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The role of oilseed radish root mass in assessing the efficiency of green manuring systems

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Abstract. This study provides an integrated evaluation of oilseed radish root mass in the context of its use as a long-term green manure. Under conditions characterised by optimal hydrothermal regimes, the crop exhibited a pronounced capacity for root mass accumulation, reaching 13.28 t ha^{-1} (2.71 t ha^{-1} in dry matter (DM)) under spring sowing conditions and 8.03 t ha^{-1} (1.76 t ha^{-1} in dry matter) under summer sowing conditions. The corresponding mean root-system productivity coefficients were 1.86 and 2.49, respectively. Analysis of the biochemical composition of root residues, averaged across sowing periods, revealed relatively low nitrogen levels (1.45% DM) alongside elevated carbon content (40.29% DM). The residues were additionally characterised by elevated concentrations of crude fat (2.07% DM) and crude fibre (42.7% DM), as well as a notable presence of glucosinolates (17.79 µmoles g^{-1} DM), with ash content averaging 6.26% DM. Statistical analysis indicated that the variability of these biochemical parameters was moderately associated with thermal conditions, with coefficients of determination ranging from 23% to 44% in relation to mean daily air temperature, whereas precipitation showed an inverse relationship (25–49%). Based on the calculated biochemical ratios, the root mass can be classified as a material with the maximum achievable fertilizer potential (kg ha^{-1} active ingredient) $N_{34.7}P_{11.6}K_{89.8}Ca_{11.7}S_{16.6}$. At the same time, its relatively high carbon and fibre contents indicate a potentially slow mineralisation pattern. These results demonstrate that root biomass should be explicitly incorporated into assessments of green-manure efficiency, as its contribution extends beyond aboveground biomass and includes both nutrient inputs and longer-term carbon and biologically active compound inputs to the soil.

Key words: green manure, biochemical composition, root system, mineralisation, fertilisation.

INTRODUCTION

Maintaining soil fertility through conventional organic inputs is becoming increasingly difficult. In particular, the use of manure as a major source of organic matter is becoming less practical within modern agricultural management systems because of economic constraints and structural changes in livestock production. An increasing proportion of livestock-derived organic materials is no longer returned to agricultural soils (Kaletnik et al., 2019) but is increasingly redirected towards bioenergy production.

Processes such as anaerobic digestion convert organic substrates into biogas and consequently reduce the amount of these materials available for direct soil application (Finney & Kaye, 2017; Kaletnik & Lutkovska, 2020; Lei et al., 2022; Tokarchuk et al., 2023). These changes highlight the need to strengthen internal nutrient and organic matter cycling within agroecosystems and to identify management practices capable of generating organic inputs directly within the production system.

Among such approaches, green manuring has particular importance because plant biomass is produced in situ, thereby reducing dependence on external organic resources and transportation (Toungos & Bulus, 2019; Lutkovska & Kaletnik, 2020; Ma et al., 2020; Kaletnik et al., 2022; Li et al., 2024). Green manure crops can contribute to soil organic matter replenishment, nutrient cycling, weed suppression, improvement of soil structural properties and phytosanitary regulation (Hartmann et al., 2015; Duff et al., 2020; Deus et al., 2022; Israt & Parimal, 2023). Their role is therefore increasingly considered within broader strategies for maintaining soil fertility and improving the resilience of agricultural systems under changing climatic conditions (Pimentel et al., 2023). In this context, green manuring should be considered not simply as the incorporation of aboveground plant biomass, but as a biological mechanism through which plant-derived organic matter and nutrients are returned to the soil and subsequently transformed by soil organisms (Sajjad et al., 2019; Salisu et al., 2025). Its functioning is therefore closely associated with the internal resource-cycling processes characteristic of natural ecosystems (Chapagain et al., 2020; dos Santos Nascimento et al., 2021; Zhang et al., 2023).

However, the efficiency of green manuring cannot be adequately assessed solely on the basis of the amount of aboveground biomass produced. Biomass quantity is important, but its biochemical composition determines decomposition dynamics, nutrient immobilisation and release, and ultimately the contribution of the incorporated material to soil fertility. The response of green-manure crops to sowing time and environmental conditions also affects the amount and quality of biomass available for incorporation. Consequently, assessment approaches should consider not only aboveground biomass production but also the biochemical characteristics of the material returned to the soil (Mikó et al., 2016; Lyu et al., 2024).

An additional and frequently underestimated component of this assessment is belowground biomass. Root systems represent a substantial pathway of organic matter and nutrient input into soil and differ from aboveground residues in their chemical composition, carbon-to-nitrogen relationships, structural compounds and decomposition behaviour. Following incorporation of green-manure crops, root-derived and shoot-derived residues decompose simultaneously and interact within the soil environment, potentially affecting nutrient immobilisation, mineralisation and the subsequent transformation of soil organic matter. Consequently, excluding root biomass from green-manure assessments may result in an incomplete estimation of the total organic matter and nutrient contribution of the crop and may bias evaluations of green-manuring efficiency (Couëdel et al., 2018; Israt & Parimal, 2023; Tsytsiura, 2024, 2024a).

