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Influence of biochemical composition of above-ground biomass of oilseed radish on the expediency of its green manure application

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Abstract. Over a ten-year period, the volumes of formed ground biomass of oil radish and its biochemical composition were estimated for spring and summer plantings in terms of its green manure application. The formed leaf and stem mass of the oil radish variety Zhuravka was studied using official AOAC international analysis methods, liquid chromatography, methods of field evaluation of yield and weight and equivalent indicators. The effectiveness of green manure application was assessed by the method of multicriteria-decision support. Oil radish was confirmed to have a high adaptive potential at the maximum level of determination of bioproductivity, with an optimal moisture and temperature supply of up to 40%. The long-term average productive and biochemical portfolio of oil radish was identified as follows: 21.19 t/ha of leaf-stem ground mass with 62.3% soil cover 70 days after sowing, 2.8% nitrogen, 22.8% fibre, 0.6% phosphorus, 3.8% potassium, 16.6 μmol/g glucosinolates at the C/N ratio of 14.7, 83% plant-mass quality, and 48.1 mol/ha biofumigation potential based on glucosinolate aucumulation. The study confirmed the high potential of oilseed-radish adaptability to the regimes of unstable moisture of territories, finding interannual variation of the total bioproductivity and biochemical parameters of leaf-mass quality with the value of the variation coefficient ranging 23.6–31.2%, depending on the sowing date. The effectiveness of oilseed radish was also revealed by comparison with the similar interannual variation of hydrothermal conditions of vegetation (the amount of precipitation 48.2%, average daily temperature 27.5%, moisture coefficient 68.1%, and aridity index 58.9%). Oilseed radish was found to be agrobiologically and agrotechnologically feasibile to be used in the system of both spring and summer (intermediate) green manure technologies in grey loess soils under conditions of unstable moisture, as indicated by its bioproductivity and biochemical quality of leaf mass, as well as the results of the components of the multicriteria assessment of the plant as green manure, the value of normalised weight coefficients ranging 0.62–0.99

Keywords: *Raphanus sativus* L. var. *oleiformis* Pers.; concept of multifunctional cover crop; leaf and stem mass; green manure technologies; biofumigation potential; multicriteria decision support analysis.

Introduction

The vector of modern agricultural technologies is aimed at changing approaches to the fertilisation system. The change in these approaches is driven by several main reasons, including the growing trend towards reducing the accumulation of classic organic fertilisers in the form of livestock waste, the rising cost of a range of widely used mineral fertilisers, both macro- and micro-formulations, and changes in logistics due to the effects of the COVID-19 pandemic and current global challenges (Radić et al., 2022). One the most effective and potentially feasible solution is considered to be the classic green manure with a long world history (Bhogal et al., 2019).

The positivity of green manure was considered an effective source of replenishment of soil organic matter with optimised modes of its subsequent humification and normalisation of the positive ratio in terms of the rate of humus mineralisation (Lee et al., 2023), having a positive effect on the complex of soil properties (Ansari et al., 2022). The latter is important in the soil conservation system, since the world's soil cover has pronounced signs of various types of degradation to varying degrees. Today, high rates of dehumification, acidification, and physiccal degradation in the form of soil compaction, loss of agronomically valuable structure and the proportion of water-resistant aggregates are already pronounced degradation threats. These features in combination significantly worsen the water and air properties of soils, reduce their agrochemical potential and significantly worsen soil fertility conditions (Panagos et al., 2016). On the other hand, it was noted that the feasibility of green manure should be based on the study of the effectiveness of its use considering a wide range of issues, from the effect on crop productivity to its role in preventing soil erosion. At the same time, it is still important to find optimal technological options for application of green manure on crops, starting with selection of best candidates for single-component and multi-component application, taking into account potential productivity, options for long-term use and assessment of the susceptibility of soil and climatic resources of the relevant area. Such an approach can identify the best options of using green manure, with the maximum positive effect and guarantee of optimisation of alternative fertilisation, ensuring a positive balance of organic matter in soils while maintaining soil fertility parameters, without compromising the structure of agricultural production in the respective areas (Singh et al., 2023).

At the same time, green manure is an important and necessary element of Ukrainian agriculture in terms of ensuring a modern soil-conservation system and a deficit-free balance of humus and soil nutrients, while ensuring the optimisation of physical, chemical, water-air properties, and soil regimes (Lykhochvor et al., 2022), especially on soils with an average level of soil fertility potential, which include grey and dark-grey loess soils (Moldavan et al., 2023).

The objective of this study was to study the potential of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) as a green manure crop in grey loess soils under conditions of unstable moisture, by analyzing the biochemical composition of the aboveground biomass produced at two different sowing dates. The study aimed to identify the key factors that determine the feasibility of using oilseed radish as a green manure.

Materials and methods

The oilseed-radish variety Zhuravka was used. Sowing was conducted in unfertilised soil using a conventional row method with a seeding rate of 2.5 million seeds per hectare, at a spacing of 15 cm between rows.This sowing variant corresponded to the accepted variant of forage crop and green manure use of oilseed radish (Tsytsiura, 2020, 2020 a). We studied two systems of timing of planting oil radish as an intermediate cover crop for multipurpose use:

System 1: We sowed oil radish in early spring, after intermediate cultivation to a depth of 10-12 cm, in late April. This was done after autumn ploughing at a depth of 20-22 cm when the oilseed radish biomass had reached its optimal phenological phase for multifunctional use ((flowering phase (BBCH 64–67)).

System 2: We sowed oil radish in summer immediately after harvesting the precursor crop, using combined tillage (flat cutter + rotary loosening with leveling) to a depth of 12-14 cm in late July. This was done when the oilseed radish biomass had reached its optimal phenological phase for multifunctional use ((flowering phase (BBCH 64–67) in the second or third decade of October)

The experimental plots were formed in quadruplicate by the method of small plot randomization (total plot area of 35 m^2, accounting area 25 m^2). Phenological periodization of development of the oilseed radish was determined in accordance with the international scale of BBCH (UPOV, 2017).

Criteria for analysis. To prove the effectiveness and expediency of using the leaf-stem mass formed over a multi-year period, a systematic variant of the 'multiple-criteria decision analysis' was applied (Taherdoost & Madanchian, 2023). To implement this analysis, we used a complete analytical hierarchy process with a step-by-step application of the 'analytical hierarchy process' scheme using the Saaty pairwise comparison scale from 1 to 9 points (Saaty et al., 2012) and the 'TOPSIS method' scheme for making an optimal decision (Ramírez-García et al., 2015; El Amine et al., 2016; Hajduk, 2021).

Fig. 1. Location of the research and general view of the object of research of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) variety Zhuravka

The criteria of the analytical block of the main accounting indicators were selected based on the concept of a multifunctional cover crop (Justes & Richard, 2017). The concept of selecting green manure for specific soil and climatic zones involves finding and combining crops that are tolerant of growing conditions in various seasons. This involves accumulating a large amount of nutrient-rich biomass, both above- and underground, through intensive decomposition in the soil, which can improve soil health and other benefits. (Scavo et al., 2022).

Main accounting indicators. The formed aboveground biomass of oilseed radish plants was recorded at the stage of full flowering (BBCH 64–67) at 4 randomised plots using the method of trial plots of 1 m^2 in each repetition (16 plots in total) with subsequent weighing. To ensure a uniform comparison of the above-ground bioproductivity of the plants, the leaf and stem mass was converted into dry matter equivalent by determining the dry matter content in samples of leaf and stem mass, determined by oven drying at 105 °C and then ashing the dried samples at 550 °C (Undersander et al., 1993).

Ground surface (vegetation cover) was determined starting from the phenophase of formation of true leaf (BBCH 12–13) with an interval of 5 days until the flowering phase (BBCH 64–67). To account for this indicator, we used the methodology of Ramirez-Garcia et al. (2012) based on digital photographs of the marked surface (Canon EOS 750D Kit + Canon EF 50 mm f/1.8 STM) taken from a perspective at 1.5 m height.

The C/N ratio was calculated as the ratio of total organic carbon to total nitrogen (Anzola-Rojas et al., 2014). The content of total organic carbon in the dry mass of plants after mechanical grinding was determined using a laboratory analyser of total organic carbon of the TOC-LCPH series (SpectraLab Scientific Inc., Canada, 2012) according to the standard protocol of low-temperature thermocatalytic oxidation of plant material. The total nitrogen content was determined according to the official method AOAC 978.04 by the Kjeldahl method in dry biomass using a KjeLROC Kd-310 analyser (OPSIS Liquid-LINE, Sweden, 2014).

Nitrogen uptake (g/m^2) was calculated according to the method proposed by Letey et al. (1982) and Gastal & Lemaire (2002), taking into account the complete absence of nitrogen fertilisers, which met the necessary condition: nitrogen accumulation = nitrogen uptake. The quality of plant material was determined according to Quemada & Cabrera (1995). The content of glucosinolates was determined in frozen plants using high-performance liquid chromatography according to the standard methods (ISO 9167:2019), taking into account Arguello et al. (1999). Fibre content was determined according to the official method AOAC 978.10, gravimetrically as the residue remaining after acid and alkaline digestion. The content of total phosphorus and potassium was measured using AOAC Official Method 931.01 and AOAC Official Method 956.01.

