no strong selection pressure for certain fungal pathotypes [186]. Quantitative resistance is especially important for field crop protection, as the greatest damage to yield and product quality is caused by damage to adult plants [187–188]. The type of resistance can be determined only by the presence (or absence) of race-specific resistance genes in the tested genotype of B. napus genotype under test and avirulence alleles in *L. maculans* isolates used for inoculation in controlled environments or field experiments. Field (age) resistance can be caused not only by small genes, but also by race-specific master genes. It can be controlled by a major gene to which the field population of *L. maculans* carries avirulent isolates or by many genes with small effects. There are usually no differences in the symptoms of phomose

spot development on the leaves of young plants of varieties with and without polygenic resistance to L. maculans, but at the end of the season, varieties with quantitative resistance do not develop stem ulcers or are less severe than varieties without this resistance [189].

All the major race-specific phomosis resistance genes identified so far were found in the A-genome of *B. napus* and none were found in the C-genome [190]. To date, several such genes have been identified and genetically mapped in B. napus, several such genes have been identified and genetically mapped (Table 4.22).

It is not yet clear whether the Rlml, Rlm^3, Rlm^4, Rlm^7, Rlm^9 genes are a cluster of closely related factors [227]. It is believed that Rlml is different from Rlm^3 because, while present in the same variety, they are genetically mapped at different positions. The Rlml and Rlm^4 genes are linked to each other, are not allergic and can be present in the same variety as the Rlml and Rlm^3 genes. At the same time, the Rlm^3 and Rlm^4 genes, which occur in many rapeseed varieties, are rarely present together in the same genotype and may be allelic forms of the same gene. No varieties have been found that contain both Rlm^7 and Rlm^9 genes. It is also not clear whether Rlm^4 and Rlm^7 are different genes or allelic forms of the same resistance gene. The LEM1, LmRl, cRlmm and cRlmrb genes present in different B. napus cultivars are mapped to chromosome A7 [228–229]. It was found that the LEM1 gene of juvenile resistance to isolate c Avrl-2-4-7 [230] is localised in the region of a large tandem duplication. The LEM1, LmRl, cRlmm and cRlmrb genes may be identical to the Rlm^4 gene [231]. French varieties Major, Jet Neuf and Australian varieties Maluka, Dunkeld, Skipton carry the Rlm^4 gene [232].

The race-specific genes Rlm^8, Rlmll, LepR1-LepR4 were found in the A-genome of *B. rapa* (Table 4.22). The LepR3 gene, which was introduced into rapeseed from *B. rapa* ssp. *sylvestris*, is the first cloned gene for rapeseed resistance to phomosis. It belongs to the family of receptor-like proteins. The recessive resistance gene LepR4, which causes a wide range of resistance and is mapped to chromosome A6, is represented by two different alleles – LepR4a and LepR4b [233]. In addition, B. rapa may contain genes previously identified in B. napus, – Rlm^1, Rlm^2, Rlm^4, Rlm^7, which are located in the same position in *B. rapa* and *B. napus* [234]. For example, using fine mapping, the localisation of the LepR3 and Rlm^2 genes was found to coincide [235].

Table 4.22

Main resistance genes of some cruciferous crops to Leptosphaeria maculans (Desm.) Ces. et de Not. [191]

Resistance gene	The source of the gene	Localisation in a chromosome *B. napus*	References
Rlm^{1}	*B. napus* (AACC, 2n = 38)*	A7	[192–196]
Rlm^{2}	*B. napus**	A10	[197–201]
Rlm^{3}	*B. napus*	A7	[202]
Rlm^{4} = *LEM1*	*B. napus**	A7	[203–207]
Rlm^{5}	*B. juncea* (L.) Czern. (AABB, 2n = 36) Sareptic (Indian, brown (brown sarason) mustard)	A8	
Rlm^{6} = *Jlm*^{1}	*B. juncea*	A8	[208–211]
Rlm^{7}	*B. napus**	A7	[212–214]
Rlm^{8}	*B. rapa L.* (AA, 2n = 20)	–	
Rlm^{9}	*B. napus*	A7	[215–216]
Rlm10	*B. nigra* (L.) W. D. J. Koch (BB, 2n = 16) black (French or real) mustard	A7	[217]
Rlm11	*B. rapa*	Dispensoma	[205]
LepR1	*B. rapa* ssp. *sylvestris* Janch.	*Al*	[218–219]
LepR2	*B. rapa* ssp. *sylvestris*	A10	
LepR3	*B. rapa* ssp. *sylvestris*	A10	[220–221]
LepR4	*B. rapa* ssp. *sylvestris*	A6	[222]
rjlm^{2}	*B. juncea*	–	[223–224]
LmFr1	*B. napus*	A7	[225]
cRlmj	*B. napus*	A7	
aRlmj	*B. napus*	A7	[226]

Note * – the gene is also present in B. rapa, "-" – not determined.

In the species B. nigra with a B-genome, two resistance genes, Rlm^{1} and Rlm10, were identified [236]. The Rlm10 gene introduced into rapeseed is localised in B. napus in chromosome A7 [237]. Rlml rapeseed plants have better resistance to L. maculans in the cotyledon phase and at the adult stage of development, when the gene is overexpressed in B. napus. It is important to note that the Rlm^{1} gene belongs to the family of serine/threonine kinases [238]. It was pointed out that it controls a large proportion of age-related

resistance (about 70% of phenotypic variation). It was noted that the age resistance of Maxol was mainly due to the presence of the Rlm^1 gene, which is effective when the population is dominated by fungal isolates with $AvrLm^1$ [239]. The resistance gene Rlm^2 is also associated with age-related resistance to phomosis, either as having a residual effect on age-related resistance or as being linked to other genes located in this QTL and causing a part of the variation in age-related resistance [240].

The resistance to L. maculans of the amphiploid species B. juncea is mediated by two genes, named Rlm^5 and Rlm^6 [241]. In addition, the recessive gene $rjlm^2$ was identified in *B. napus* hybrids, which originates from B. juncea and is very effective against a wide range of *L. maculans* isolates at the cotyledon stage. Based on resistance gene analogues (RGAs), a SCAR marker was developed that is closely linked to the $rjlm^2$ resistance locus in *B. napus, B. rapa* and *B. oleracea*. Sequence analysis of this gene showed significant homology of two putative R-genes in the resistance gene cluster in chromosome 5 of *Arabidopsis thaliana* [242]. Introgression of Rlm^6 resistance genes [243] and $rjlm^2$ [244] in B. napus led to its effective resistance to *L. maculans* isolates at the seedling stage.

In the presence of major resistance genes in plant genotypes and complementary avirulence genes in fungal isolates, a typical gene-for-gene interaction between Brassica and L. maculans was observed, first established in the study of the flax rust phytopathosystem [245]. It involves the direct or indirect recognition by a protein encoding a plant resistance gene of an effector controlled by a specific pathogen avirulence gene [246–248]. When the R-gene corresponds to the complementary Avr-gene, the spread is stable (race-specific resistance) [249–251]. The *B. napus* genome has also been sequenced [252].

Thus, all known major genes of oilseed rape resistance to *L. maculans* are localised in the A-genome. Some genes are introduced into the genome of rapeseed from other species (*B. rapa, B. juncea, B. nigra*). In the Brassica – *L. maculans* phytopathosystem, pathogen avirulence genes interact with complementary plant resistance genes in a gene-for-gene manner [253–259]. Some major genes contribute to field resistance. For example, Rlm^1 can control a larger proportion of age-related resistance (about 70% of phenotypic variation) if the pathogen population has a low frequency of isolates virulent to this gene [260]. The Rlm^2 gene contributes

to age-related resistance either through a residual effect or through linkage with other genes localised in the same region. In addition to the main juvenile resistance genes, small genes of quantitative (partial, field) resistance of rapeseed to phomosis were identified, and using association mapping, resistance loci were identified not only in the A- but also in the C-genome of rapeseed [261–267]. It should be noted that the genetics of rapeseed resistance to L. biglobosa is practically not studied

So, once again, the best way to manage phomosis is to grow resistant varieties and lines, but due to the selection pressure exerted by race-specific genes on fungal populations with a high potential for virulence, varieties with major resistance genes quickly become susceptible. Studies conducted in Europe and Australia have shown that *L. maculans* populations using the same major resistance gene in many varieties grown over large areas quickly overcome this resistance [268]. A study of *L. maculans* isolates collected around the world showed that many of the known major resistance genes have already been overcome [269]. For example, as a result of crossing B. napus and B. rapa ssp. sylvestris, a phomosis-resistant variety Surpass 400 was developed [270], probably with the resistance genes LepRl, LepR2 and LepR3 introduced from *B. rapa* [271–272]. Surpass 400 was released commercially and had high resistance to phomosis in the field. However, after 3 years, this resistance became ineffective due to the rapid increase in local fungal populations of isolates with virulence to the LepR3 gene [273]. In Australia, phomosis incidence in sylvestris-resistant varieties was higher than in polygenic varieties that lack effective major resistance genes [274]. There is evidence of phomosis resistance breaking down in varieties in France [275–276], where, after the introduction of rapeseed varieties with the Rlml gene, it was overcome within 3 years. In France in 2000 [277] and in Australia in 2003, the breakdown of variety resistance was the result of a rapid change in the frequency of A-virulence genes, which depends on the resistance genes present in the cultivars grown. For example, in France, an increase in the area under Rlml rapeseed led to a large fungal population size and a high concentration of pathogen isolates with the avrLml gene, and subsequent sexual recombination and changes in agricultural practices (shorter crop rotations and minimal tillage) contributed to an increase in the frequency of virulent alleles [278]. There is also evidence of the gradual eradication of the major resistance genes