Despite this importance, root biomass remains insufficiently integrated into green-manure assessment frameworks. In many studies, the contribution of roots is treated as a secondary characteristic, estimated indirectly from aboveground productivity or omitted from calculations of the total biomass returned to soil. Such approaches provide limited information on the actual quantity and quality of belowground organic inputs and consequently restrict understanding of their contribution to long-term soil organic matter formation and transformation (Liu et al., 2020; Park et al., 2022). This limitation is particularly relevant for long-term green-manure systems, in which repeated incorporation of root-derived material may contribute to soil organic matter dynamics even when its decomposition occurs more slowly than that of aboveground residues.

Cruciferous crops are particularly relevant in this context because of their broad ecological adaptability and multifunctional role in agricultural systems. They can establish under contrasting moisture regimes and are therefore suitable for use across diverse agroecological conditions (Centurión et al., 2022; Wang et al., 2022). Their aboveground biomass production, chemical composition and phytosanitary effects have been extensively investigated, whereas comparatively less attention has been given to the quantitative contribution and biochemical characteristics of their root systems, particularly in relation to the simultaneous transformation of shoot and root residues following incorporation (Couëdel et al., 2018; Israt & Parimal, 2023).

This imbalance between the well-documented contribution of aboveground biomass and the comparatively limited assessment of root-derived inputs represents an important methodological gap in evaluating green-manure efficiency. In particular, insufficient information is available on how the quantity, biochemical composition and nutrient content of root biomass contribute to the overall fertilising potential of green-manure crops and how these characteristics vary under different sowing periods and hydrothermal conditions. Addressing this gap requires the root system to be considered as an independent and quantifiable component of the organic matter and nutrient budget generated by green-manure crops rather than as an auxiliary characteristic of aboveground productivity.

Oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) provides a suitable model for addressing this problem because of its capacity for rapid biomass formation, adaptation to contrasting environmental conditions and accumulation of chemically diverse organic compounds. However, its root biomass has received considerably less attention than its aboveground biomass when assessing its overall contribution to green-manure systems. Therefore, the specific scientific problem addressed in this study was to determine whether and to what extent oilseed radish root biomass can provide an independent quantitative and qualitative component for evaluating green-manure efficiency.

Accordingly, the aim of this study was to quantify the accumulation of oilseed radish root biomass, characterise its biochemical composition and nutrient contribution, assess its relationship with hydrothermal conditions, and determine its potential contribution to the integrated evaluation of green-manuring efficiency under long-term cultivation. Particular attention was given to the differences associated with spring and summer sowing periods and to the potential implications of root-residue composition for subsequent decomposition and nutrient release. Conducting the study without external fertiliser inputs on soils of moderate fertility provides an opportunity to evaluate the contribution of biologically generated root-derived organic matter under conditions in which internal nutrient-cycling processes are expressed more distinctly.

MATERIALS AND METHODS

The study was conducted over a ten-year period (2014–2024) under field conditions at Vinnytsia National Agrarian University (49°11′31″ N, 28°22′16″ E). The experimental site is characterised by Grey Forest soils, classified as Greyi-Luvic Phaeozems according to WRB and Haplic Greyzems under the FAO system, with a silty clay loam texture. The soil was considered moderately fertile. The humus content averaged 2.68%, while the level of easily hydrolysable nitrogen reached 81.5 mg kg^{-1}. The concentrations of available phosphorus and exchangeable potassium were 176.1 and 110.8 mg kg^{-1}, respectively. The soil reaction was slightly acidic, with a pH_{KCl} of 5.8, and hydrolytic acidity reached 3.29 mg-eq per 100 g of soil.

Experimental design. The experiment was designed to investigate the green-manure value of the root biomass formed by oilseed radish under two green-manure cultivation treatments differing in sowing time: spring and summer sowing, taking into account established approaches to green-manure systems based on spring-sown cruciferous species (Adu, 2014). The study formed part of a broader systematic assessment of the role of oilseed radish as a multipurpose crop, with particular emphasis on its green-manure, bioenergy, and soil-rehabilitation effects. A detailed description of the experimental design has been provided in earlier publications (Tsytsiura, 2024, 2024a, 2025, 2025a, 2026, 2026a).

The objective of the present study was to conduct a biochemical assessment of the root biomass of oilseed radish cultivated as a green manure in established agrophytocenoses under two sowing-time treatments – spring and summer sowing. The green-manure treatments were implemented within a crop-rotation system.

The spring-sown oilseed radish treatment was used as an element of a bio-organic fertilization system for winter wheat, involving intermediate green-manure cultivation of oilseed radish following grain maize. This crop-rotation link was maintained throughout the entire experimental period. Under this treatment, oilseed radish served as the principal intermediate green-manure crop occupying the field between main crops.

The summer-sown treatment involved intermediate green-manure cultivation of oilseed radish following pea in the crop-rotation sequence pea-oilseed radish (intermediate green manure)-grain maize. The interval between green-manure fields within the crop rotation, with a return to the same field, was 3 years, in order to avoid potential phytotoxic effects associated with repeated cultivation of cruciferous green-manure crops, in accordance with Tiemann et al. (2015).