The biomass of oilseed radish was converted to a comparable composition to average cattle manure, with a dry matter content of 10-15% (similar to the oilseed radish plants) and standardised nutrient concentrations of 3.2 g/kg nitrogen, 2.0 g/kg phosphorus, and 3.8 g/kg potassium, as reported by Brown (2021)

Analysis of weather conditions. The hydrothermal regimes of the vegetation period of oilseed radish of different sowing dates for the period 2014–2023 were assessed by the hydrothermal coefficient (HTC) (formula 1), De Marton aridity index (IDM) (Moral et al., 2016) (formula 2), Vysotsky-Ivanov moisture coefficient (Kh) (Latief et al., 2017) (formula 3).

$$\mathrm{HTC} = \frac{\sum P}{0.1 \times \sum t_{>10}} \quad (1)$$

where ΣP – the sum of precipitation (mm) for the period with temperatures above 10 °C, Σt > 10 – the sum of effective temperatures for the same period.

Ranking of GTC values (Latief et al., 2017): HTC > 1.6 – excessive humidity, HTC 1.3–1.6 – wet conditions, HTC 1.0–1.3 – moderately dry conditions, HTC 0.7–1.0 – dry conditions, HTC 0.4–0.7 – very dry conditions.

$$\mathrm{I_{DM}} = \frac{12\mathrm{P}}{\mathrm{t_{av.}}+10} \quad (2)$$

where P and $t_{av.}$ – the amount of precipitation and average air temperature in the respective month.

According to Baltas (2007), this indicator, with adaptation, classifies the climate type of the territory into: arid IDM < 10; semi-arid 10 ≤ IDM < 20; transitional 20 ≤ IDM < 24; semi-humid 24 ≤ IDM < 28; humid 28 ≤ IDM < 35; very humid 35 ≤ IDM ≤ 55; extremely humid IDM > 55.

$$K_h = \frac{P}{E} \quad (3)$$

where K_h – moisture coefficient; P – total precipitation for the analysed period (mm); E – evapotranspiration (mm) for the analysed period, calculated according to Latief et al. (2017) using the formula 4) (mm).

$$E = 0{,}0018 \times (25 + t)^2 \times (100 - a) \quad (4)$$

where t – the average air temperature for the period (°C); a – the average relative humidity for the analysed period (%).

The degree of humidification was assessed according to the following gradation (Latief et al., 2017): Kh > 1.0 – territory (period of time) with excessive humidification, Kh close to 1 – optimal humidification, Kh = 1.0–0.6 – unstable humidification, Kh = 0.6–0.3 – insufficient humidification.

Statistical analysis. For the statistical evaluation of the results, the basic and integration indicators of biological statistics were used in accordance with Wong (2018) in the statistical software Statistica 10 (StatSoft – Dell Software Company, USA, 2013), Past 4.0 software (Øyvind Hammer, Norway, 2014) and the R software package (version R statistic 3.1.2, 2014). The following indicators were used for statistical calculation of the obtained averages: arithmetic mean (± standard deviation) and coefficient of variation. To assess the closeness of the relationship between the indicators, Spearman's correlation analysis was applied and, based on the obtained pairwise correlation coefficients, determination coefficients were determined in accordance with Formula 5 with the estimation of values for the level of statistical significance P < 0.05–0.001.

$$d_{yx} = r_{ij}^2 \times 100 \quad (5)$$

where r_{ij} is the correlation coefficient between the *i*-th and *j*-th indicator.

The reliability of the difference in indicators within the inter-annual comparison was assessed on the basis of analysis of variance with correction of the results according to the Tukey test (for the level of P < 0.05).

Results

The period of study was distinguished by different hydrothermal conditions of oilseed-radish vegetation period in the experiment for both spring and summer plantings. We arranged three groups according to available moisture during the period of leaf-mass formation in spring (Table 1), particularly years with intensive moisture supply against the background of moderate average daily temperatures, years with moderate moisture supply against the background of high temperature conditions, and years with moisture deficit against the background of intensive increase in average daily temperatures. The first group included 2014, 2019, 2020, and 2021. The second group included 2016, 2022 and 2023. The third group included 2015, 2017, and 2018. The unevenness of precipitation throughout the assessment period, expressed in the coefficient of variation in precipitation amount, was 37.3%, with 6.4% variability in average daily temperature. At the same time, the inter-monthly variability of the applied parametric coefficients of moisture was higher than 1 for the coefficient of variation, which confirms the unevenness of moisture by month. A similar nature of formation was observed for weather conditions during the summer sowing of oilseed radish (Table 2). At the same time, the interannual variability of hydrothermal conditions of the vegetation period of oilseed radish during the summer sowing period was significantly lower: the interannual coefficient of variation was 33.6% in the amount of precipitation and 5.8% in the average aboveground temperature, with 0.47-0.89 range in intermonthly moisture coefficient variability. For the summer sowing period, a similar grouping was applied to years with intensive moisture against the background of elevated average daily temperatures, years with moderate moisture against the background of elevated temperatures, and years with a moisture deficit against the background of intensive increase in average daily temperatures. The first group included 2022, 2017, and 2018. The second group included 2014, 2016, 2020, and 2023. The third group included 2015, 2019, and 2021. During the growing season, compared to the spring sowing dates, for the summer sowing dates, we observed an average 0.9% increase in precipitations, 12.5% increase in average daily temperature, 26.9% decrease in the hydrothermal coefficient, 45.6% decrease in the De Marton aridity coefficient, and 36.1% decrease in the Vysotsky-Ivanov moisture coefficient. That is, over the period from 2023 to 2024, there was an increase in the overall aridity of the vegetation period for oilseed radish plants sown during the summer season.

This is clearly evidenced by the graphs of precipitation and average daily temperature dynamics during the research period (Fig. 2). According to the coefficient of variation in the consolidated system for both sowing dates, the variability for the precipitation amount was 48.4%, the average daily temperature 27.5%, the De Marton aridity index 58.9%, and the Vysotsky-Ivanov moisture coefficient 68.1%.

The increase in aridification was mainly caused by a significant rise in average daily temperatures, which overwhelmed the relatively small difference in precipitation. This was particularly pronounced in mid-July to August in some years, especially when temperatures exceeded 25°C. Taking into account these features, the advantages of spring sowing over summer sowing in green manure technologies for oilseed radish have been found from the agrotechnological point of view, as it minimised weather-related issues and maximised plant biomass production.

Given the intensity of the temperature regime, the role of moisture supply will increase, which will limit the possibility of effective use of oilseed radish as green manure in areas with highly unstable moisture. This primarily concerns soil and climatic zones with a hydrothermal coefficient below 0.5–0.7.

Table 1
Indicators of hydrothermal support of the vegetation period of oilseed radish variety Zhuravka in spring sowing, 2014–2023

Year	For the period April–June		Months of the growing season								
			April			May			June		
	amount of precipitation, mm	average daily air temperature, °C	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)
2014	339.6	13.84	0.72	45.7	1.18	3.93	88.9	2.11	1.55	34.8	0.83
2015	142.3	14.36	0.64	37.3	0.78	0.92	20.6	0.41	0.72	16.9	0.27
2016	193.4	15.06	0.30	21.6	0.44	0.49	40.4	0.99	1.27	29.9	0.75
2017	125.1	14.07	3.92	39.2	0.75	0.78	16.8	0.34	0.50	11.9	0.22
2018	170.8	16.38	0.29	10.8	0.19	0.31	7.2	0.12	4.40	103.7	2.31
2019	398.5	15.39	0.57	33.5	0.72	4.9	111.0	3.29	1.68	41.4	0.96
2020	343.8	13.67	0.09	36.4	0.50	5.33	106.4	3.18	1.55	37.3	0.89
2021	282.8	13.26	0.23	38.8	0.96	3.13	66.7	1.64	1.68	39.8	1.00
2022	242.1	14.30	0.56	57.4	2.33	1.43	31.3	0.79	1.50	36.1	0.85
2023	239.8	14.18	1.54	91.5	3.33	0.08	1.9	0.04	1.64	38.9	0.87

Table 2
Indicators of hydrothermal support of the vegetation period of oilseed radish variety Zhuravka during the summer sowing period, 2014–2023