Rlm^9, Rlm^2 and Rlm^4 in France, and the Rlm^4 gene in Australia, following widespread use of varieties containing these race-specific genes [279]. It is known that rotation of varieties protected by different resistance genes can reduce the frequency of virulent isolates to a particular resistance gene by reducing the selection pressure of this gene on the fungal population, so phomosis can be controlled by using the appropriate R-genes. For example, the Rlm^4 gene was present in 53% of Australian varieties until 2002, and now this number has dropped to 29%. In Canada, the Rlm^2 and Rlm^4 genes are effective for breeding [280]. In addition, other useful genes can be introduced into Canadian rapeseed varieties – Rlm^5, Rlm^6, Rlm^7 and Rlm11 [281]. High efficiency of Rlm^6 and Rlm^7 resistance genes noted in Europe [282]. However, field experience using the Rlm^6 gene introduced into *B. napus* from *B. júncea* showed rapid overcoming of resistance [283]. In Australia, the Rlm^6 gene is known to have already lost its effectiveness, and an increase in the frequency of virulence to this gene occurred in its absence in cultivars [284] through the clutch AvrLml and $AvrLm^6$ [285–286]. In France, after the introduction of varieties with the Rlm^7 gene, 36% of virulent isolates were found to be resistant to this gene in 3 years. Thus, within a few years after the introduction of varieties containing the main race-specific resistance genes, the effectiveness of some of them decreases, which limits the usefulness of these genes for phomosis control when used in varieties grown on large areas [287–289].

In order to determine the effectiveness of known major resistance genes for their use in breeding, it is necessary to regularly monitor the frequency of avirulence/virulence genes in the population of the phomosis pathogen. It is important to rotate resistance genes in time and space. For example, in Australia, in 2003, the development of phomosis increased 3 years after the commercial release of varieties with Sylvestris resistance. However, as the area under alternative resistance varieties increased, the frequency of virulent *L. maculans* isolates on Sylvestris-resistant varieties decreased by 2005 [290–291], In other words, there was a rise and fall in the development of the disease in varieties with Sylvestris resistance. In Canada, the incidence of phomosis in rapeseed crops increased from 2005 to 2012, which correlated with an increase in the frequency of virulent isolates of the Rlm^3 resistance gene. This was due to the pressure of selection of the Rlm^3 gene on the pathogen population due to the increase in the

cultivated area under varieties with Rlm^3 during this period. The increase in damage from phomosis was also caused by a 2-year crop rotation instead of a 4-year one due to the intensification of oilseed rape production [292]. A strategy similar to the one used in Australia for sylvestris resistance could be used to change the situation in this country.

Rotation of different resistance genes may be an acceptable approach to minimise selection pressure on avirulent isolates towards rapid virulence evolution and overcome resistance genes, which will increase the duration of resistance in varieties. The rotation of genes is also aimed at reducing the spread of phomosis by reducing the inoculum. To increase the duration of resistance, it is necessary to identify many different resistance genes to diversify their use in the varieties being developed in order to determine a strategy for managing phomosis through genotype placement [293]. The duration of the effectiveness of race-specific resistance genes depends on the size of the *L. maculans* population, which is directly related to the amount of affected rapeseed residues, and therefore appropriate agronomic practices, such as less intensive rapeseed rotation, should be applied to maintain resistance.

Thus, successful rapeseed production and phomosis management requires control strategies such as variety selection or rotation of major resistance genes over time, combined with good quantitative resistance and best agricultural practices. Rotation of cultivars containing different genes or combinations of resistance genes is recommended every 4 years to minimise selection pressure on the fungal population and increase the duration of resistance [294]. However, not all resistance genes can be used in crop rotation. For example, varieties with Rlm^1 should not be replaced with varieties with Rlm^6, because selection of fungal isolates with virulence to the Rlm^1 gene also leads to an increase in the frequency of virulence to Rlm^6, because the $AvrLm^1$ and $AvrLm^6$ genes are closely linked in the pathogen genome. Thus, an understanding of the genetic interaction between resistance genes and avirulence genes is required to develop a strategy for rotating race-specific resistance genes.

Many plant breeders and phytopathologists believe that one of the important goals is to develop varieties with long-term resistance, but this is not an easy task [295]. The resistance of a variety is considered to be long-lasting if it persists for a long time when grown on large areas under

favourable conditions for the development of the disease. It is believed that non-race-specific resistance should be more durable, as a wide range of pathotypes is reproduced on varieties with such resistance without much selection pressure to increase virulence. Thus, polygenic resistance is usually long-lasting. However, over time, in some B. napus cultivars, polygenic resistance also becomes less effective due to changes in virulence and aggressiveness (ability to cause severe disease) in the L. maculans population. This is because polygenic resistance is also characterised by variety x isolate interactions, as it may include a race-specific component [296].

One of the effective strategies to increase long-term resistance to phomosis is to breed rapeseed varieties by combining juvenile and age-related genes. Juvenile and age-related resistance play an important role in phomosis control. The interaction of specific R genes and their corresponding avirulence genes at the seedling stage usually results in a very low disease severity at the adult stage [297]. In addition, the combination of the main resistance genes with polygenes increases the duration of resistance by slowing down the adaptation and reproduction of virulent isolates to race-specific genes, i.e., rape samples with juvenile and age-related resistance genes may be characterised by longer R-gene resistance [298–301]. This points to the need to identify and combine both existing and new genes for qualitative and quantitative resistance to phomosis. In order to effectively use race-specific resistance genes alone or in conjunction with quantitative resistance, the pathogen must be monitored at regular intervals to identify fungal isolates with virulence to the resistance genes used. Thus, one of the strategies for breeding for phomosis resistance can be the use of single major genes or their combinations in different combinations (gene pyramiding) on a genetic background with a high level of non-race-specific resistance. This is possible with MAS using markers that are closely linked to race-specific resistance genes and QTLs associated with non-race-specific resistance. The use of specific master genes will depend on the virulence structure of the pathogen population. The presence of a genetic background with non-race-specific resistance will prevent large yield losses of varieties in the event that the race-specific resistance genes present in them are overcome. The duration of resistance can be increased by using not only pyramids of major resistance genes introduced into a single variety, but

also mixtures of varieties or species with different resistance genes at the level of one field, inter-field diversification, and, of course, agronomic practices [302].

However, the diversification of varieties by resistance genes and their rotation in time and space makes it possible to manage phomosis [303]. Rotation of cultivars containing different genes or combinations of resistance genes is recommended every 4 years [304]. All this points to the need to identify and combine both existing and new genes for qualitative and quantitative resistance to phomosis. The current approach is genome-wide association mapping, which allows identifying markers for known and new resistance loci in the collection of parental forms and promising rapeseed breeding material for further use in marker-assisted selection in a particular zone [305–306].

Protection of rapeseed against *L. biglobosa*, which can cause significant damage, especially to varieties with effective main resistance genes against *L. maculans*, should also be considered [307–308].

To combat blackleg, different countries treat seeds and spray soil and plants with fungicides. Pesticides (seed treatment, fungicides for spraying soil and plants) are used to combat phomosis. For example, in Canada, seed treatment, which began in 1978, is recommended even if phomosis is not detected in seed lots. In the field, it is necessary to spray plants with the product at an earlier time, because when the fungus infects the stem, the disease is no longer controlled by the fungicide. Thus, in Western Europe, fungicide spraying for chemical control of phomosis is used in autumn/winter when spots appear on the leaves [309–310]. Various combinations of seed treatments, soil and foliar fungicides are used to control rapeseed phomosis. In Canada, carbatin, thiram and iprodione are used for seed treatment, in Europe, thiram and iprodione, and in Australia, iprodione.

Flutriafol is used as part of fertility pellets and provides long-term protection for seedlings. The use of foliar fungicides is economically justified when crop yields are high, inoculum levels are high and the variety is low in resistance. In Canada, propiconazole is sometimes used, but it does not provide complete control [311]. In western Europe, where high crop yields economically justify the use of foliar fungicides, treatments with difenoconazole, difenoconazole in a mixture with carbendazim, flusilazole in a mixture with carbendazim are used to control phomosis [312].

The optimal time to apply fungicides in Western Europe is autumn, 6 months before symptoms appear on the stems.

Fungicides are effective for a limited time due to their degradation and the emergence of new untreated leaves. The timing of fungicide applications is based on the presence of spots on the leaves of young plants. However, damage may not develop on young leaves for a long time, despite the presence of infection. The fungus reaches the stem before leaf damage appears and becomes insensitive to fungicides.