The total experimental area was 250 m^2, from which four accounting plots of 25 m^2 each were selected using complete randomization. The control treatment consisted of a non-green-manured treatment. For yield assessment, the control was applied to the subsequent main crops following the green-manure treatments, namely winter wheat and grain maize.

The biochemical and fertilization potential of oilseed radish as a green-manure crop was evaluated by comparing the effects of the two green-manure sowing times.

Green manure treatment in spring sowing. The oilseed radish variety 'Zhuravka' was sown as a green-manure crop at a rate of 2.5 million viable seeds ha^{-1}, with a 15 cm row spacing. Sowing was carried out in early April (10–15 April), while biomass incorporation was performed at the anthesis stage (BBCH 64-67), typically during the second half of June (12–20 June), which is considered optimal for this crop (Duff et al., 2020). The radish biomass was incorporated at flowering (BBCH 64-67), corresponding to the optimal green-manure stage according to Kemper (2024). The plants were mown and chopped using an FX-315 rotary mower-shredder (Canada) and subsequently incorporated into the soil using heavy disc harrows (BDN-2.4) with variable disc attack angles, similar to the Lemken Rubin technology (Germany), to a depth of 14–16 cm. The depth of subsequent tillage following green-manure incorporation varied according to the agroecological zone and the subsequent crop, with a multi-year mean tillage depth of 20.00 ± 4.57 cm.

Green manure treatment in summer sowing. The same oilseed radish variety (‘Zhuravka’) was used, with the same seeding rate and target plant density as in the spring-sowing treatment. Sowing was carried out immediately after harvesting the preceding crop, typically between 10 and 20 July, using intermediate tillage consisting of flat-cutter cultivation followed by rotary loosening and leveling to a depth of 12–16 cm. The oilseed radish biomass was incorporated using the same technological procedure as in the spring-sowing treatment, typically during the second to third decade of October. The depth of subsequent tillage following green-manure incorporation was 22.55 ± 6.31 cm.

Growth stages were determined using the BBCH scale (UPOV, 2017). Aboveground biomass was measured at the anthesis stage using 1 m² sampling units (four samples per replicate), followed by weighing of the collected biomass. Root-system productivity was assessed concurrently using the monolith method, which is widely used in studies of cruciferous crops (Talgre, 2013; Adu, 2014; Upendra et al., 2017; Tsytsiura, 2025, 2025a).

Root biomass sampling and monolith analysis. Sampling of root biomass for biochemical analysis was conducted within a single cycle of soil monolith analysis, 5–7 days before the incorporation of green-manure biomass into the soil.

Soil monoliths were obtained from a vertical soil profile at 10-cm depth increments to a total depth of 60 cm for both sowing-time treatments. Two soil monoliths were analyzed within each replicate, resulting in a total of eight monoliths. The locations for monolith sampling were selected randomly within the central part of each experimental replicate. To account for spatial variability within the plots, the sampling positions were systematically shifted among replicates according to the sequence upper-central-lower part of the accounting plot. This sampling design enabled the characterization of the vertical distribution of root biomass throughout the 0–60 cm soil profile while minimizing potential bias associated with localized spatial heterogeneity within individual experimental plots. Two rows of plants were included in the analysis with a depth of coverage of up to 10 plants in quadruplicate for each replication. Open-topped metal boxes with pointed edges (scoop type, wall thickness 3 mm) measuring 30 cm × 33.3 cm × 10 cm (accounting volume ~0.01 m^3) were used. To trim the monolithic layer along the outer front wall, a vertical pointed metal plate measuring 10 cm × 34 cm × 0.3 cm was used. This made it possible to compact the walls of the monolith. Micromonoliths were labelled and packed in airtight sampling bags and then stored at 5 °C until washed out for soil removal. A sieve column (laboratory wire mesh sieves of 4.0 mm, 2.0 mm, 1.0 mm, 0.5 mm and 0.25 mm) was used for the washing separation of roots. Non-root materials were removed manually. The selected roots were stored in plastic containers at 5 °C and subsequently air-dried for 24 h. The measured values were then recalculated on a per-hectare basis based on the sampling area. To ensure comparability, dry matter content was determined, allowing the conversion of fresh mass into standardized dry mass values.

Root classification and biomass assessment. No classification of roots according to their morphological categories was applied for the determination of the accumulated root biomass. A detailed description of the methodology used is provided in a previous publication (Tsytsiura, 2025). For the visualization of the morphometric development and spatial distribution of the root system within the soil monolith, layer-by-layer soil washing was performed in selected years. Soil was removed in layers corresponding to washing depths of 2.5, 10, 20, and 30 cm, following the methodology of Adu (2014). Ordinary water was applied using a Bradas (Poland) manual low-volume, high-pressure (LVHP) sprayer.