Year	For the period July–October		Months of the growing season											
			July			August			September			October		
	amount of precipitation, mm	average daily air temperature, °C	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)	hydrothermal coefficient (HTC)	aridity index De Marton (I_{DM})	moisture coefficient Vysotsky-Ivanov (K_h)
2014	250.8	15.4	1.31	32.7	0.77	1.05	26.0	0.51	1.25	25.7	0.56	1.77	35.8	0.93
2015	160.8	16.6	0.32	8.1	0.14	0.12	3.1	0.05	1.18	26.8	0.63	3.04	49.4	1.25
2016	212.7	15.6	1.06	26.5	0.55	0.90	22.0	0.43	0.01	2.5	0.05	0.55	63.4	2.45
2017	318.0	16.0	1.52	37.5	0.72	0.82	20.7	0.38	3.10	61.2	1.57	1.07	30.0	1.26
2018	273.4	16.4	2.16	53.4	1.63	0.59	14.6	0.30	1.38	27.2	0.71	0.87	27.6	0.95
2019	161.7	16.0	1.01	24.4	0.56	0.24	5.9	0.11	0.99	20.7	0.42	0.38	27.4	0.93
2020	245.4	17.6	0.59	14.7	0.31	0.53	13.2	0.22	0.86	27.5	0.54	2.54	60.6	3.05
2021	176.9	15.4	0.78	20.1	0.45	1.46	35.7	0.91	0.71	17.6	0.51	0.00	1.7	0.04
2022	436.6	16.0	0.90	22.4	0.58	1.71	43.1	1.06	4.96	98.1	2.60	3.17	51.4	1.50
2023	247.1	18.3	1.41	35.8	0.82	0.65	16.9	0.36	1.01	23.4	0.63	1.03	29.9	0.93

Based on the presented annual dynamics of temperature and moisture regime (Fig. 2), we identified the critical months for the growth of oilseed radish. For the spring sowing period, it was June. For the summer sowing period, it was the period from late July to mid-August. At the same time, we noted that oilseed radish plants had an increase in adaptive resistance to elevated average daily temperatures with sufficient and even excessive moisture, while maintaining high growth rates both in morphometric and weight terms. The long-term limit of moisture supply both against the background of low average daily temperatures and against the background of their intensively increasing values caused a decrease in the growth rates of oilseed radish, and intensive declines in plant habitus and leafiness, specifically the share of the assimilative apparatus in the total plant biomass. Based on this analysis, it was found that for oilseed radish, the optimal hydrothermal regimes of the growing season include a hydrothermal coefficient of 0.8–1.0 for average daily temperatures with a slow increase at 14–18 °C and 1.0–1.2 for average daily temperatures with a rapid increase at 18–25 °C. Such regimes changed the regulation of optimal conditions for the growing season by shifting the sowing dates of oilseed radish from spring to summer, which should be taken into account in the technologies of oilseed radish use as green manure in areas with unstable moisture.

As a result, taking into account the optimal parameters for growth processes, the years of research were placed in the following order of increasing favourability for growth processes in spring plantings: 2017–2015–2016–2018–2021–2022–2023–2014–2020–2019. For the summer sowing period, the similar series was as follows: 2015–2021–2019–2016–2023–2014–2020–2018–2017–2022.

In terms of dry matter, the average level of aboveground biomass formed during the evaluation period was 3.10 t/ha (23.6% interannual variation) for the spring sowing period and 2.82 t/ha (27.5%) for the summer sowing period (Fig. 3). According to the results of the statistical evaluation, four significantly different groups were formed for the spring sowing period, with dry matter yields ranging 2.0 t/ha in the first group to 4.1 t/ha in the fourth group. For summer sowing, with a general decrease in the average productivity of plant biomass yield by 9.0%, three significantly significant groups were identified: 1.5 t/ha in the first and 3.4 t/ha in the third. This grouping is consistent with the analysis of the influence of hydrothermal on productivity of oilseed radish during the growing season. Taking into account the small number of significantly different groups by the formed leaf and stem mass against the background of more different hydrothermal regimes, a significant adaptation resource of oilseed radish was determined. This confirms the possibility of its effective use along with traditional cruciferous plants.

The ground-cover index is an important indicator of the growth rate of biomass and the rate of soil-surface coverage in the field of view. Based on the results of accounting dynamic growth of the leaf-stem mass, we identified the interval of intensive growth of this indicator in the interphase phenological period from the beginning of flowering (BBCH 50–52) to its completion (BBCH 68–69) (Fig. 4).

In the summer sowing period, both a more intensive growth and a more intensive decline in the dynamics of the ground-cover index were determined. Thus, on the 70th day after sowing, the indicator was 73.8% (with an interannual variation of 22.4%) for spring plantings and 50.7% (29.9%) for summer plantings. The maximum value of the indicator in the summer sowing period was achieved much sooner than in the spring sowing variant, but the dynamics of its decline in the post-peak period was also significantly higher. Based on the data for the summer sowing period, the optimal variant of using oilseed radish as a cover crop was in the period 45–55 days after sowing, and for the spring sowing variant, it is possible to prolong it up to 70 days.

The interval between the maximum incremental dynamics of the index from the beginning of flowering (BBCH 50–52) to its completion (BBCH 68–69) was also identified. At the same time, we also saw the reverse process of intensive decline due to death of leaves on days 55–75 after sowing. As a result, the maximum level of ground cover was achieved in the average long-term record of 60 days after sowing in spring (with fluctuations in the range of 71.2–93.7 with the average of 83.7%) and 50 days after sowing in summer (60.3–90.4% and 79.9%, respectively).

The nature of the dynamic curve of ground-cover formation with a reliable level of approximation ($P < 0.001$) for both spring and summer plantings was described by a polynomial (third degree) equation. This allowed us to confirm the determined nature of increase in the index to its peak value 60 days after sowing in spring and 54 days after sowing in summer. The subsequent decrease in the index was due to the already mentioned decline in leafiness of the plants.

The assessment of the biochemical composition of the generated biomass is important from the point of view of the value of the respective crop as green manure. Tables 3-4 present the results of such an assessment of aboveground biomass of the studied plantings conducted in the phonological optimum period.

According to estimates, the leaf and stem mass of oilseed radish can be attributed to the stable total organic-carbon content within a rather narrow range of 38-42% of dry mass, which – against the background of high total nitrogen content of 2.5-3.1% on average – forms a mass with low C/N ratio of 11 to 19 units, depending on sowing date and year of observation. At the same time, the protein content of the mass increased significantly in all years of evaluation when the sowing dates were shifted from spring to intermediate summer with 1.23 average growth rate of the summer/spring ratio of.

We attribute this ratio to increase in the overall stress during the growing season, in particular, increased average daily temperature, accompanied by increase in the overall aridity of growth conditions (Table 1), which ultimately ensured the formation of a stressful protein complex, and a morphological disparity in the formation of stem, leaf apparatus, and generative parts of plants with a shift to more protein-containing leaves and generative parts. It should be noted that the significant differences in climatic parameters of the growing season at different sowing dates of oilseed radish also affected other indicators of the biochemical composition of the leaf and stem mass of oilseed radish. This was also confirmed by comparing the main biochemical components of the spring sowing period with similar long-term averages of the summer sowing period. The coefficients of this ratio in the interval of years of research were obtained for fibre content 0.79–0.89, total nitrogen 0.74–0.85, organic carbon 0.91–0.99, phosphorus 0.89–0.98, potassium 0.85–0.94, and glucosinolate 0.82–0.88.