For the past 5 years, Bayer has been offering an innovative solution in Ukraine and other countries of the world – Tilmore fungicide – to protect both winter and spring rape from a range of diseases, as well as an effective growth-regulating effect to increase winter hardiness of winter rape. The combination of two active substances – protioconazole from the triazolinthion class and tebuconazole from the triazole class – in an effective formulation has a protective and therapeutic effect on the pathogens of the main diseases of rapeseed (phomosis, Alternaria, cylindrosporium, etc.), destroys both existing and latent forms of infections, which significantly increases the wintering of winter rapeseed.

The use of fungicides after a certain stage of plant development is not necessary, as new leaf lesions do not lead to a strong degree of stem cancer development and do not cause yield losses [313]. This stage depends on climatic conditions and parasite-host relationships. In the UK, the most widely used forecast for rape phomosis is based on the presence of leaf spots in autumn. Such a forecast does not always indicate the optimal timing of fungicide application, as the fungus can reach the stem and escape the fungicide. There are prospects for developing a more accurate forecast based on the interaction of weather factors and ascospore maturation, as well as for using immunological or molecular methods to detect ascospores in the air and asymptomatic infection in leaves. France has developed a system for predicting the timing of fungicide treatments based on epidemic risk and agronomic factors [314]. The risk of infection is determined by weather and biological factors (7 days with rain after sowing, pseudothecia maturity or the first detection of more than 20 ascospores in the air per day). If the risk of infection is high, the decision to use fungicides is based on agronomic factors such as variety resistance, soil type, and the stage and degree of plant development.

In addition, higher doses of triazoles are required for chemical protection of rapeseed against *L. biglobosa* than for control of *L. maculans* [315]. Since many of the most effective fungicides are not allowed under the new EU legislation, there is a great need for breeding rapeseed varieties with resistance to both *L. maculans* and *L. biglobosa* [316].

For the conditions of Ukraine, the systemic disease identification and control card has the following technological sequence:

Manifestations of the disease: It occurs on cotyledons, leaves, stems and pods. The causative agent Leptosphaeriamaculans (sexual stage) produces ascospores, Phomalingam (asexual stage) – picnics; Leaf damage takes the form of irregularly shaped spots of greyish-white or ashy colour, often covered with black specks;

The stem is affected in the root part or in the places of leaf attachment;

Phomosis on the stem is manifested in the form of dry ulcers with black edges that encircle the base of the stem and lead to lodging of the plant;

Seeds grown in an infected field may contain the infection and can help to prevent the disease from spreading.

Control measures for phomosis

Agronomic measures: observance of crop rotation; ploughing and destruction of plant residues; control of carrion and weeds.

Chemical measures: seed treatment to control infection of seeds with the phomosis pathogen; foliar treatments (growth regulators are helpful).

Use of tolerant hybrids.

Favourable conditions for the development of the disease:

Warm, humid conditions increase the risk of phomosis and the spread of the disease; Rain drops help ascospores to spread from the stubble; splashing drops scatter pycnidospores; Wind carries ascospores over long distances (up to several kilometres); High humidity promotes spore germination and initiates fungal growth;

Moisture in the early stages of plant development (up to the 6-leaf stage) plays an important role in the emergence of this disease.

The rows and conditions in which the early phase takes place have a significant impact on the final outcome of a phomosis outbreak;

The impact of the disease is more severe as temperatures rise towards the end of the growing season.

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4.5. Integrated systems and methods for clubroot control in cruciferous crop agrocenoses

Clubroot, caused by the soil-biotrophic obligate pathogen Plasmodiophora brassicae Woronin, is one of the most damaging diseases of cruciferous crops worldwide [1–3]. In many regions, clubroot causes serious damage to a number of cruciferous vegetable crops. Like Plasmodiophoridae, the pathogen belongs to the Rhizaria group of protists [4–5]. Together with the phyla Stramenopiles (also known as Heterokonta) and Alveolata, Rhizaria represent the eukaryotic supergroup SAR, which is a highly diverse group of eukaryotic organisms [6]. Clubroot causes root tumours that lead to impaired water and nutrient absorption. As a result, the infection can lead to wilting and stunted growth (Figs 4.27–4.28). Oilseed rape yield losses can range from a 10% reduction in yield to complete yield loss, including plant loss and reduced seed count per pod [7]. Disease development and cellular changes in host plants after infection have recently been described in detail [8–9].

Successful management of the disease is difficult because chemical control of clubroot is not permitted or has not been successful. In the soil, the pathogen survives as extremely tough, thick-walled dormant spores. These spores are easily transported from field to field through contaminated soil by machinery, animals, water or wind [10]. Thus, the disease can spread rapidly over large areas. The spread of the pathogen was recorded as early as the 18th century. In the 19th century, clubroot was first described in Ukraine [11]. It is assumed that the clubroot arrived with immigrants, the colonisation movement and the first settlers from Europe to North America [12], South America [13] and Australia [14], who probably transmitted the pathogen with contaminated food and fodder, or with contaminated soil.

Currently, foot-and-mouth disease is recorded on all continents (except Antarctica) and in more than 75 countries [15]. It is very likely that the disease is spread throughout the world where cruciferous crops are grown or cruciferous plants are present. The regions where the pathogen occurs with a high population density are predominantly humid temperate regions [16]. Expansion of sown areas and intermediate crop rotation contribute to an increase in the damage caused by this pathogen.

Figure 4.27 – Modelling the type of clubroot on rapeseed roots (upper position – the beginning of the formation and decomposition of the affected root with the release of spores, lower position – fully formed signs of clubroot) [17]

Figure 4.28 – Winter oilseed rape plants affected (left) and unaffected by clubroot [7]

An important factor in the control of clubroot is the implementation of effective host plant resistance. Not all known R-genes are active against all races, and resistance can be undermined by new races of pathogens. Crop management practices are widely used to control the disease. However, control measures such as crop rotation and increasing soil pH are not sufficient to reduce the spread of the disease. In order to improve control strategies, research into biological control measures has played an increasingly important role in recent years. In addition, the strengthening of plants with growth stimulants is becoming increasingly important.

If the host plants are repeatedly grown in the field, dormant spores of the pathogen can accumulate in the soil [18]. These spores are persistent and can remain in the soil for many years, leading to infection of cruciferous plants even after several years of cultivation [19]. Estimated [20], that the infection level in the field decreases below the level of detection only after 17.3 years. However, more than a 2-year break in cultivation and a diverse crop rotation scheme can reduce the number of dormant spores in the soil [21–22].

In order to control the P. brassicae pathogen, it is essential to know the optimal environmental conditions that lead to an outbreak of the disease. The causative agent of clubroot was described in 1878 [23], and more than 50 years later, its life cycle was shown for the first time [24]. Since then, the environmental conditions that are optimal for the development of the disease and contribute to its spread have been studied in detail [25–26].

Soil temperature and moisture play an important role in the development of the disease. The highest infection rates and symptom severity are observed at temperatures of 21–25 °C. At temperatures well below 20 °C, the damage is significantly reduced [27–29] For successful disease development, high soil moisture is required, especially during the first two weeks after inoculation or during the first and second infection [30]. KIn addition, soil moisture promotes the spread of mobile zoospores [31]. Soil type has little effect on the intensity of infection. However, sandy soils and soils with a low humus content have been shown to inhibit the development of the disease [32] and that the damage was lower on light sandy loam soils than on loamy soils or clay [33–35].

Another important factor for the development of clubroot is soil pH. A low pH value (pH 5 to < 7) in the soil promotes spore germination [36–37]

and usually leads to a stronger infestation. As the pH value increases, starting at around 7.2, new infestations hardly occur in most cases [38–41].

Thus, the most favourable conditions for clubroot development are high summer temperatures combined with light acidic soils and good soil moisture in the first weeks after sowing. It can be assumed that this will have a significant regional and interannual impact on the spread of the disease.

To date, the most thorough summary of edaphic and environmental factors that are crucial for the development of clubroot on cruciferous plant species was made in the study by R.G. Dixon [1]. Below, we provide a literary summary of his work, leaving a list of literary citations and formulations by this author.

Plasmodiophora brassicae Wor., the microbe that causes plant cankers in the Brassicaceae family, is very well adapted to live successfully for three reasons. Firstly, it is robust, well protected and apparently long-lived dormant soil-borne spores allow this organism to withstand adverse conditions, and yet these dormant structures seem to be able to react quickly as soon as a suitable host plant appears. Secondly, when this host is available, the primary zoospores that emerge from perennial spores have efficient means of movement, penetration and invasion. These features allow *P. brassicae* to make the best use of the soil environment, its profile, and the rhizosphere. Thirdly, after entering the host environment, *P. brassicae* reproductive cycles are protected from adverse external conditions, which allows the production of numerous new dormant spores that eventually restore the potential of soil pathogenic material [42–43]. During this phase, the pathogen has the ability to change the host's metabolic activity to its advantage. Only for a short time and at short distances in the soil are the primary zoospores exposed to unfavourable conditions. While in this phase of the soil, the fragile and vulnerable single-layered zoospores, equipped with double flagella, float in the soil due to the film of soil moisture from germinated dormant spores to the outer surfaces of root hairs. This is the most vulnerable part of the entire P. brassicae life cycle. However, this phase has not received the scientific attention it deserves, possibly because the tools necessary for such a study are either absent or too imperfect. There is some evidence to suggest that soil chemical and physical components affect *P. brassicae* itself, mostly gathered as a result of attempts to create extremely unfavourable conditions and thus stop the host from invading, thereby controlling the disease. Little

is known about how *P. brassicae* interacts with its biological environment, except for a few studies of microbes that, by analogy with the developmental cycle of *P. brassicae*, may offer elements of strategies for controlling the pathogen.