For the calculation of the accounted root biomass, the mean root biomass determined from eight soil monoliths sampled to a depth of 60 cm was used. The resulting root biomass was converted to t ha^{-1} using Formula 1:

$$M_{t\,ha^{-1}} = \frac{M_g}{A \times 100} \quad (1)$$

where mg – mean mass of dry (fresh) roots per soil monolith based on eight sampling replicates, g; A – surface area of the soil monolith, m^2; and 100 – conversion factor for expressing root biomass in t ha^{-1}

Biochemical analysis. All biochemical parameters of the root biomass were expressed on a dry-matter basis. Determination of dry matter (DM) was carried out by drying samples to constant weight at 105 °C, followed by ashing at 550 °C to quantify the mineral fraction (AOAC, 2005). Prior to analysis, dried samples were homogenized using a laboratory mill (Vilitek VLM-16, 800 g capacity, 2.2 L chamber).

The chemical composition of the biomass was analysed using standardized methodologies in accordance with AOAC (2005) guidelines. Crude ash (CA), crude fibre (CFb), crude fat (CF), and crude protein (CP) were determined using the respective official procedures.

Crude protein content was calculated from total nitrogen (TNC) using a conversion coefficient of 6.25 (AOAC, 2005). Total nitrogen content (TKN) was measured by the Kjeldahl method using a KjelROC Kd-310 analyzer, following ISO 17025 requirements.

Structural carbohydrate fractions were assessed using detergent fibre analysis techniques. Neutral detergent fibre (NDF) and acid detergent fibre (ADF) were determined according to AOAC methods (AOAC, 2005), while Klason lignin (KL) was quantified using the NREL protocol.

Cellulose was determined by subtracting KL from ADF, whereas hemicellulose was obtained as the difference between NDF and KL, following the Van Soest approach (FOSS, 2018). The concentration of glucosinolates (GSL), a key biochemical characteristic of cruciferous crops, was determined in accordance with ISO 9167:2019 (2019). The mineral composition of root mass was evaluated through the determination of AOAC International (AOAC, 2005): phosphorus content was determined colorimetrically after wet digestion (AOAC 965.17); potassium was quantified using atomic absorption spectrophotometry (AOAC 968.08); sulfur content was determined turbidimetrically as sulfate (AOAC 923.01).

Calcium levels were quantified by means of a modified complexometric approach based on established methodologies (Nielsen, 2010).

Total organic carbon (TOC) content was measured using a TOC analyzer (TOC-LCPH series). Nitrogen-free extractives (NfE) were estimated by difference, calculated as the remainder after subtracting crude protein, crude fibre, crude fat, and crude ash from 100% dry matter. The carbon-to-nitrogen (C/N) ratio was then obtained as the ratio between total organic carbon and total nitrogen content.

Climatic conditions throughout the study period were characterised using an integrated set of indicators designed to reflect the combined moisture and thermal regime.

The hydrothermal coefficient (HTC) was calculated as (formula 2):

$$HTC = \frac{\sum R}{0.1 \times \sum t_{>10}} \quad (2)$$

where $\sum R$ represents total precipitation (mm) during the period with mean daily temperatures above 10 °C, and $\sum t_{>10}$ is the sum of effective temperatures over the same period. According to established classifications, HTC values indicate moisture conditions ranging from excessively humid (>1.6) to very dry (0.4–0.7).

The De Martonne aridity index was calculated as (formula 3):

$$I_{DM} = \frac{12P_m}{T_m + 10}, \quad (3)$$

where P_m is monthly precipitation (mm); T_m is mean monthly air temperature (°C). This index allowed classification of climatic conditions from arid to extremely humid.

The Vysotsky-Ivanov moisture coefficient (K_h) was determined as the ratio between precipitation and evapotranspiration (formula 4):

$$K_h = \frac{P}{E} \quad (4)$$

where P is total precipitation (mm) and E is evapotranspiration (mm), calculated based on air temperature (t, °C) and relative humidity (a, %). Values of K_h close to 1 indicate optimal moisture conditions, while lower values reflect increasing moisture deficiency.

Visualization of root decomposition. To visualize the predicted pattern of soil decomposition of oilseed radish roots, the litter-bag method described by Olson (1963), with modifications adapted to field conditions, was used. Nylon mesh bags measuring 20 cm in width × 30 cm in length, with a 1 mm mesh opening, were used. A total of 16 litter bags were prepared. Each bag contained 20 taproot segments of oilseed radish with lateral branching. The bags were randomly distributed within the experimental plot at four locations, with four bags assigned to each location. This arrangement was used to ensure comparable environmental conditions throughout the sequential sampling stages. The litter bags were deployed in the treatment with spring-sown oilseed radish green manure.Each bag was labelled according to the experimental treatment. The identification marker consisted of a wooden stake up to 1 m in height bearing an attached label. Each litter bag was secured to the corresponding stake using nylon thread. The litter bags were buried horizontally in the soil at a depth of 12–15 cm, corresponding to the typical incorporation depth of green-manure biomass under the experimental field conditions. The bags were sequentially removed from the soil for visual inspection and photographic documentation after 10, 30, 50, and 70 days of decomposition. At each sampling date, one bag was collected from each of the four locations. The results of the sequential visual assessment of the soil decomposition process of the taproot portions of oilseed radish were presented as a dynamic comparative photographic figure.