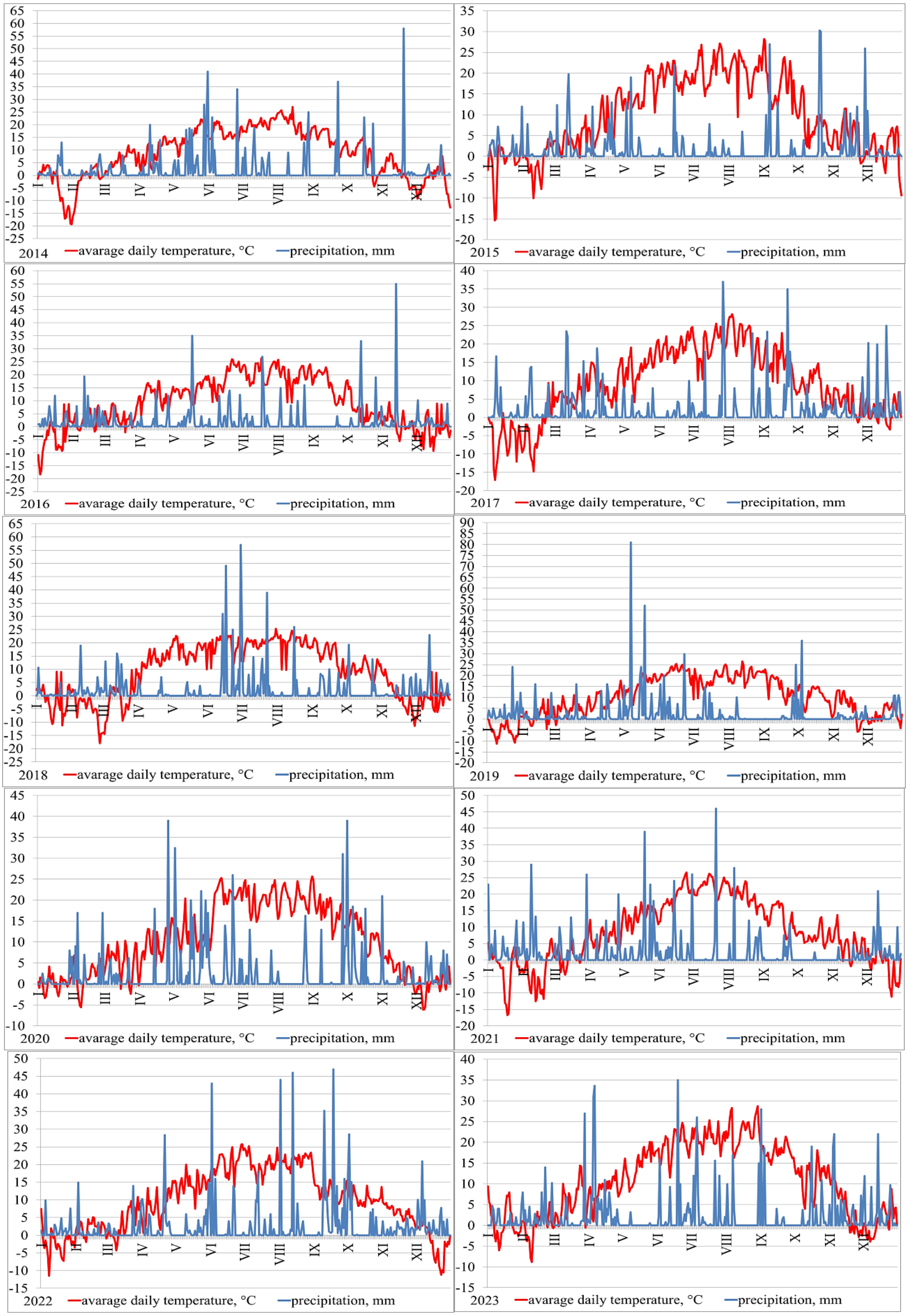

Fig. 2. Dynamics of annual hydrothermal conditions over the study period, 2014–2023

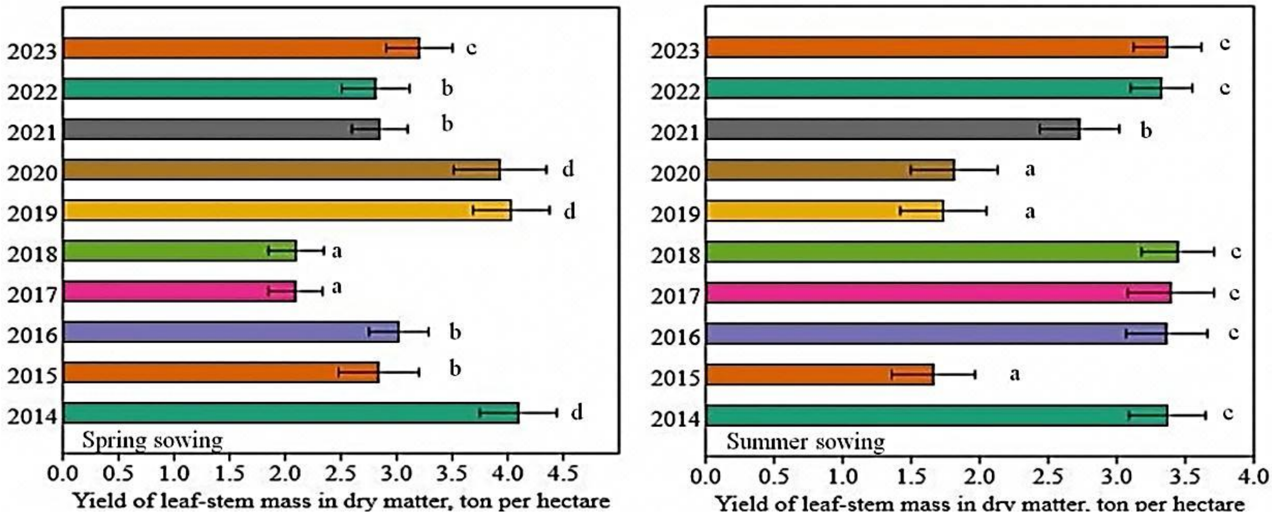

Fig. 3. Formed above-ground leaf mass of oilseed radish plants at different sowing dates in terms of dry matter (t/ha, x ± SD), 2014–2023: different letters indicate values that differed significantly from each other at the level of P < 0.05

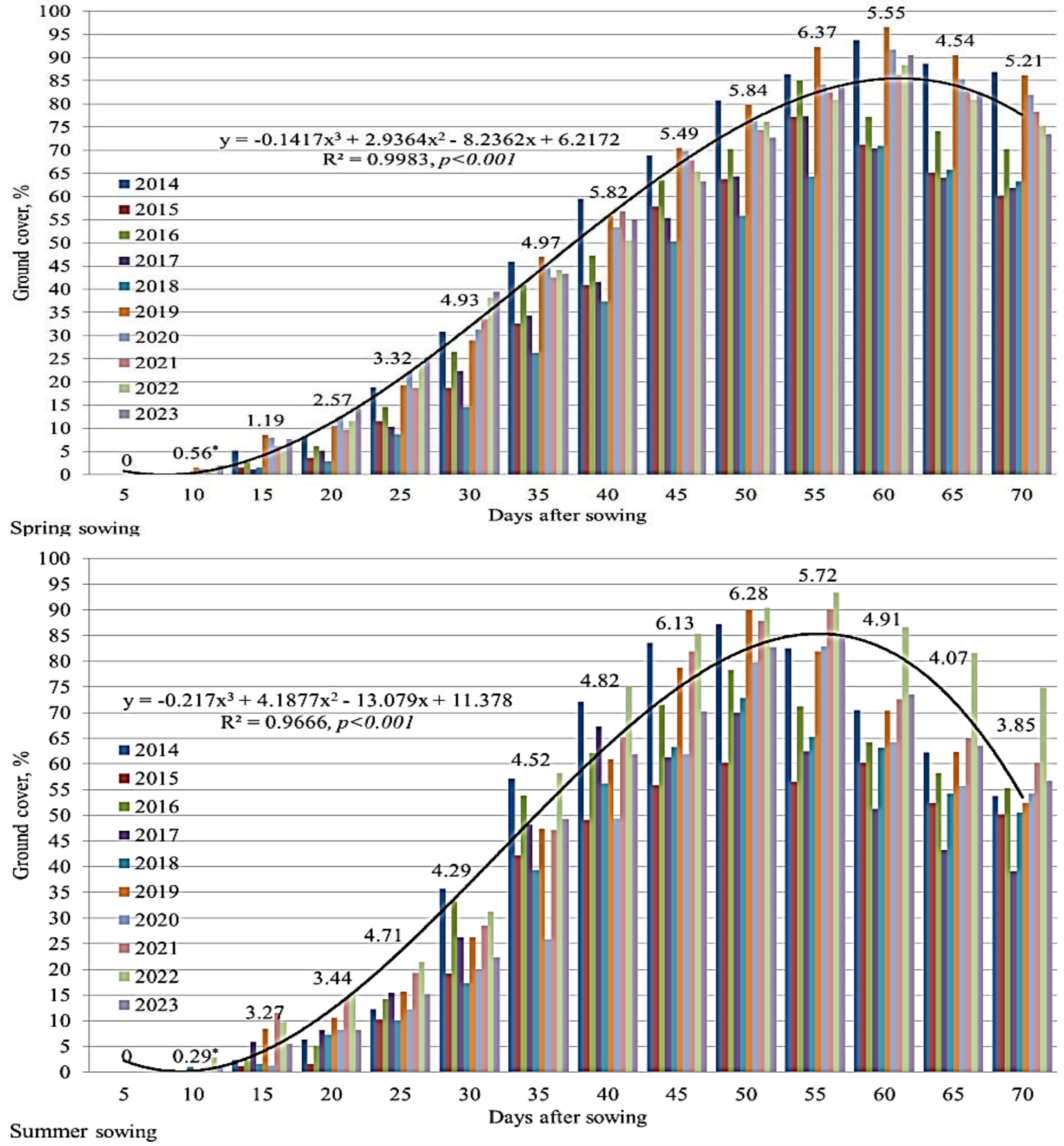

Fig. 4. Dynamics of ground cover (%) for oilseed radish at different sowing dates, 2014–2023: * – R_{min} value for $p_{adj} < 0.05$ according to Tukey's criterion for the group of comparison of accounting years in the group of accounting periods of days after sowing

As a result, the leaf and stem mass of oilseed radish of different sowing dates had different criterion scores for the green manure use of the formed biomass. It should also be noted that the biomass of oilseed radish at the interval value of the C/N ratio in the context of research years (taking into account the standard deviation for the full cycle of losses) in the range of 8.73–20.11 with interannual variation of 12.3% for spring sowing and 15. 4% for the summer sowing period fully meets the criteria of the category "green manure" and is expected to ensure rapid decomposition of fresh biomass in soil, especially under conditions of sufficient moisture supply against the background of high average daily temperatures. In the case of summer sowing, the decomposition rate, despite the 17% lower C/N ratio on average throughout assessment period, will be predictably slower due to significantly lower temperature level during the period of direct use of biomass in the form of green manure.