The dormant spores of *P. brassicae* are an obvious place to start when considering the ecological interactions of the pathogen. These robust spores are designed to ensure the long-term survival and reproduction of *P. brassicae*, and have evolved to remain viable in the soil despite exposure to adverse weather conditions for many seasons. Field studies show that their half-life is at least 3.6 years, and some spores can survive for at least 18 years in the absence of suitable hosts before spore populations decline to levels that are undetectable from the point of view of potential infection of cruciferous plant species [44].

Temperature, moisture content and position in the soil profile affect spore life expectancy [45–46]. The pH level of the soil obviously affects the rate of formation of primary zoospores, the number of which increases in acidic soils compared to alkaline soils [47], but without significant changes in overall germination. Spore dormancy and the need for external stimulants are elements of the initial relationship between P. brassicae and the environment [48]. Only a few spores from plant root debris in the soil germinate immediately [49]. However, certain external stimuli may be required to initiate the infection process [50–51]. The germination readiness of spores released from the roots of the host plant has been studied by a number of researchers [52–56]. In general, they concluded that bacteria and other organisms destroy diseased tissue in the host plant and "prepare" the spores for more efficient germination. But these secondary microbes are not essential for the germination process itself. Unknown mechanisms present inside the dormant spore initiate germination and control its speed. It turns out that these mechanisms in some spores act quite separately from other spores, as not all spores germinate synchronously. Rainwater and floodwater spread *P. brassicae* over quite long distances, especially on slopes. Wind carries spores collected with light, dry, dusty soil particles over even greater distances. Earthworms [57] and possibly moles, root nematodes and insects can be potential vectors [58–59] *P. brassicae* in soil. Spores spread with the manure [60] and on the farm animals themselves, as they are able to withstand the animal gut environment. The farm animals

and their food supplies that arrived with European colonists in the New World and Australasia are likely to have been vectors of *P. brassicae* in virgin areas.

Dirty machinery, wheels, crates and piles are all potential vehicles for the spread of *P. brassicae*. Wild and weedy Brassicaceae, as well as infected crop seedlings, harbour and spread the pathogen. Once established in the soil profile, further distribution is related to soil textural and structural properties, as well as the frequency and intensity of agricultural operations. Soil compaction and loosening by rotational tillage reduces the movement of spores into the subsoil, as does a strong humus-accumulative horizon of the soil profile with an active rhizosphere. The dormant spore population density decreases with increasing soil depth, with more than 97% of the total *P. brassicae* inoculum present in the surface soil layer (0–5 cm depth) and only a small number of dormant spores found below 40 cm [61].

Since the density of dormant spores is influenced by soil type, pH and host susceptibility, the combination of these factors determines the intensity of the inoculation potential at a particular site. It follows that after germination in a particular environment, the inoculatory potential of *P. brassicae* creates dose-response curves [62] unique to that particular location. During germination, the volume of dormant spores increases as the vacuoles enlarge and the walls thicken and become more transparent [63–64].

One zoospore is released from each dormant spore, leaving behind cytoplasmic residues. Germination is characterised by the loss of refractory globules, which are characteristic of the reserves in dormant spores, probably indicating enzymatic mobilisation of these resources. Immersion of spores in water can stimulate germination [65]. Ayers [66] germinated within 1 to 10 days using tap water, with the germination rate depending on the maturity of the spores. The absolute need for a stimulating environment may be questionable, as Honig (1931) [67] induced germination at temperatures below 21 ^{0}C in the absence of seedling roots. The optimum temperature for spore germination at rest is 24 ^{o}C and pH 6.0–6.7, with an upper lethal temperature of 45 ^{o}C and visible light inhibiting germination. Spores can be stored as dense suspensions at 3–4 ^{o}C for 3 years without loss of viability [68], apparently withstand anaerobic conditions and do not die at -20 ^{o}C for 3 days. It is standard practice to store galls at -20 ^{o}C

for several years as a seeding material [69]. These few pieces of information are sufficient to define dormant P. brassicae spores as very robust, able to withstand very unfavourable conditions. Comparative experiments aimed at determining the effect of temperature on dormant spore germination, motility and host infection require that spore maturity, age and hydrogen ion concentration in the immediate vicinity of the host-microbe interaction be known, standardised and reproducible. Evidence for the influence of the host on spore germination at rest is provided by Niwa and others (2008) [70] who reported a significant increase in the percentage of germinated spores (without nucleus) in rhizospheres where the host *B. rapa* var. perviridis was present.

The participation of root exudates as stimulants of spore germination at rest was investigated and subsequently confirmed [71–75]. Concluded [76], that the germination stimulating effect is nonspecific and can come from exudates of many species, not only from *P. brassicae* host exudates. This is supported by the data that root exudates of both calabash and perennial ryegrass stimulate spore germination. It was found that [77–78] that most germination (75%) is induced by root exudates of susceptible cruciferous host plants. It was also found that [79] that an abiotic stimulant may be present in root exudates, especially in exudates of susceptible and resistant Chinese cabbage varieties. Complex carbohydrate compounds found in cabbage exudates stimulated germination of pathogen spores [80]. It is possible that several factors can consistently influence germination [81]. Thus, it was found that the release of calcium ions from spores induces their germination. The exudate of the host plant stimulated the germination of the spores, which in turn released a second stimulating factor that encouraged further activity. The environment in which the host plant grows affects the composition of the exudate, for example, drought promotes the release of amino acids. Identified [82] calcium as a factor in the inhibition of *P. brassicae* in the soil and, consequently, a negative impact on germination, but it is recognised that this element does not act in isolation from the influence of soil microbial flora. Similar conclusions were drawn by another researcher [83] which used a comparable range of calcium sources. The number of dormant spores was adversely affected by the introduction of high-calcium BOF slag into the soil [84]. Direct evidence that the inhibition of spore germination is the main reason for the inhibition of pathogens at

neutral pH is provided by another study [85]. The number of germinated dormant spores in the soil correlates with the level of root hair infestation. When the calcium content of the soil decreased, the number of germinated spores and the level of root hair infestation also decreased. Therefore, not only does the host exudate affect germination, but also the number of spores available for germination is in some way related to the presence of calcium in the soil. Potentially, calcium and pH can affect the lifespan and viability of dormant spores in situ in the soil. Calcium-rich compost or calcium carbonate, which changes the soil pH from 6.0 to 6.9 and from 6.2 to 7.1, respectively, significantly reduces the percentage of germinated spores in the rhizosphere and the number of root hair infections. This study provides direct evidence that spore germination and subsequent colonisation of root hairs is slowed by calcium and alkaline pH values. Previously, was founded [86] that the introduction of a large amount of organic matter over 15 years increased the concentration of calcium in the soil, changed the pH to alkaline values, as a result of which the soil, which was previously favourable for the development of the clubroot, became unfavourable for their development.

Organic matter inhibited *P. brassicae* infection, and fine particle size fractions (< 5 mm) were most effective at changing the pH. Calcium hydroxide, calcium carbonate and potassium hydroxide also inhibited infection, with potassium hydroxide being the least effective [87]. The addition of sulphuric acid facilitated the development of infection by acidifying the soil.

It is concluded that soil pH has a significant impact on infection processes, and that calcium makes a separate contribution to these effects, with both factors acting in unison. Dormant spores from "non-natural" sources, such as callus crops, are less capable of germination than spores from whole plant galls [88]. This may be due to the fact that such spores are physiologically different from naturally grown spores, possibly due to the callus culture system.

The number of dormant spores per diseased plant increased at low disease severity values, but then remained almost constant for plants with symptoms of category "3" and above [89–92]. The average number of dormant spores per diseased plant ranged from 93 to 109, regardless of the disease index value, apparently crossing the saturation threshold. When the

load of dormant spores in the soil reaches even moderate concentrations, the severity of the disease increases [93].

Direct knowledge about the movement of zoospores is very limited, as it concerns behaviour after release from dormancy until incubation on the root surface in soil (Figs. 4.29–4.30).