Root imaging and morphometric assessment. For visualization and documentation of the root decomposition process, a Canon EOS 750D DSLR camera equipped with an 18–135 mm IS STM lens, supplemented by a Canon EF 100 mm f/2.8 Macro lens with a UV filter, was used. Images were obtained in orthogonal projection relative to the soil surface, with a standard measurement ruler included in the field of view for scale calibration. Artificial shading was applied during image acquisition according to the approach described by Xingming et al. (2021).

For microscopic examination of root structures, USB microscopy was performed using a Sigeta MCMOS 5100 5.1 MP USB 2.0 microscope with the corresponding imaging software. Root measurements and observations were additionally supported by digital scanning of plant roots, followed by analysis of the scanned images using ImageJ software (v. 1.5). A measurement ruler was included during image acquisition to provide dimensional calibration. Scanned images were obtained using a CanoScan LiDE 700F scanner and the corresponding software.

Statistical analysis. Statistical processing was performed using the standard procedures for descriptive and variation statistics described by Rumsey (2016), using Statistica 10 (StatSoft–Dell Software, USA) and the R statistical computing environment (v. 4.6.0) (R Foundation for Statistical Computing, Vienna, Austria).

For each measured indicator, the following descriptive statistics were calculated: minimum and maximum values, arithmetic mean, median, standard deviation, and coefficient of variation (CV). In addition, Pearson correlation analysis was performed for the complete dataset. The statistical significance of correlation coefficients was assessed using Student's t-test at significance levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$.

Differences in the studied indicators among years and green-manure sowing-time treatments were evaluated using a two-way analysis of variance (Two-way ANOVA with replication). Before ANOVA, the assumptions concerning the distribution and homogeneity of variance were assessed using the Shapiro–Wilk test and Levene's test, respectively. The overall ANOVA design comprised two green-manure sowing-time treatments (spring and summer) × 11 years of assessment, with four replicates per treatment combination, giving a total sample size of N = 88. Where significant effects were detected, Fisher's least significant difference (LSD) test was calculated at the $p < 0.05$ significance level. In addition, Tukey's HSD post-hoc test was used to identify statistically significant differences among treatment means, with differences indicated by letter-based grouping at $p < 0.05$. The letter assignment was based on the pairwise differences obtained from the Tukey HSD procedure.

To estimate the proportion of variability explained by the relationships between variables, the coefficient of determination was calculated as dxy (formua 5):

$$d_{xy} = r^2 \times 100 \qquad (5)$$

where r is the correlation coefficient.

The overall pattern of interactions among the analysed parameters was examined using a correlation graph (G) (formula 6), which provided the strength and connectivity of statistical relationships within the system.

$$G = \sum_{|r_{ij}| \geq a} |r_{ij}| \qquad (6)$$

RESULTS AND DISCUSSION

Long-term observations under contrasting hydrothermal regimes revealed a high degree of ecological adaptability of oilseed radish. Over the course of the study, substantial interannual variation was recorded, with precipitation levels varying by 33.77% and mean daily air temperature by 17.56%. These fluctuations were also reflected in the broad ranges of hydrothermal indices, including I_{DM} (2.52–111.4), K_h (0.052–3.29), and HTC (0.015–4.902) (Fig. 1). Despite this variability, the crop exhibited a relatively stable level of productivity, confirming its capacity for consistent performance under diverse environmental conditions and supporting its classification as a highly adaptable cover crop suitable for different sowing periods. The evaluation of bioproductivity parameters (Fig. 2), together with previously reported data for grey forest soils of moderate fertility, revealed pronounced differences between sowing periods. Under spring sowing conditions, the accumulation of aboveground mass was consistently higher, reaching an average of 23.69 t ha^{-1} over the experimental period. In contrast, summer sowing was associated with reduced mass formation, with a mean value of 17.57 t ha^{-1}.

Interannual variability was considerable, amounting to 29.85% and 35.69%, respectively, reflecting the strong dependence of biomass production on environmental conditions.

A comparable trend was observed when mass was expressed in terms of dry matter. In the spring variant, the average reached 3.07 t ha^{-1}, whereas in the summer sowing variant it declined to 2.72 t ha^{-1}. Year-to-year variation remained evident, with coefficients of 23% and 31%, respectively, indicating relatively greater stability of dry matter accumulation compared to fresh mass. Root-system development followed the same general pattern, although it was characterised by higher variability. In terms of fresh weight, root mass averaged 8.47 t ha^{-1} under spring sowing and 5.27 t ha^{-1} under summer sowing. When converted to dry matter, these values corresponded to 1.78 and 1.20 t ha^{-1}, respectively.

The interannual variability of root mass was more pronounced than that of aboveground mass, ranging from 40.9% to 44.7%, indicating greater sensitivity of root development to hydrothermal conditions. A consistent decline in total bioproductivity was observed when sowing was under summer sowing conditions.

On average, this reduction amounted to 34.87% over the long-term period. Such a tendency is typical of cruciferous green manure crops and is associated with shorter vegetation periods and less favorable moisture and temperature conditions during later sowing dates.