Regarding the content of glucosinolates, this indicator is important in the criterion system of multifunctional cover crops from the point of view of providing the corresponding crop, first of all, with a broad-spectrum biofumigation effect by incorporating the formed plant biomass into soil, which reduces the germination of weed seeds, soil fungicidal effect against a number of harmful pathogens due to the soil transformation of glucosinolates into isothiocyanates. At the same time, the average long-term content of glucosinolates in the aboveground biomass of oilseed radish was 13.57 μmol/g of absolutely dry matter (interannual variation of 8.3%) in spring plantings and 19.70 μmol/g of absolutely dry matter (10.6%) in summer plantings, which confirms the already mentioned increase in their concentration with increase in the overall stress of the growing season, taking into account the level of average daily temperatures.

Table 3
Main indicators of quality of formed aboveground biomass of oilseed radish at different sowing dates, 2014–2023

Year	Total organic carbon content, % ofa dry matter	Total nitrogen content, % of dry matter	The ratio of total organic carbon to total nitrogen content (C/N)	Nitrogen uptake, g m^{-2}	Quality of plant mass, % of dry matter	Glucose nolate content, μmol/g dry substance	Content of fibre, % of dry matter
Spring sowing season							
2014	38.25 ± 0.57^{b}	2.81 ± 0.44^{d}	13.61 ± 1.18^{b}	11.46 ± 1.53^{d}	81.36 ± 0.82^{a}	12.08 ± 0.45^{b}	19.22 ± 0.64^{a}
2015	40.22 ± 0.81^{d}	2.41 ± 0.31^{b}	16.69 ± 1.60^{d}	6.83 ± 0.81^{b}	86.35 ± 0.84^{c}	13.52 ± 0.43^{e}	23.07 ± 0.65^{e}
2016	39.14 ± 0.48^{c}	2.29 ± 0.21^{a}	17.09 ± 1.67^{e}	6.93 ± 0.84^{b}	84.32 ± 0.98^{b}	14.51 ± 0.37^{g}	21.75 ± 0.42^{c}
2017	41.12 ± 0.65^{e}	2.55 ± 0.30^{c}	16.13 ± 1.83^{d}	5.33 ± 0.60^{a}	86.43 ± 0.65^{c}	16.08 ± 0.87^{i}	23.24 ± 0.30^{e}
2018	39.77 ± 0.78^{c}	2.42 ± 0.09^{b}	16.43 ± 0.71^{d}	5.11 ± 0.90^{a}	87.10 ± 1.15^{d}	15.56 ± 0.57^{h}	21.52 ± 1.00^{b}
2019	37.14 ± 1.14^{a}	3.07 ± 0.13^{e}	12.10 ± 0.86^{a}	12.38 ± 1.09^{e}	84.59 ± 0.88^{b}	11.89 ± 0.44^{a}	19.17 ± 0.87^{a}
2020	40.09 ± 0.43^{d}	2.27 ± 0.20^{a}	17.66 ± 1.37^{e}	8.92 ± 0.83^{c}	86.21 ± 1.08^{c}	12.44 ± 0.60^{c}	20.97 ± 0.83^{b}
2021	37.95 ± 0.73^{a}	2.04 ± 0.13^{a}	18.60 ± 1.44^{f}	5.80 ±0.45^{a}	84.74 ± 1.33^{b}	12.77 ± 0.40^{d}	21.83 ± 0.43^{c}
2022	38.44 ± 0.46^{b}	2.33 ± 0.20^{b}	16.50 ± 1.48^{d}	6.56 ± 0.71^{b}	84.52 ± 1.07^{b}	13.84 ± 0.52^{f}	22.19 ± 0.58^{d}
2023	38.89 ± 0.42^{b}	2.72 ± 0.16^{d}	14.30 ± 0.96^{c}	8.71 ± 0.59^{c}	84.26 ± 1.39^{b}	12.97 ± 0.59^{d}	22.29 ± 0.87^{d}
Summer sowing season							
2014	41.03 ± 1.34^{c}	2.79 ± 0.21^{b}	14.71 ± 1.18^{e}	9.39 ± 1.12^{d}	81.46 ± 0.88^{b}	18.55 ± 1.04^{c}	23.32 ± 0.82^{b}
2015	39.82 ± 1.31^{b}	2.38 ± 0.26^{a}	16.73 ± 1.60^{g}	3.95 ± 0.46^{a}	80.44 ± 0.72^{a}	21.58 ± 1.56^{f}	26.72 ± 0.70^{f}
2016	40.59 ± 1.78^{c}	2.94 ± 0.34^{b}	13.81 ± 2.18^{d}	9.87 ± 1.50^{d}	81.00 ± 1.33^{a}	18.19 ± 1.09^{b}	23.89 ± 0.61^{c}
2017	38.51 ± 0.79^{a}	3.18 ± 0.32^{c}	12.11 ± 1.35^{c}	10.80 ± 1.26^{e}	81.53 ± 1.84^{b}	17.92 ± 0.60^{b}	22.97 ± 0.75^{a}
2018	38.09 ± 1.71^{a}	3.32 ± 0.39^{c}	11.47 ± 1.41^{b}	11.45 ± 1.42^{e}	81.46 ± 0.78^{b}	21.02 ± 0.53^{e}	23.69 ± 0.99^{b}
2019	40.87 ± 0.82^{c}	2.58 ± 0.26^{a}	15.84 ± 1.73^{f}	4.48 ± 0.51^{a}	81.04 ± 0.78^{a}	21.19 ± 0.56^{e}	25.33 ± 1.03^{e}
2020	38.44 ± 0.85^{a}	3.27 ±0.22^{c}	11.76 ± 1.03^{c}	5.95 ± 0.68^{b}	80.69 ± 0.68^{a}	19.75 ± 0.52^{d}	24.17 ± 0.85^{c}
2021	41.29 ± 0.76^{d}	3.09 ± 0.24^{c}	13.36 ± 1.06^{d}	8.45 ± 1.07^{c}	80.43 ± 0.52^{a}	21.53 ± 0.70^{f}	24.85 ± 0.64^{d}
2022	38.98 ± 1.73^{a}	3.67 ± 0.52^{d}	10.62 ± 2.11^{a}	12.26 ± 1.18^{f}	81.08 ± 0.71^{a}	17.17 ± 0.63^{a}	22.51 ± 0.79^{a}
2023	39.15 ± 0.89^{b}	3.43 ± 0.50^{d}	11.41 ±1.51^{b}	11.55 ± 1.74^{e}	81.16 ± 0.98^{a}	20.09 ± 0.47^{d}	23.92 ± 0.64^{c}

Note: different letters indicate values that differed significantly from each other in the column direction for each indicator in the table based on the results of the comparison using the Tukey's test with the Bonferroni correction.

The obtained indicators of the quality of the formed aboveground biomass and its value above 80% gave grounds to attribute the vegetative mass of oilseed radish formed both in spring and summer sowing to the suitable for mulching by spreading of chopped mass on the soil surface in technological variants of bioconservation agriculture, producing a biofumigation effect, as revealed by content of glucosinolates.

The study of the indicators of accumulation of basic nutrients in the formed biomass of oilseed radish is comparable to their concentration noted in Table 4. The average long-term ratio of N:P:K content and accumulation in the aboveground biomass was determined in the following expression (with indication of the range of values): 1.00 (0.65–1.59):0.24 (0.18–0.40):1.39 (1.04–2.05) for spring sowing and 1.00 (0.51–1.39):0.20 (0.11–0.25):1.21 (0.70–1.70) for summer sowing. Based on the determined ratios, intensive growth processes for the formation of oilseed-radish leaf mass is expected to be high with sufficient supply of soil with available forms of nitrogen and potassium. With regard to phosphorus, at low levels of accumulation of the element, the period of its critical need shifted to the early stages of growing season. The determined nature of accumulation also showed a high positive reaction of oilseed radish to additional mineral nutrition, especially during the period of active growth of vegetative mass, which according to our studies corresponded to 30–35 days after sowing in spring and 25 days after sowing in summer (Fig. 4). Thus, the observed high levels of productivity of oilseed radish at lower levels of consumption of the main elements allow us to recommend it as green-manure intermediate crops in the links of crop rotations. This was confirmed by the results of equivalent transformation of the formed aboveground mass of oilseed radish in terms of content of organic and dry matter in cattle manure. Such a transfer, which provided an average long-term indicator in the equivalent amount of about 20 t/ha, proved the effectiveness of using oilseed radish at both sowing dates in the system of bioorganic fertilisation technologies and rehabilitation of degraded soils by directly applying green manure.