Since the first studies of *P. brassicae*, soil moisture has been empirically considered as the medium through which host contact is achieved. In practice, of course, the influence of seasonal water supply varies, so although clubroot is considered a disease of wet soils, there are

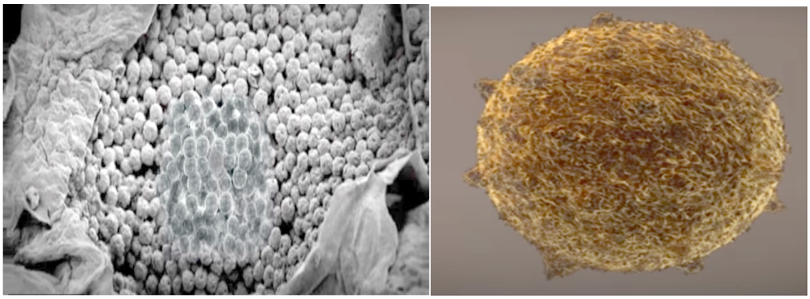

Figure 4.29 – Spores of *Plasmodiophora brassicae* [94]

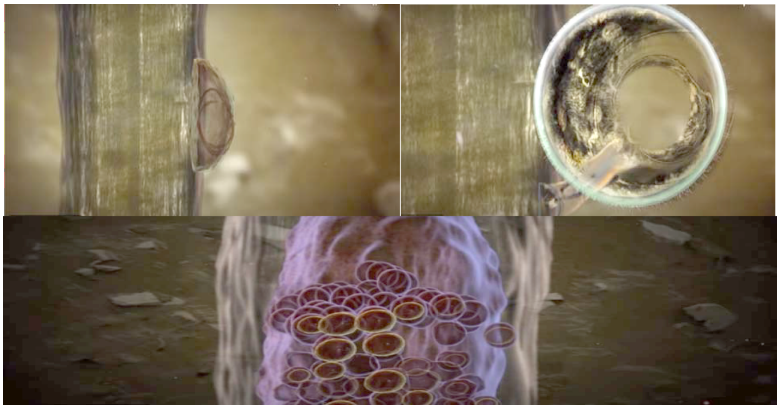

Figure 4.30 – The process of clubroot infection through the rhizosphere root hair system of rapeseed [94]

many reports of its intensity increasing in dry seasons or in dry areas. This probably reflects the loss of productive root systems, which makes the leaves very sensitive to water stress during periods of moisture deficit. It is believed that clubroot is associated with hydromorphic, poorly drained soils, and the disease is most severe after prolonged wet weather. For this reason, soil moisture is classified as the dominant environmental factor in the interaction with *P. brassicae*.

When soil moisture exceeds 50% of the moisture capacity, the disease develops very rapidly, indirectly demonstrating the speed at which primary zoospores move. Differences in the effect of soil moisture content may reflect differences in soil texture used by different researchers. Texture may influence the motility of P. brassicae zoospores, as suggested [95] because in their experiments, sand and soil mixtures caused the highest levels of infection. The infection developed at a moisture content of 9% in mineral soils, while organic soils require a moisture content of 60% [96]. Where soil moisture increased from 50% of the maximum water-holding capacity to saturation, disease severity increased. Underlined [97]. The dependence of zoospore microbes on free water existing between soil particles for the movement of zoospores. Free water is critical for the formation, release and dispersal of zoospores and can influence the processes of incursion and penetration at the root hair surface. The distances travelled by soil-borne zoospores are relatively short, probably between 10–20 mm, based on information for *Olpidium brassicae* or *Synchitrium endobioticum*, which are related to *P. brassicae*. Root hair infection occurred up to 75 mm from the source of *P. brassicae* infection in soils where free water movement was minimised [98].

Mathematical modelling [99], demonstrated a link between soil moisture and host invasion. Temperature was considered to be less important than soil moisture as a factor influencing the successful movement and invasion of *P. brassicae* than soil moisture. It has been studied with contradictory results in the same way as soil moisture and for similar reasons. A strong infection developed on acidic soils at an air temperature of 16.6 ^{0}C, while on alkaline soils the disease manifestation was less pronounced. The development of the disease was more favourable when working with alkaline soils at an air temperature of 23 ^{0}C [100]. As with soil moisture, the results [101] showed that the creation of conditions in which one of the main environmental

factors was very favourable to the pathogen allowed the disease to develop, despite other seemingly unfavourable factors. Previously, it was believed that temperatures below 20 °C were a barrier to the development of the disease [102–103]. But it showed [104-105] that the symptoms of the pathogen develop in the range from 9 to 30 ^{0}C.

The minimum temperature for the infection of root hairs of certain cruciferous plant species was also determined to be 12–14 ^{0}C. Research [106] have shown that in the early stages of root hair infection, temperatures of > 22.5 °C are required immediately after inoculation. Once root hair infection is complete, lower temperatures are sufficient to support symptom formation.

Growth analysis research [107], showed that temperature is the most important regulatory factor in the second week after inoculation, when root hair colonisation reaches its peak and zoosporangia are formed. It is possible that the predominance of individual environmental factors varies depending on the stage of the pathogen's life cycle.

The following assumptions were made [108]: "when one factor limits the manifestation of a disease (e.g. pH), another can significantly modulate its level (e.g. temperature)". This means that one factor sets the actual limit, while the other interacts with it to determine the frequency or intensity. It is also assumed [109] that pathogen can develop at 7 °C with daily temperature fluctuations and an increase in day length from 8 to 12 hours.

Light, sandy, humus-rich and clayey soils are thought to be the most favourable for the disease. As with the interaction between clubroot and acidity or alkalinity, there is a lack of rigorously tested scientific evidence on disease development and soil characteristics. Soil type affects the ability of physiological races of P. brassicae to pathogenise the disease. Clay and loamy soils are prone to compaction and have a pronounced neutral reaction of the environment, which leads to an interaction between favourable and inhibitory effects [110].

The conditions in which dormant spores are stored affect their viability [111] while germination is stimulated and increased by the presence of host root exudate. Interacting factors, such as humidity, temperature, pH, light intensity, as well as intrinsic factors including spore size, age and nutritional status, influenced the overall outcome of the host-parasite interaction.

The conclusion was made [112] that under environmentally unconstrained conditions and below the threshold level of infection required for maximum disease severity, canker severity is proportional to the increase in inoculum concentration and total root hair infection. Above this threshold, an increase in spore concentration may result in a higher level of root hair infection, but is not associated with an increase in disease severity. The Webster's threshold is actually a saturation point beyond which the physiological and biochemical processes that regulate the development of symptoms in the plant cannot be disrupted by the inoculum load. Saturation itself is not fixed and unchanging, as Webster's work supported the idea that only a small percentage of spores in an inoculum can cause a successful infection or invasion at any given time. The saturation of the root hair space in the root area under study, the distribution of spores around susceptible root hairs and the distance they can travel in the soil are all factors that influence the likelihood that an additional spore will be able to cause infection and cause a clubroot.

At the same time, the two-stage life cycle of *P. brassicae* inevitably means that only a limited number of invasive zoospores can ultimately cause symptoms. In addition, there may be competition for rhizosphere space between different physiological races of *P. Brassicae* [113]. Both antagonistic and synergistic relationships between *P. brassicae* races can affect the relationships between physiological forms [114–117]. In any population of *P. brassicae* spores, there may be a range of viability or infectivity, so that some spores, once infected, progress through the life cycle more quickly than others.

It is reported [118], that more than one physiological race of *P. brassicae* can occur in a population or in a suspension of spores obtained from a single spore formation.

Host resistance can be seen as an environmental component that influences the success of *P. brassicae*. From this point of view, it becomes an additional sink for the energy expended on spore penetration. The process of overcoming host resistance may be a function of the biological fitness of successive waves of zoospore infestations, both primary and secondary, as well as the reduction of overall host resistance. Ultimately, successful infections develop in the root hairs of resistant cultivars.

It turns out [119] that specific resistance is expressed against the secondary phase of the *P. brassicae* life cycle. Therefore, during this phase, *P. brassicae* can expend more energy, to no avail in the presence of resistance, but more successfully in the absence of such resistance. Given the highly polygenic nature of some forms of *P. brassicae* resistance, especially in *B. oleracea*, these events may go some way to explaining the time gaps between infections that result in less advanced infection states on assessment days when plants are exposed to lower inoculum concentrations. As a result, the number of infections falls below the observed threshold and is not, in practice, taken into account in the analyses used to determine the value of resistant genotypes. These phenomena have led to much debate as to what constitutes visible or phenotypic resistance to *P. Brassicae* [120].

Perhaps the most controversial issue related to clubroot is the calcium content of the soil and the associated hydrogen ion content (pH). As noted earlier, calcium is a fundamental factor in the life cycles of both *P. brassicae* and its hosts. Detailed long-term experiments have confirmed this [121–127]. It is clear that calcium has the greatest impact when it is present between spore germination and post-penetration to root hairs. The latter period seems to be the time when root hair infection has the greatest impact on the subsequent formation of plasmodia. A very important finding is that high calcium concentrations at pH 6.2 or 7.2 reduce the total number of root infections and the rate of maturation through the plasmodial, sporangial and zoosporangial stages compared to the control. Elevated calcium concentrations completely suppress the late stages of *P. brassicae* development in the root hair, even when high doses of inoculum are applied [128].