The results are consistent with previously reported patterns, confirming the regular decrease in productivity associated with delayed sowing. In general, the findings indicate that oilseed radish is capable of producing substantial mass across a wide range of environmental conditions.

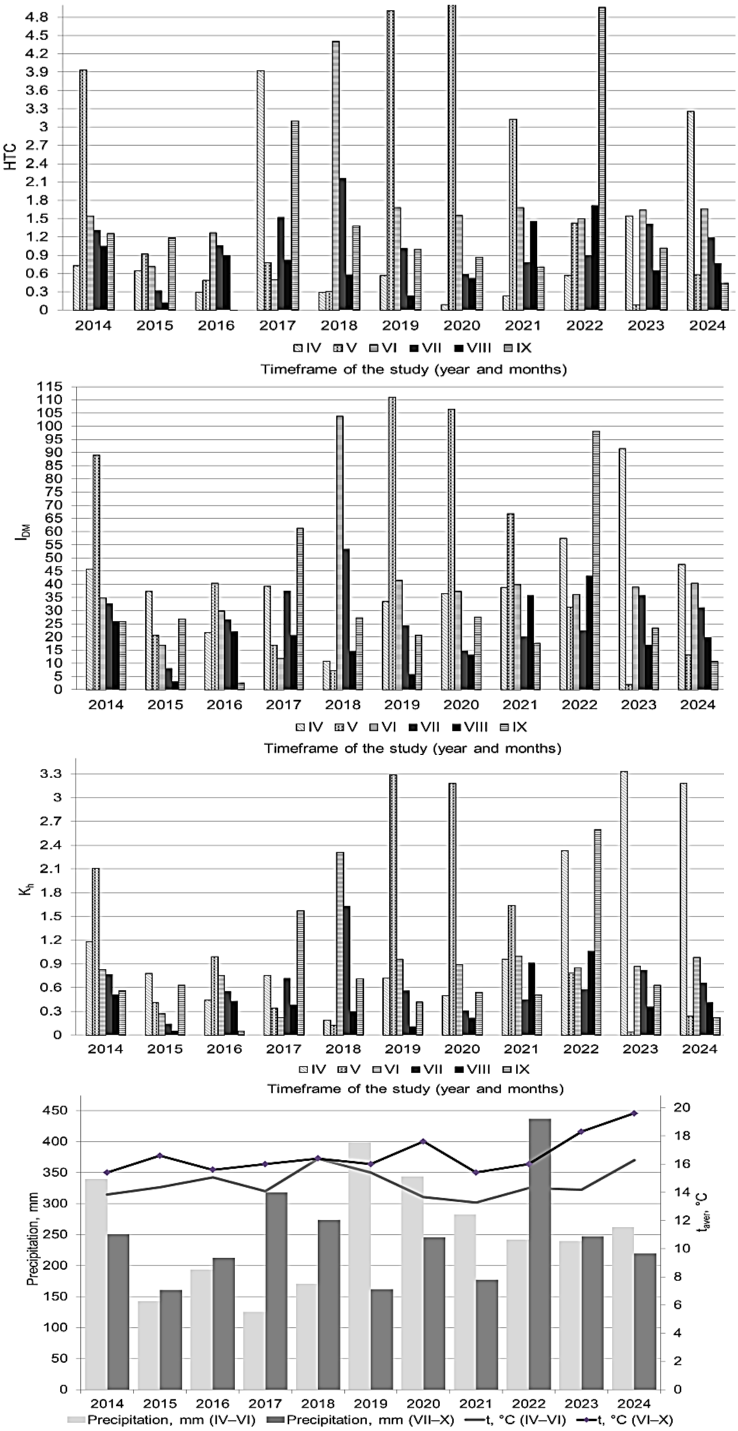

Figure 1. Evaluation of meteorological conditions during the active growth period of oilseed radish under contrasting summer–autumn regimes (Dfa–Dfb climate zone, Köppen–Geiger classification), 2014–2024.