The results of the correlation analysis confirmed the conclusions about the determining role of hydrothermal conditions of vegetation period of oilseed radish in the formation of both the levels of its bioproductivity and the biochemical composition of the leaf mass (Table 5). At the level of $P < 0.05$ statistical significance, we saw a close direct dependence of the yield of leaf mass in dry matter (t/ha) on the amount of precipitation (with a coefficient of determination of 51.7%), hydrothermal coefficient (19.4%), De Marton aridity index (43.2%), and Vysotsky-Ivanov moisture coefficient (37.5%). At the same time, the long-term relationship with the average daily temperature was negative, with the level of determination of 8.5%. This confirmed the previously mentioned role of hydrothermal regime in the formation of productivity of oilseed radish. From the point of view of protein content in the formed mass, a positive direction of connection was found both for the amount of precipitation (coefficient of determination 20.0%) and for the average daily temperature (39.8%).

As a result, this formed a general negative relationship between the main indices of hydrothermal regime and the indicator of carbon-to-nitrogen ratio in plant mass with a significant dependence only on amount of precipitation (the coefficient of determination of 23.4%) and the level of average daily temperature (36.2%). Regarding the indicator of plant-mass quality, a direct forming effect was found for all relational indices of moisture (at the coefficient of determination in the range of 10.5–23.8%) and an inverse forming effect for the indicator of average daily temperature (29.7%). Regarding the glucosinolate content, high inverse relationship was determined both with the amount of precipitation (42.4%) and with all the coefficients of the hydrothermal regime of the growing season of oilseed radish (the coefficient of determination in the interval of 31.2–71.2%). At the same time, the average daily temperature was directly related to the content of glucosinolates (the coefficient of determination of 34.8%). A similar pattern of dependence was found between the fibre content and synonymous parallels by assessing the dependence of organic carbon content as a skeletal element of plant cellular and mechanical structures. The accumulation of phosphorus and potassium in the plant biomass was found to be inversely related to precipitation and temperature, as reflected by the 15.8-48.6% coefficient of determination. This inverse relationship was more pronounced when oilseed radish was sown for green manure purposes in summer rather than spring, as indicated by the increased total ash content of leaf biomass. Furthermore, the negative dependence of both elements on leaf-mass yield was confirmed, with coefficients of determination of 23.7% for phosphorus and 29.5% for potassium. At the same time, a close direct relationship between the content of phosphorus and potassium was determined with 85.0% determination level. Therefore, given the high nitrogen content, we may consider the leaf mass of oilseed radish valuable in terms of elemental composition and the potential for equivalent replacement of classic organic fertilisers with green manure.

Table 4
Content and accumulation of main nutrients in aboveground biomass of oilseed radish at different sowing dates, 2014–2023

Year	Phosphorus content, % of dry matter	Potassium content, % of dry matter	Accumulation in aboveground plant biomass, kg/ha			Accumulation of glucosinolates, Mol/ha	Equivalent of biomass produced to cattle manure
			nitrogen	phosphorus	potassium		
Spring sowing season							
2014	0.54 ± 0.06^{a}	2.71 ± 0.11^{b}	114.61 ± 15.27^{d}	22.14 ± 2.70^{c}	111.15 ± 9.64^{d}	49.5 ± 3.8^{d}	23.0 ± 2.3^{d}
2015	0.62 ± 0.05^{b}	3.96 ± 0.09^{e}	68.34 ± 8.05^{b}	17.62 ± 1.71^{b}	112.56 ± 9.22^{d}	38.4 ± 2.9^{b}	18.9 ± 1.9^{b}
2016	0.77 ± 0.17^{c}	4.74 ± 0.24^{f}	69.32 ± 8.38^{b}	23.19 ± 4.95^{c}	143.27 ± 10.32^{f}	43.8 ± 3.1^{c}	22.8 ± 2.4^{d}
2017	0.85 ± 0.08^{d}	5.72 ± 0.38^{g}	53.28 ± 6.04^{a}	17.76 ± 1.65^{b}	119.68 ± 10.73^{e}	33.6 ± 2.7^{a}	18.9 ± 2.0^{b}
2018	0.69 ± 0.07^{b}	3.74 ± 0.20^{d}	51.08 ± 9.02^{a}	14.58 ± 3.00^{a}	78.54 ± 10.69^{a}	32.7 ± 2.6^{a}	13.7 ± 1.8^{a}
2019	0.52 ± 0.05^{a}	2.25 ± 0.11^{a}	123.81 ± 10.91^{e}	21.05 ±3.56^{c}	90.61 ± 5.69^{b}	47.9 ± 3.5^{d}	21.7 ± 2.3^{c}
2020	0.63 ± 0.08^{b}	4.08 ± 0.16^{e}	89.21 ± 8.25^{c}	24.79 ± 3.46^{d}	160.26 ± 4.34^{g}	48.9 ± 2.4^{d}	26.1 ± 2.9^{e}
2021	0.48 ± 0.09^{a}	2.87 ± 0.37^{b}	58.03 ± 4.48^{a}	13.88 ± 4.07^{a}	81.32 ± 8.28^{a}	36.4 ± 2.5^{b}	13.9 ± 1.6^{a}
2022	0.51 ± 0.03^{a}	3.03 ± 0.10^{c}	65.62 ± 7.09^{b}	14.35 ± 1.12^{a}	85.26 ± 4.59^{a}	38.9 ± 2.6^{b}	15.2 ± 1.8^{a}
2023	0.61 ± 0.06^{b}	3.19 ± 0.31^{c}	87.14 ± 5.89^{c}	19.50 ±1.36^{b}	101.96 ± 6.37^{c}	41.5 ± 2.9^{c}	19.6 ± 2.2^{b}
Summer sowing season							
2014	0.57 ± 0.09^{a}	3.52 ± 0.36^{b}	93.94 ± 11.22^{d}	19.50 ±5.27^{c}	118.21 ± 12.98^{d}	62.5 ± 5.3^{b}	22.0 ± 1.7^{d}
2015	0.71 ± 0.10^{b}	4.71 ± 0.20^{e}	39.51 ± 4.58^{a}	11.88 ± 2.50^{a}	78.38 ± 7.71^{b}	35.8 ± 3.2^{a}	12.6 ± 1.2^{a}
2016	0.67 ± 0.07^{b}	3.89 ± 0.14^{c}	98.71 ± 14.96^{d}	22.32 ± 0.16^{e}	130.87 ± 15.65^{e}	61.1 ± 4.8^{b}	24.3 ± 1.9^{e}
2017	0.59 ± 0.09^{a}	3.33 ± 0.46^{b}	108.00 ± 12.61^{e}	20.04 ± 3.26^{d}	113.53 ± 20.25^{d}	60.8 ± 4.5^{b}	23.1 ± 1.8^{d}
2018	0.65 ± 0.07^{b}	4.35 ± 0.16^{d}	114.45 ± 14.26^{e}	22.42 ± 2.64^{e}	150.09 ± 11.32^{f}	72.5 ± 6.2^{d}	28.1 ± 2.2^{g}
2019	0.78 ± 0.07^{c}	4.98 ± 0.15^{e}	44.75 ± 5.09^{a}	13.56 ± 1.81^{b}	86.49 ± 7.42^{b}	36.7 ± 3.5^{a}	14.2 ± 1.3^{b}
2020	0.54 ± 0.06^{a}	3.39 ±0.23^{b}	59.46 ± 6.82^{b}	9.77 ± 0.74^{a}	61.51 ± 5.40^{a}	36.0 ± 3.6^{a}	12.5 ± 1.5^{a}
2021	0.64 ± 0.09^{b}	3.57 ± 0.34^{b}	84.48 ± 10.67^{c}	17.56 ±3.53^{c}	97.64 ± 13.52^{c}	58.8 ± 4.7^{b}	19.2 ± 2.2^{c}
2022	0.52 ± 0.03^{a}	3.05 ± 0.20^{a}	122.58 ± 21.80^{f}	17.28 ± 1.17^{c}	101.62 ± 10.79^{c}	57.2 ± 4.4^{b}	23.1 ± 1.9^{d}
2023	0.59 ± 0.08^{a}	3.82 ± 0.40^{c}	115.51 ± 17.38^{e}	19.79 ±1.68^{d}	129.07 ± 18.97^{e}	67.7 ± 5.1^{c}	25.6 ± 2.2^{f}

Note: different letters indicate values which reliably differed one from another in the direction of the column for each indicator of the table according to the results of comparison using the Tukey test with Bonferroni correction.