Also demonstrated [129] that the effect of pH is independent of calcium concentration, and found that alkaline pH reduces the total number of infected root hairs and slows the maturation of plasmodia, sporangia and zoosporangia. The effect of pH on the maturation of root-hair infections is activated by alkaline pH within 3 days of penetration. Prolonged exposure for more than 3 days has no additional effect. There may be a double effect, as alkaline pH increases the sensitivity of the host and P. brassicae to calcium and also increases the efficiency of calcium uptake. The effects of pH and calcium are remarkably similar, but this does not necessarily mean that they are identical, as some researchers have suggested.

They can regulate the pathogenic potential of the seed quite separately. Since pH regulates the response to calcium, intracellular function can be further modified. The high concentration of H^+ ions in plant tissues is potentially antagonistic to calcium. The permeability of membranes decreases both at alkaline pH and at high calcium content. Such an environment can affect the growth and reproduction of P. brassicae, as it proliferates in epidermal cells, root hairs and epidermis, or in the bark cells of the host plant. The alkaline environment can affect primary and secondary invasion, bark migration and cell hypertrophy.

It was also demonstrated that in the absence of boron, the inhibitory effect of calcium on root hair infection is suppressed, and it was suggested that lime may not be able to reduce the development of canker in soils deficient in boron. The following results were achieved [130–136] a significant reduction in the disease index when sodium tetraborate was applied to acidic granite soils during three consecutive years of field research. Later studies have shown that an environment with an increased concentration of boron has a significant effect on both the root-hair and cortical phases of P. brassicae. At all stages of the life cycle of P. brassicae in planta, boron affects the microbe. There is also a correlation with the amount of boron in the plant, which depends on the uptake in time and space, determined by the size of the plant root system and its ability to absorb boron.

Little is known about the relationships between *P. brassicae* and macro- and microflora and fauna in the soil. Free-floating *P. brassicae* zoospores are undoubtedly a threat to other soil biota. Cases of "disease suppression" may well be associated with the presence of such organisms, which can increase in undetermined quantities either naturally or as a result of agricultural activities. The addition of organic or inorganic fertilisers that stimulate the microflora has a significant impact on the survival of P. brassicae. Bacteria such as Bacillus spp. and fluorescent Pseudomonas spp. are recognised to have an impact on P. brassicae growth [137]. Since spore dormancy walls contain chitin, it is likely that chitinolytic bacteria may be the main antagonists of *P. brassicae*, reducing the potential of the inoculum [138]. Antibiosis induced by microbial sources has generally been viewed as a means of biological control of *P. brassicae* rather than as an advancement in understanding the ecological relationships between organisms. Extensive studies of soil suppressive capacity against *P. brassicae* were conducted by

researchers in the Fukushima area of northern Honshu, Japan. It was found that the haplic andozoic soils were more favourable to *P. brassicae* than the low humus andozoic soils, even though the latter had high concentrations of spores. It has been suggested that the suppressive effect of low-humic andosols is associated with the presence of biological antagonists. Biological inhibition of *P. brassicae* in the presence of Chinese cabbage (*B. raopa*) host plants is reported to be the result of the presence of the soil endophytic fungus *Heteroconium chaetospira* [139].

Crop rotations, especially those containing maize (*Zea mays*), suppressed the activity of *P. Brassicae* [140]. This may be due to ecological interactions and biological control. Primary plasmodia were found in the root cultures of both susceptible and resistant varieties, but secondary plasmodia multiplied only in the cultures of susceptible hosts. It was concluded that the reason for this difference was the alkalisation of the root culture of resistant varieties.

The fungus *Heteroconium chaetospira* suppressed the activity of *P. brassicae* even where the physical soil conditions (moisture and pH) were favourable [141]. Other representatives of soil microflora, such as Bacillus spp., Pseudomonas spp. and Trichoderma spp. reduce the activity of *P. Brassicae* [142] and *Streptomyces* [143–144]. Soil environments created by host and non-host plants, such as leeks (*Allium porrum*), winter rye (*Secale cereale*) and perennial ryegrass (*Lolium perenne*), tended to reduce *P. brassicae* growth in greenhouse studies, but in the field, these effects were less effective.

Thus, clubroot is potentially the most serious disease of cruciferous crops, especially cabbage and closely related crops. It is caused by the parasitic phytopathogen *Plasmodiophora brassicae* Woronin, which is soil-borne and causes economic losses in many regions of the world [145]. In 1878, Mikhail S. Voronin was the first to recognise a plasmodiophoric organism as a causative agent of clubroot and named it *Plasmodiophora brassicae* [146]. Later, this disease was registered in many countries on different continents.

The disease can progress significantly without showing any visible above-ground symptoms. The earliest above-ground symptoms are stunted plant development, flag-like leaves and wilting of the entire plant on hot sunny days, as if the plant is suffering from a water deficit. It looks like wilting when there is enough moisture in the soil. However, the above-

ground symptoms are not enough to diagnose a clubroot infestation. You need to dig up the roots. When such plants are dug up, you can see a hypertrophied root system. The infected root forms "mace-like" nodules on the main and lateral parts of the root system, depending on the type of host plant and the nature of the infection. There are several types of clubbing: (a) clubbing of the entire main and lateral root systems, as in cabbage, (b) clubbing of the main root only, while the lateral roots are free, (c) clubbing of the lateral roots only, while the main root is free, (d) clubbing in the form of a tumour, as in radish, (e) dark decomposed several spots in the root system.

The life cycle of Plasmodiophora brassicae Wor. has three stages: survival in the soil as dormant spores, infection of root hairs and infection of the bark. The life cycle of P. brassicae Wor. begins with spore dormancy. The pathogen persists as dormant spores in the soil or on plant debris. The dormant spore has the ability to survive for a considerable period of time in the soil in the absence of a host crop (Figure 4.31).

Dormant spores in the soil can germinate even after 17 years (Figure 4.32). They release primary zoospores that swim to the surface of root hairs, where they penetrate the cell wall. Primary zoospores are pyriform and bivalve [148], with unequal bifid flagella: one short with a blunt end and the other longer with a pointed end. This stage is known as the root hair infection stage [149]. The pathogens then form primary plasmodia within the root hair. The plasmodia undergo a series of nuclear divisions in synchronisation; eventually, the plasmodia turn into zoosporangia. Each zoosporangium gives rise to 4–16 secondary zoospores, which are released

Figure 4.31 – Cruciferous species that can be hosts of clubrooted cowpea [147]

into the soil, ready to penetrate the cortical tissue of the main root system, a process called cortical infection [150]. Later, the pathogen develops into secondary plasmodia, which are associated with cellular hypertrophy, leading to the formation of galls in tissues. Finally, these plasmodia develop into a new generation of dormant spores that are released into the soil as overwintering structures [151].

In the absence of a host, P. brassicae survives as haploid dormant spores 3–5 μm in diameter. The dormant spore is a very stable structure. Its cell wall (including the membrane) consists of approximately 25% chitin, 2.5% other carbohydrates, 34% protein and 18% lipids [152].

Germination of dormant spores leads to the release of a biflagellate zoospore (primary zoospore). The germination rate increases with the maturity of the spores, increases with increasing humidity and temperature, decreases with alkaline pH and varies depending on the content of certain inorganic ions in the soil [153–154]. In contrast to thick-walled dormant

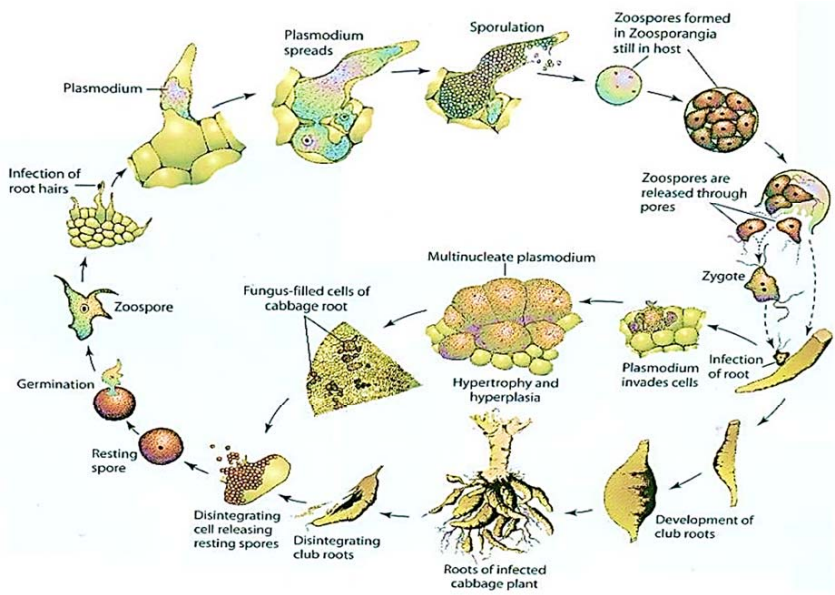

Figure 4.32 – Developmental cycle of cruciferous disease caused by *Plasmodiophora brassicae* [156]

spores, zoospores are sensitive to various types of environmental stress. Without access to the host plant, zoospores are thought to survive only for short periods of time [155].