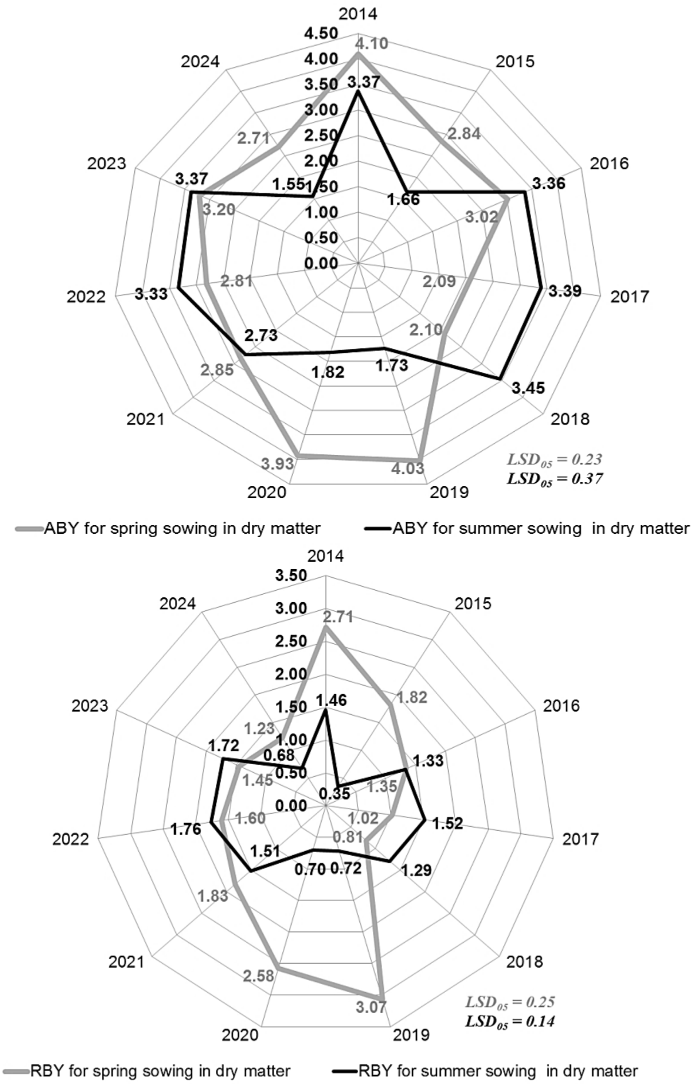

Figure 2. Above- and belowground productivity of oilseed radish at the anthesis stage (BBCH 64-67) under contrasting sowing periods, t ha^{-1} (2014–2024).

Note: ABY – aboveground mass yield, t ha⁻; RBY – root mass yield, t ha^{-1}.

However, sowing time remains a key factor influencing the level of realized productivity, particularly with regard to root mass formation, which demonstrated a higher sensitivity to external environmental factors.

These findings are consistent with earlier criterion-based evaluations of oilseed radish as a multifunctional cover crop and align with existing classification approaches for crops cultivated under conditions of unstable moisture supply (Tsytsiura, 2024; Wong et al., 2024; Kemper et al., 2025). Although a decline in root mass productivity was observed under summer sowing, reaching up to 37.78%, the agrochemical value of the biomass remained relatively stable, decreasing only by a factor of 1.27 compared to the spring variant.

Notably, biofumigation potential was largely maintained, indicating the persistence of key biochemical properties even under stress conditions. Such responses are consistent with previously described patterns for cruciferous green manure crops exposed to limited moisture, where reductions in productivity are often accompanied by the preservation of qualitative characteristics (Hu et al., 2018; Hansen et al., 2021; Deus et al., 2022; Quintarelli et al., 2022). This suggests that oilseed radish is capable of sustaining its functional role in soil improvement systems even under suboptimal hydrothermal conditions.

Comparison with other cruciferous species further emphasises these advantages. Under moisture-deficient conditions, where root mass production in related crops may decrease by 17.0–47.8% relative to optimal environments, oilseed radish consistently maintained a leading position among spring-sown cruciferous green manure species. This was reflected not only in mass accumulation but also in the retention of its agrochemical properties, confirming its suitability for inclusion in adaptive cropping systems.

Morphological examination of the root system revealed a well-defined taproot architecture, characterised by a thickened core axis and a network of lateral roots of the first to fourth order. Based on an extensive dataset of scanned root images (annual sample size N = 500), stable morphometric characteristics were identified. Within the 0–30 cm soil layer, the average taproot length under spring sowing reached 21.51 ± 5.06 cm, with an upper diameter of 15.08 ± 3.48 mm and a lower diameter of 3.65 ± 1.92 mm.

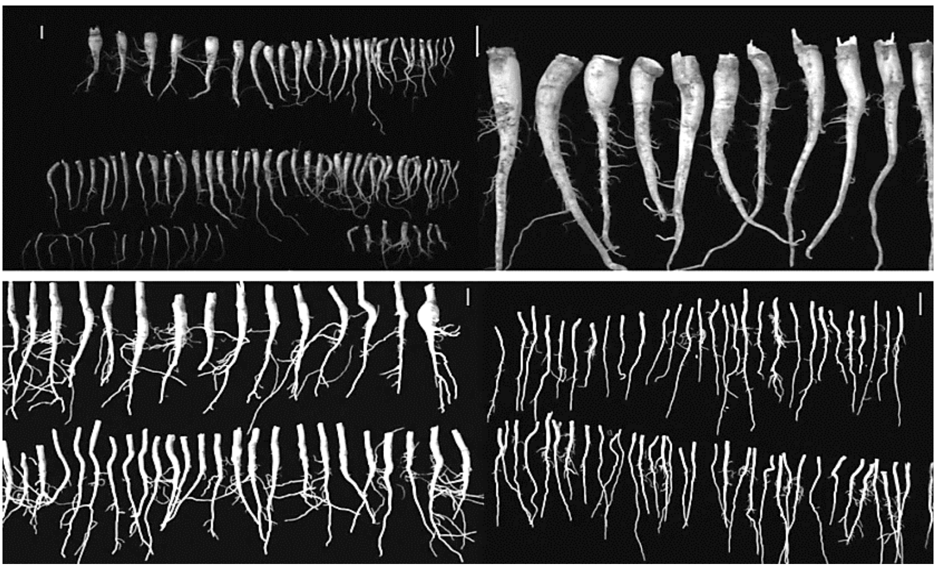

Figure 3. Morphological characteristics of oilseed radish taproots with first-order branching elements at the anthesis stage (BBCH 64-67), depending on sowing period: spring sowing conditions (upper image) and summer sowing conditions (lower image), 2024. Sampling was performed from the middle row of 1 m² plots in two spatially separated replicates.