Table 5
Spearman's rank correlation coefficients of the dependence of the yield of formed biomass and its quality on hydrothermal parameters of vegetation for oilseed radish for the period 2014–2023 (for the combined system of sowing dates-repeated years of cultivation, n = 80)

–	2	3	4	5	6	7	8	9	10	11	12	13	14
1	–0.066	0.771*	0.831*	0.839*	0.719*	–0.632*	0.447*	–0.484*	0.162	–0.651*	–0.587*	–0.697*	–0.694*
2	–	–0.237*	–0.420*	–0.314*	–0.292*	–0.020	0.631*	–0.602*	–0.545*	0.590*	0.512*	0.063	0.117
3	–	–	0.814*	0.684*	0.440*	–0.403*	0.163	–0.174	0.365*	–0.559*	–0.623*	–0.397*	–0.413*
4	–	–	–	0.940*	0.657*	–0.619*	–0.016	–0.052	0.488*	–0.844*	–0.852*	–0.596*	–0.678*
5	–	–	–	–	0.612*	–0.698*	0.108	–0.190	0.324*	–0.787*	–0.736*	–0.669*	–0.731*
6	–	–	–	–	–	–0.388*	0.272*	–0.323*	0.352*	–0.690*	–0.675*	–0.487*	–0.543
7	–	–	–	–	–	–	–0.188	0.305*	–0.222*	0.479*	0.533*	0.627*	0.630
8	–	–	–	–	–	–	–	–0.984*	–0.301*	0.139	0.126	–0.273*	–0.261*
9	–	–	–	–	–	–	–	–	0.221*	–0.071	–0.034	0.324*	0.344*
10	–	–	–	–	–	–	–	–	–	–0.510*	–0.698*	–0.113	–0.230*
11	–	–	–	–	–	–	–	–	–	–	0.834*	0.578*	0.654*
12	–	–	–	–	–	–	–	–	–	–	–	0.408*	0.563*
13	–	–	–	–	–	–	–	–	–	–	–	–	0.922*

Note: *significant correlation coefficients at $P < 0.05$; indicator indices: 1 = amount of precipitation during the growing season (mm); 2 = average daily temperature during the growing season (℃); 3 = hydrothermal coefficient during the growing season (HTC); 4 = De Marton aridity index (IDM); 5 = Vysotsky-Ivanov moisture coefficient (Kh); 6 = leaf mass yield (t/ha in dry matter); 7 = total organic carbon content (% on dry matter); 8 = total nitrogen content (% on dry matter); 9 = ratio of total organic carbon to total nitrogen content (C/N); 10 = plant mass quality (% on dry matter); 11 = glucosinolate content (μmol/g dry matter); 12 = fibre content (% on dry matter); 13 = phosphorus content (% on dry matter); 14 = potassium content (% on dry matter).

Evaluating oilseed radish as a multifunctional cover crop requires attributing component coefficients to the resulting equations, as presented in Table 6, taking into account similar studies on other cruciferous species used as green manure in modern agricultural technologies. In particular, for the indicator 'ground cover', the medium level of significance (attribute 3) was chosen, taking into account the green-manure production under both the high and low cover options.

For the indicator of aboveground biomass formed, attribute 5 was chosen with the desired growth dynamics (important), given the importance of the green manure used, but with a restriction on the choice of attributes 6–9 (extremely important), since the efficiency of decomposition of green manure and the possibility of such a process is determined by both the level of soil fertility and the amount of biomass incorporated into the soil against the background of the hydrothermal regime. For the C/N ratio, the desired decline dynamics with an average attribute of 2 was chosen, taking into account the observed correlation of this indicator with the hydrothermal regime during the research period and the requirements for the selection of green manure, where a lower value of this ratio with a high level of predicted probability ensures rapid decomposition of plant mass in the soil, which was especially important for summer green manure of oilseed radish with a short period of active (dose) soil decomposition.

The attribute for the quality of plant mass was selected similarly to the one for the aboveground biomass. The attribute for the glucosinolate content was selected with a tendency of the desired increase in the value of very important (7), considering the requirements for biofumigant properties in cruciferous species used in bioorganic green manure systems. For the fibre content indicator, the desirable trend of formation was chosen in the value of decreasing with the attribute of medium importance (3), taking into account the well-known rates of fibre decomposition in the soil, which are significantly lower for biomass with a high content of lignified mechanical tissues and fibre-containing structures.

The formed array of initial data on the importance of the studied traits in the formation of the direction of use of oilseed radish allowed us to obtain their normalised matrix. As a result, according to the results of multicriteria analysis within different sowing dates, the final sums of normalised and weight-adjusted coefficients were obtained (Table 7).

Thus, optimum for sowing dates of oilseed radish ranged depending on years. The largest number of maximum values of the adjusted coefficients was observed for the conditions of 2019 for the spring sowing period and for the conditions of 2022 for the summer sowing period. Therefore, oilseed radish is an effective candidate for the system of multifunctional use of cover crops according to the criterion of 'green manure crop'.

Discussion

From the point of view of any assessment of the direction of use of a particular plant, it is important to study its adaptability in the context of the region of implementation (Sugumar et al., 2024). From this point of view, oilseed radish, in comparison with traditional cruciferous crops, has demonstrated a number of adaptive mechanisms that qualitatively distinguish it and allow it to be recommended for wider use, in particular as an effective green manure crop. A number of studies (Khan, 2020; Bocianowski & Liersch, 2021; Pullens et al., 2021) have noted that cruciferous plants are sensitive to ashification and more tolerant of temperature conditions. At the same time, spring and winter rape significantly reduces its productivity under the condition of a simultaneous combination of precipitation deficit and increasing average daily temperatures.

Table 6
Adjusted attributive importance of indicators that determine the feasibility of green manure use of oilseed radish for both sowing dates (for conditions of 2014–2023)

Category of use	Ground coverage, %	Formed aboveground plant biomass, kg of dry matter/m^2	Ratio of total organic carbon to total nitrogen (C/N)	Nitrogen uptake, g/m^2	Quality of plant mass, % of dry matter	Glucose nolate content, μmol/g dry substance	Content of fibre, % of dry matter
The value of the attributive coefficient for the indicator on the scale from 1 to 9 points*.	3	5	2	3	5	7	3
Optimal trend formation when comparing valuation options	increase	increase	decrease	decrease	increase	increase	decrease
Aggregate equation of utility of indicators for green manure application of oilseed radish plant biomass	3 (Ground coverage) + 5 (Formed aboveground plant biomass) – 2 C/N – 3 (Nitrogen uptake) + 5 (Quality of plant mass) + 7 (Glucose nolate content) – 3 (Content of fibre)						

Note: attributes selected based on the analysis of publications: Kirkegaard & Sarwar, 1998; Eberlein et al., 1998; Gimsing & Kirkegaard, 2006; Bangarwa et al., 2011; Ramírez-García et al., 2015; Flores-Sánchez et al., 2016; Jabnoun-Khiareddine et al., 2016; Stubbs & Kennedy, 2017; Hu et al., 2018; Heuermann et a., 2019; Li et al., 2019; Liu et al., 2020; 2020; Ait Kaci Ahmed et al., 2022; Lei et al., 2022; Wang et al., 2022; Waisen et al., 2022; Israt & Parimal, 2023; Källén, 2023.

Table 7
Sum of normalised values of weighting coefficients for traits obtained for green manure use of oilseed radish as a multifunctional cover crop, 2014–2023

Year of research	Green manure: spring sowing season	Green manure: summer sowing season	Rating by value
2014	0.88[b]	0.91[c]	1
2015	0.75[f]	0.62[h]	10
2016	0.80[e]	0.89[d]	7
2017	0.80[e]	0.87[e]	9
2018	0.80[e]	0.89[d]	8
2019	0.91[a]	0.76[g]	4
2020	0.85[c]	0.79[f]	6
2021	0.82[d]	0.87[e]	5
2022	0.83[d]	0.99[a]	3
2023	0.85[c]	0.93[b]	2
Average	0.83	0.85	–
Consistency index (CI)	0.34	0.42	–

Note: lowercase index letters indicate statistical differences ($P < 0.05$).

The optimal hydrothermal regime for rapeseed before the flowering phase involves a moderate moisture regime with 250–300 mm precipitation and 0.9–1.2 hydrothermal coefficient of (Puhl et al., 2019; Agahi et al., 2020). It was reported (Kashyap et al., 2023; Pillai & Walia, 2024) that mustard varieties exhibit a higher adaptability to varying climatic conditions. Specifically, they can thrive in areas with moderate to high aridity (200–250 mm precipitation before flowering) and 0.8–1.0 hydrothermal coefficien. According to Quezada-Martinez et al. (2021) and Verma et al. (2023), wild forms of cruciferous plants are much more tolerant to high temperatures and moisture deficit and can effectively grow and develop up to the flowering phase already at 80–120 mm of precipitation and a hydrothermal coefficient of 0.5–0.8.

According to our estimates, oilseed radish has a wide range of adaptations. This qualitatively distinguishes it from other cruciferous plants and confirms the presence of pre-adaptation systems inherent in wild forms of cruciferous plant species. This positively correlates with the possibility of its long-term use under conditions of unstable moisture in green manure technologies.

In continuation of the identified adaptive potential of oilseed radish plants, it was useful to assess the achieved level of bioproductivity of oilseed radish compared to other cruciferous species used as intermediate crops in the system of existing green-manure agrotechnological solutions.

Quintarelli et al. (2022) classified oilseed radish as a high-yielding cover crop for conditions of sufficient moisture. A number of researchers (Ramirez-Garcia et al., 2012; Hansen et al., 2021; Nilsson et al., 2022) noted its sufficient level of adaptability for cultivation in various intermediate technological schemes with different sowing dates, including sowing before 15 August and an average bioproductivity level above 15 t/ha.