The abundance and virulence of the pathogen, the susceptibility of the host plant and the suitability of environmental factors influence the severity of the disease. When a plant is infected with a pathogen, environmental factors affect the severity of the disease and the growth, development and yield of the plant.

Clubroot causes huge losses in cabbage yields. In addition, it is almost impossible to eradicate the pathogen from the field once it has been infected. Once a field is infected, management practices to reduce the frequency and severity of the disease include increasing the pH by liming [157], use of decoy plants to reduce the load of pathogen spores in the soil [158], inhibition of germination of dormant spores by means of a neutral pH [159], use of biological products and biocontrol agents [160], postponement of the harvest date for cruciferous vegetable crops to October, when the average air temperature before harvesting is appropriate [161], reducing the density of spores in the soil through crop rotation, steam and nutrient application [162].

Cultural practices, such as crop rotation and improved drainage conditions, can protect crops from disease to a certain extent; however, when infestations are severe, disease control is usually not satisfactory [163]. Some plants, such as lettuce (Lactucasativa), spinach (Spinaceaoleracea) and Italian ryegrass (*Lolium multiflorum*), can be used to reduce root hair infection and clubroot damage. The statement that prevention is much better than cure is the best fit for this disease – once a field is infected, it is very difficult to make it free of the pathogen again. Prevention can be achieved by applying lime to fields with an acidic soil reaction [164]. In addition, a neutral pH level (pH = 7) inhibits the germination of dormant spores [165].

Additionally, it is reported that due to high market prices for rapeseed, the area under rapeseed has increased and crop rotation has narrowed [166]. This has led to an increase in problems with the pathogen and, therefore, another important factor in clubroot control is to maintain crop rotation. A break of more than 2 years or diverse crop rotations can reduce severe clubroot epidemics [167]. In addition, the previous crop can also have an impact on clubroot infection. A recent study compared different preceding

crops before sowing rapeseed. The results showed a 40 and 50% reduction in disease index and incidence, respectively, when soybeans were sown before rapeseed [168]. In addition, microbiological analysis of the soil showed that more bacteria and fungi with known biocontrol functions were found in soybean-rape soil than in soil where corn or other crops were grown [169].

Soil and crop management practices, such as crop rotation, fallow and nutrient application, can reduce the density of pathogen spores in the soil [170]. Recently it has been shown that dormant spores are very sensitive to ultraviolet light [171]. Therefore, tillage practices that bring dormant spores to the soil surface to be exposed to sunlight can be an effective way to support clubroot management.

During one growing cycle of a susceptible variety, the number of dormant spores in the soil increased to 2 x 108/g soil, and that of a resistant variety to 1.7 x 107/g soil, compared to fallow soil.

In addition, sanitation is an important aspect of clubroot prevention. Preventing the movement of dormant spores to a pathogen-free field. As spores live in the soil and move through the soil mass, anything that can move them into pathogen-free soil is a source of the pathogen, such as farm machinery, tractor tyres, boots, tools, livestock and containers. Soil can also be transported with running water. Soil from an infested field can be transported to water sources and other clean fields, which is often problematic during floods. Soil moisture management, especially in the root zone, plays a key role in clubroot control. High soil moisture means that there is a high probability that the bivalve zoospores can infect healthy plants. Over-irrigation and waterlogging should therefore be strictly avoided. Soil has the ability to hold, move and infiltrate a certain amount of water. It is important to improve the physical properties of the soil to accelerate the infiltration of excess soil water into the root zone. To do this, the soil needs organic fertilisers, less tillage and less compaction.

Crop residues, especially root parts, are a source of inoculum or a reservoir of pathogens. Therefore, they should be removed from the field and destroyed after harvesting the economically useful parts of plants. This practice gradually reduces the spore load in the soil.

Boron in the form of borax (boric acid) can suppress clubroot. Boron inhibits both the primary and secondary stages of infection [172].

An aspect that is often overlooked by practitioners is that dormant spores are very easily carried with soil particles, such as machinery, footwear, surface water or animals, thus spreading the disease. In addition, dormant spores have also been shown to be carried by wind-blown dust or soil erosion from field to field [173]. Therefore, measures that can reduce the transfer of spores from field to field, such as sanitising agricultural machinery or measures that help prevent soil erosion, prevent initial infection of fields [174–175].

As soon as the spores enter the field, they are spread not only by cruciferous crops, but also by cruciferous weeds, intercrops and rapeseed residues, which serve as alternative host plants [176], that can be infected by the carpet at any time and therefore should be removed in a timely manner [177].

Sowing resistant varieties is an effective way to suppress the disease. Several resistant loci have been identified by quantitative trait loci mapping in *Brassica napus* and *B. rapa* [178–180] The most widely used resistance loci originate from *B. rapa*; however, these loci do not confer resistance to all *P. brassicae* pathotypes or pathotypes can overcome resistance. Therefore, breeding for resistance remains an important tool for *P. brassicae* control [181].

In addition, pH regulation by liming is an effective way to control clubroot of vegetable cruciferous plants. Although liming is traditionally used as a control measure, it has certain caveats [182-184]. One reason is that the term "liming" refers to the use of different lime compositions. Most commonly, lime is used with different proportions of calcium carbonate (often mixed with Mg^{2+}) [185], cyanamide [186]. In addition, a combination of calcium carbonate and calcium sulphate or calcium hydroxide was used [187]. Calcium oxide, also known as burnt lime or quicklime, is only occasionally used [188]. In addition to the calcium concentration, other factors such as the amount of lime, the date of application and the pH of the soil can affect the development of clubroot. However [189] it is not the effect of calcium that is decisive, but rather the pH of the soil. The germination of dormant spores is drastically reduced at neutral soil pH. Due to the variety of substances and differences in soils, the comparisons of most field trials or greenhouse studies on the effect of lime on clubroot development are rather controversial.

The lack of effective control measures against *P. brassicae* makes it necessary to explore other, new control options. In particular, the use of biological control measures can help reduce the number of soil-borne pathogens. However, the complex life cycle of P. brassicae makes it difficult to apply biological control mechanisms against this pathogen. At least three phases can be used for control: (i) germination of dormant spores or secondary spores that initiate (ii) primary infection of root hairs and secondary infection of root cortex; (iii) antagonism or competition with the pathogen developing in the root tissue of the host plant. In addition, biological control options may include induction of resistance in host plants and changes in microbial communities in the soil rhizosphere [190].

The biological control agents that have been investigated are bacteria or fungi, including oomycetes. The mechanisms are mostly parasitism, antagonism of secondary toxic metabolites or competition. Many studies have illustrated the potential of biological control against soil fungi in the strict sense of the word. This refers to a direct antagonistic or inhibitory effect on the pathogen, rather than indirect effects such as plant growth stimulation or induction of plant resistance [191–192].

Organisms such as, for example, Trichoderma spp. and *Bacillus subtilis sensulato* are commercially used in many products to control various groups of plant pathogens [193–197]. There are numerous examples that illustrate that excellent control results can be achieved in trials *in vitro* [198]. Whereas in field trials, these successful control results often cannot be confirmed [199]. Therefore, for successful control, it is necessary to select proven control measures for clubroot.

The bacteria of the *Bacillus subtilis* species complex are well studied in terms of their biocontrol activity against plant pathogens. These bacteria are capable of producing many hydrolytic enzymes and various secondary metabolites with antimicrobial properties [200]. One of the very well characterised biological control agents patented in China is the *B. subtilis* XF-1 strain. Like other bacillus strains, it produces fungicins, which are a group of non-ribosomal lipopeptides. These metabolites have fungicidal activity and are involved in the biocontrol of many Bacillus species [201–202]. Dormant P. *brassicae* spores directly treated with fungicides were destroyed and the cell contents leaked out [203]. Nevertheless, the mode of action of fengicin was demonstrated on *B. subtilis* NCD-2, which

showed a decreasing effect on the development of clubroot; whereas, when using fungicin, the defective mutants did not show any effect against the clubroot pathogen [204].

Recently, in addition to the new strain *B. amyloliquefaciens*, another member of this genus, *B. velezensis*, has recently been described as a biocontrol agent against *P. brassicae*.

Several species of bacteria in the genus Lysobacter are known for their activity against soil pathogens. These bacteria synthesise many hydrolytic enzymes and antimicrobial compounds, and there are several commercial products against soil fungal pathogens [205]. By screening bacterial strains from vegetable rhizosphere soil, *Lysobacter antibioticus* strains were isolated, and their culture filtrates reduced the incidence of nodule fungi on Chinese cabbage after application as a soil application or seed treatment.

Another strain of Streptomyces, *S. platensis* 3–10, was used to optimise the culture medium and achieved up to 80% inhibition of dormant clubroot spore germination [206]. Recently, a strain of *Bacillus cereus*, MZ-12, isolated from the rhizosphere soil of asymptomatic *B. campestris* (pak choi), showed an inhibitory effect on the germination of dormant spores. Joint inoculation of pak choi plants with *P. brassicae* and MZ-12 spores led to a 64% reduction in the formation of nodule galls [207].