At the same time, under conditions of unstable moisture, it was found (Ugrenović et al., 2019; Safaei et al., 2022; Țîței, 2022) that the yield of aboveground biomass of such crops as white mustard, spring rape, forage radish (var. Tillage radish (Daikon radish)) is in the range of 12–27 t/ha, and such of winter rape (taking into account biomass in the early summer period) is in the range of 25–60 t/ha. The high sensitivity of these cruciferous species to moisture regime was noted, especially at summer sowing dates, when this deficit in areas of unstable moisture is most pronounced. Based on these results, oilseed radish should be classified as a highly productive crop with developed adaptive mechanisms of plant biomass formation. On the other hand, the high level of variation of the index indicated a significant role of hydrothermal conditions of the vegetation period of oilseed radish in the implementation of its bioproductivity. If we take into account the declared maximum productive potential of the varieties of this crop grown in Ukraine (Tsytsiura, 2023) at the applied sowing rate of up to 50 t/ha in spring and up to 35 t/ha in summer sowing, the level of realisation of this potential in our studies varied in different years from 27.8% to 70.0% in spring plantings and from 27.1% to 70.8% in summer plantings. Such results suggest that oilseed radish can be effectively used in various cropping systems, particularly in intermediate sowing scenarios, as an intermediary crop between main crops in rotations that combine spring and winter crops. This meets the essential criteria for multifunctional cover crops, making it a suitable option for various farming systems. As for the assessment of the ground (vegetation) cover index, an optimal vegetation cover index was recommended to be at least 70% during the potentially suitable growth period of the intermediate cover crop, considering the phenological milestone date as a reference point for optimal use (Ramírez-García et al., 2015). Based on this, oilseed radish is characterised by high rates of vegetative-mass growth over a 20–30 day period and exceeds a number of traditional cruciferous crops, including white mustard and spring rape (Bhogal et al., 2019).

To evaluate and determine the average biochemical portfolio of oilseed radish, gradations of assessments of a number of cruciferous crops were applied in the studies by Bell et al. (2020), Keim et al. (2020), Kılıç et al. (2021), Omokanye et al. (2021), Ţiţei (2022), Mbambalala et al. (2023), Sánchez et al. (2023). Based on these comparisons with other cruciferous species that are widely used in the system of long-term green manure, oilseed radish was found to have the same or 1.7–2.2% lower ash content, 0.7–2.5% lower lignin, 1.9–6.1% lower crude fibre, 1.8–3.7% lower potassium content, and 0.12–0.22% lower phosphorus content on a dry matter basis. The presented comparison confirms the value of oilseed-radish leaf mass as a potential candidate for use in the green manure system, given the possible effective cycling of the main macronutrients into the soil with oilseed radish green manure.

The optimal C/N ratio for green manure is a balance between decomposition and humus accumulationand immobilisation of mineral nutrients, ranging 13 to 25 depending on weather conditions, soil type, and use of the respective cover crop (Wadman & de Haan, 1997). This range is supported by studies on cattle manure, which reported a correlation with a C/N ratio of 16.6-25.0 (Pan et al., 2021). The biomass formed during spring sowing showed a higher degree of compliance with these intervals for green manure use. According to the recommendations of Hansen et al. (2021), its use can be optimised by using oilseed radish in mixed crops with cereals and legumes, as well as by using additional plant materials for combined green manure (e.g. straw).

It is worth noting the high biofumigation potential of oilseed-radish leaf mass, which is desirable in the variants of application for green manure of cruciferous plant species (Bhogal et al., 2019; Redha et al., 2023). The biofumigation potential of oilseed radish was also confirmed by the value of glucosinolate productivity for both sowing dates (Table 4). The values obtained were in the range of 32.7–49.5 mol/ha (with an interannual variation of 15.1%) for spring plantings and 36.0–72.5 mol/ha (24.9%) for summer plantings, taking into account the study by Duff et al. (2020), who noted 30–105 mol/ha level of this indicator for achieving multiple goals of soil biofumigation through green manure in the case of spring and summer sowing, depending on the type of cruciferous plants. At the same time, the range of 60–105 mol/ha was achieved by using different types of mustard (*Sinapis alba* (L.), *Brassica carinata* (L.), *B. juncea* (L.), *B. napus* (L.), *B. nigra* (L.)) in pure sowings or in various mixtures with radish (such species trademarks as 'Tillage Radish', 'Terranova Radish', 'Black Jack Radish'). At the achieved level of glucosinolate accumulation in the plant mass, the studied oilseed radish *Raphanus sativus* L. var. *oleiformis* Pers. can be effectively used at both sowing dates in the soil-rehabilitation system through the process of green manure biofumigation. At the same time, the issue of combining oilseed radish with other cruciferous species under conditions of unstable moisture should be further researched in the future.

According to similar estimates in the studies by Sharma et al. (2022), the obtained average long-term plant-mass quality index of 85.0% of absolutely dry matter for spring and 81.0% for summer plantings confirms the potential use of oilseed radish biomass for green mulching (Du et al., 2022) in the system of protective mulching layer in the variants of bioconservation agriculture. This type of technological solution will predictably have a higher efficiency when using plant biomass grown during the spring sowing period. As with comparison of intensity of accumulation of individual elements in oilseed radish and other cruciferous green manure plants (Szczepanek & Siwik-Ziomek, 2019; Yahbi et al., 2024), the ratio of accumulation of N:P:K in the leaf mass of rape was in the intervals 0.9–1.7:0.4–0.7:1.4–2.2, for different types of mustard it was 0.8–1.2:0.3–0.6:1.2–1.6, and for other cruciferous species used in the system of intermediate green manure use (for example, *Barbarea vulgaris* L.) it was 0.6–1.1:0.2–0.6:1.1–1.3. Oilseed radish is characterised by similar features of accumulation of basic nutrients as other cruciferous species that are widely used in the system of intermediate green manure use in the scheme of classic crop rotations. Given the study by Carr et al. (2020) and the obtained level of equivalent transformation of oilseed-radish ground biomass into classical cattle manure in the volume of 12.5–20.8 t/ha (Table 4), the efficiency of using oilseed radish at both sowing dates in the system of bioorganic fertilisation technologies and rehabilitation of degraded soils with direct application of green manure were confirmed.

We did not adopt the simple grading approach used in previous studies, such as Ramirez-Garcia et al. (2015), but instead developed a customised system to evaluate the components of the utility equation for oilseed radish biomass as a green manure (Table 6). This system was based on the indicators and values reported in scientific publiccations, reflecting our focus on a more nuanced assessment of its effecttiveness.

At the same time, the construction of the model equation of the desired format for the formation of qualitative and quantitative indicators of oilseed-radish leaf mass was based on the general requirements for green manure crops for continental climate conditions based on the results of developing green manure technology (Bhogal et al., 2019; Lei et al., 2022). The aspect of long-term use of green manure was also taken into account, which, according to the experience of the European Union (Couëdel et al., 2019; Qaswar et al., 2019), can have a variable component from winter intermediate placement in crop rotation to summer-autumn (podwinter) variant. In particular, for the conditions of the research area, we used the traditional two variants studying the effectiveness of green manure, particularly, intermediate spring (for winter crops) and intermediate summer (for spring crops with a period of overwintering). It is this option that is most common in the use of different types of cruciferous plants and is most widely regulated in recommendations on bioorganic-green-manure options for growing main crops within crop rotations of different rotation periods (Duff et al., 2020; Dorissant et al., 2022; Dzvene et al., 2023).

The analysis in the discussion is confirmed by the results of the components of multicriteria assessment of the feasibility of using oilseed radish as a green manure with a high value of normalised values of weight coefficients (Table 5) at the level of 0.62–0.99, which, taking into account the study by Saaty & Vargas (2012), proves the effectiveness of using oilseed radish as a green-manure crop for both studied sowing dates in the research area.

Conclusion

According to the results of a long-term study cycle, oilseed radish showed high productivity and adaptability. This was confirmed by the average indicators of its long-term productive and biochemical portfolio formed at a high level of variability of the hydrothermal growing season with an average determination of bioproductivity indicators by the amount of precipitation and temperature at 39.8%. For the spring sowing period, the indicators of this portfolio had the following parameters: 24.04 t ha-1of formed aboveground biomass, 73.8% soil coverage 70 days after sowing, 2.5% content (on an absolutely dry matter basis) nitrogen, 21.5% fibre, 0.6% phosphorus, 3.6% potassium, 13.57 μmol/g glucosinolates, with 16.02 C/N ratio, 85.0% plant-mass quality, and 41.2 mol/ha glucosinolate aucumulation. For the summer sowing period, similar parameters were as follows: 18.34 t/ha, 50.7%, 3.1%, 24.1% 0.6%, 4.0%, 19.70 μmol/g, 13.3%, 81.0%, 54.90 mol/ha.

Using the presented data set with the application of multiple criteria decision support analysis, we confirmed the efficiency and expediency of using oilseed radish as a green manure crop in the criterion system of multifunctional cover crops for the conditions of unstable hydrothermal regime of its vegetation period in soils with an average level of fertility.

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