In addition to free-living microorganisms in the rhizosphere or epiphytic microorganisms, endophytic microorganisms can also contribute to biological control. In most cases, endophytic bacteria derived from the rhizosphere enter the plant and colonise its tissues without any negative impact on the plant [208–209]. In many cases, this form of bacterial colonisation contributes to plant growth through various mechanisms [210]. However, the antagonistic activity of endophytic actinobacteria against colic has also been reported [211]. They isolated 81 strains of actinobacteria from surface-sterilised Chinese cabbage root tissue. Among them, they selected three strains that showed in vivo biocontrol activity against *P. brassicae*. Two of these *strains were identified as Microbispora rosea, and the third as Streptomyces* olivochromogenes.

It also tested [212] 63 strains of actinobacteria isolated from the rhizosphere of Chinese cabbage were evaluated for inhibition of germination of dormant P. brassicae spores. As a result, six strains were isolated and used in greenhouse and field trials against clubroot. Strain A316 showed

high control values of 73.69% in the greenhouse experiment and 65.91% in the field experiment.

In general, chemical control of soil-borne diseases is difficult and expensive, and is banned in many countries due to environmental impacts. Of the chemicals registered globally, the oomycete fungicides fluazinam and cyazofamide reduce clubroot damage. They are registered for the treatment of cabbage in some countries, but are not authorised in the EU for the control of clubroot. The use of these products is complicated and expensive, as they need to be applied to the soil to be effective against this pathogen. Therefore, appropriate crop management practices are important measures to control clubroot.

A number of chemicals are fungicidal against fungal plant pathogens, but the term "protozoic" is more appropriate for controlling *Plasmodiophora brassicae* Wor. as this pathogen is not a true fungus. Chemical pesticides should be used as a last resort when all other methods fail. Some chemical pesticides may be banned in one country but not in another. Fluazinam and thiazofamide are quite effective in controlling nodule rot – in advanced disease they are more effective than drugs to fight infection. Some of the most commonly used chemicals against *Plasmodiophora brassicae* Wor. are as follows: Nebizin (Flusulfamide) Among the flusulfamide (2',4-dichloro-a,a,a-trifluoro-4'-nitro-m-toluenesulfonanilide) (trade name: MTF651, Nebizin) dust and suspension formulations, the suspension formulation did not show significant differences. On the contrary, 2.4 kg/ha of flusulfamide was found to significantly reduce clubroot symptoms, including the incidence and severity of the pathogen [213]. Synthetic fungicides are promising for controlling clubroot, and mercury-based fungicides are the most effective, although they are toxic to the environment. Chemicals such as thiazophamide, fluazinam, flusulfamide, procyamidone, and calcium prohexadione reduce the intensity of corm damage by reducing pathogen inoculum density and population composition, but results have not been consistent.

After the identification and evaluation of pentachloronitrobenzene (PCNB), it was reported that chlorinated nitrobenzene could provide significant control in fields that are not heavily infested with the pathogen. In field trials conducted in Alberta, soil impregnation with PCBs (Terraclor 75% WP) reduced clubroot blight and seedling mortality and

increased plant height and assimilation surface area of canola. In greenhouse trials of chemicals, soil applications of benomyl, methyl thiophanate and NF 48 were found to have the potential to control clubroot [214].

Hydrogen peroxide (H_2O_2) is a by-product of cellular metabolism and is mainly produced in mitochondria, chloroplasts, peroxisomes, plasma membrane and cell wall [215]. It induces the expression of the PR 1 gene and systemic acquired resistance (SAR) to pathogens [216]. The CHC is a whole-plant resistance response following a previous localised exposure to a pathogen. In plant-pathogen interactions, hydrogen peroxide can limit pathogen infection by directly inhibiting the pathogen or inducing defence genes in plant cells. In addition, H_2O_2 plays a key role in the regulation of plant growth and development. H_2O_2 mediates stomatal closure induced by abscisic acid (ABA), which is an endogenous antitranspirant that reduces water loss from the leaf surface, preventing wilting of plants [217].

A number of chemicals related to alkylene bisdithiocarbamates are active against clubroot. Among them, mancozeb (manganese ethylene bisdithiocarbamate) is one of the most effective. Similarly, another chemical related to alkylene bisdithiocarbamates, Zineb (zinc ethylene bisdithiocarbamate), has been used as an alternative to benomyl, but this substance has been shown to be phytotoxic to cauliflower [218].

Carbendazim is a broad-spectrum benzimidazole. It is a metabolite of benomyl that is used for the treatment of grafts against Plasmodiophora brassicae Woronin. Carbendazim (methyl lH-benzimidazol-2-ylcarbamate) has proven effective for clubroot control only when applied at very high rates of 80–100 kg/ha, but this makes it expensive and contaminates the soil [219].

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CONCLUSION

The modern system of measures to protect cruciferous plants from diseases should be aimed at eliminating sources of infection, preventing primary plant damage and the development of secondary infection. Such goals require the development and implementation of a set of agrotechnical, immunological, chemical and other measures. Today, the main method of protecting winter rape plants from phytopathogens is chemical, which involves the selection and use of effective fungicides. However, other methods of plant protection are also of great importance, in particular agrotechnical, which is preventive in order to create favorable growing conditions for plant growth and development, as well as immunological, which consists in the introduction of resistant and tolerant to phytopathogens varieties and hybrids of rapeseed. In particular, the plant protection system may include the following measures

– placement of cruciferous crops in the crop rotation with a return to the previous place in three to four years, and the saturation of the crop rotation with cabbage crops should not exceed 25%. In addition, it is necessary to avoid using this group of crops as a precursor to other cabbage crops, as well as to observe the spatial isolation of fields from other cabbage crops, which should exceed 500 m;

– sowing of cruciferous crops should be carried out only with seeds inlaid with effective fungicidal protection and its optimal timing should be observed;

– mineral nutrition should be carried out in accordance with the results of agrochemical soil analysis;

– phytosanitary monitoring of crops should be carried out during the growing season;

– select effective drugs against diseases dominant in crops and adhere to the optimal timing of their application;

– weeds and pests should be destroyed as reservoirs and carriers of phytopathogenic infection;

– seven to ten days before harvesting, desiccate the crops to ensure simultaneous maturation of the plants and avoid seed loss;

– harvesting of cruciferous seeds should be carried out in a short time, after threshing the seeds should be cleaned, calibrated and dried to a moisture content of 7–12% depending on the type of plant;

– depending on the weather conditions, the methods of prevention and protection may vary significantly. Even seemingly insignificant factors can have a significant impact on the spread and development of diseases;

– the choice of fungicide is based on information about the sources of primary and secondary infection, the time of infection and the rate of infection growth. When justifying the choice of fungicide, the species composition of pathogens should be carefully analyzed and the product that suppresses the pathogen that causes the greatest yield losses should be selected;

When the disease is already present or is highly likely to occur, choose the best fungicide product. In addition to the effectiveness and duration of protection, you should consider its toxicity to other crops in neighboring fields and the environment. Keep in mind that most fungicides are not curative. They must be on the leaves of the plant before they are affected by the disease. In addition, a significant part of fungicides are difficult to move by the plant, at best they are "local-systemic". This means that when applied, the fungicide must cover the part of the plant that needs protection with the required droplet density. If the fungicide is systemic, the plant will absorb these drops, but the fungicide will migrate only a short distance from the application site;

– the timing of the fungicide treatment is extremely important. Disease control will only be effective if the fungicide is applied at the right time, when the plants or disease are at a certain stage of development. Even the highest quality application at the wrong time is of much less value than a mediocre application at the right time;

– droplet size does not affect disease control. The only thing that may need to be adjusted is the outflow rate. The amount of water should be increased for spraying modern cruciferous hybrids and varieties with high biomass;

– it is imperative to constantly monitor the development of diseases in cruciferous agrocenoses. In no case should phytosanitary forecasts of disease development in the region be ignored. Pay attention to the optimality of environmental factors for the development of relevant pathogens;

– combine the use of fungicides with other methods of influencing pathogenesis – selection of appropriate resistant varieties, compliance with the recommended rotation of cruciferous crops in modern crop rotations of

classical and short rotation, optimal sowing and fertilization, compliance with the recommended plant density, etc;

– it is advisable to combine the use of fungicides with herbicides and insecticides in a single integrated complex of cruciferous crops protection.

The authors of the monograph hope that the material presented in the monograph was useful both for training and for solving applied technological problems in realizing the yield potential of major cruciferous crops.

It is important to remember that plant diseases are dangerous from the point of view of their unpredictability and ability to accumulate over time. For these reasons, it is important not to ignore the planning of tactics and strategies for their control in modern adaptive technologies for growing major cruciferous crops. Recent developments in modern agriculture offer various solutions, the main ones of which are presented in this paper. Take advantage of them. It will save your money, time and be effective in the future!

Izdevniecība “Baltija Publishing”
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Iespiests tipogrāfijā SIA “Izdevniecība “Baltija Publishing”
Parakstīts iespiešanai: 2023. gada 31. oktobrī
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