Note: yellow scale bar 2 cm.

Under summer sowing conditions, these parameters decreased to 17.054.97 cm, 13.99 ± 3.33 mm, and 2.84 ± 1.41 mm, respectively (Fig. 3), indicating a clear dependence of root development on growing-season duration. The concentration of the main root mass within the upper 0–30 cm soil layer appears to be a key determinant in total root mass accumulation. In this context, the contribution of the thickened taproot component varied considerably depending on sowing time.

Under spring conditions, its share varied from 59.94% to 75.09%, with an average value of 65.06% (Cv = 9.55%). Under summer sowing conditions, the corresponding values were higher, ranging from 73.13% to 86.42%, with a mean of 78.24% (Cv = 6.52%) (Fig. 4). This shift suggests a structural redistribution of mass toward the main root axis under shortened vegetation periods. Long-term observations of root system spatial distribution within the soil profile further highlight its functional significance (Tsytsiura, 2025; 2026).

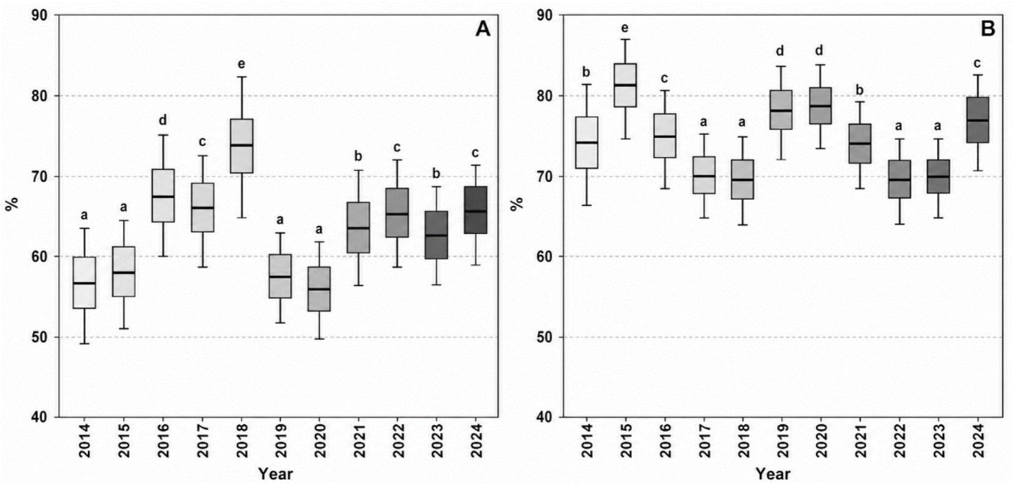

Figure 4. Relative proportion of the thickened taproot component in total root mass (%) of oilseed radish as affected by sowing period, 2014–2024.

Note: values marked with different letters differ significantly ($p < 0.05$); A – spring sowing, B – summer sowing.

Earlier studies have demonstrated that oilseed radish exerts a pronounced positive effect on the formation and development of agronomically valuable soil structure, particularly through improvements in aggregate composition and increased soil porosity. These effects may be associated, among other factors, with the intensive branching of the oilseed radish root system throughout the soil profile, which contributes to the formation of biopores and modification of the soil pore space. Over the same 11-year assessment period, the following changes in soil fertility-related physical properties relative to the control treatment were established: soil bulk density decreased by 0.019 g cm^{-3}, particle density by 0.015 g cm^{-3}, and soil hardness by 0.323 kg cm^{-2}, whereas total soil porosity increased by 0.622%, capillary porosity by 0.275%, non-capillary porosity by 0.348%, aeration porosity by 0.429%, and water absorption capacity by 0.460% (Tsytsiura, 2026, 2026a). These effects were clearly illustrated by field assessments of root architecture based on monolith analysis to a depth of 0.45 m (Fig. 5). Sequential removal of soil layers during monolith washing – from the upper 2.5 cm (Fig. 5, a) 10 cm (Fig. 5, b), 20 cm (Fig. 5, c), and 30 cm (Fig. 5, d) – revealed an intensive branching pattern extending throughout the soil profile. Branching up to the fourth order was consistently observed, forming a dense rhizosphere network closely integrated with the soil structural matrix. Such a configuration promotes improved water movement within the arable layer and contributed to effective drainage conditions. The proportion of diffusely distributed fine roots remained relatively stable over the years. On average, this fraction accounted for 34.94% of total root mass under spring sowing and 21.76% under summer sowing.

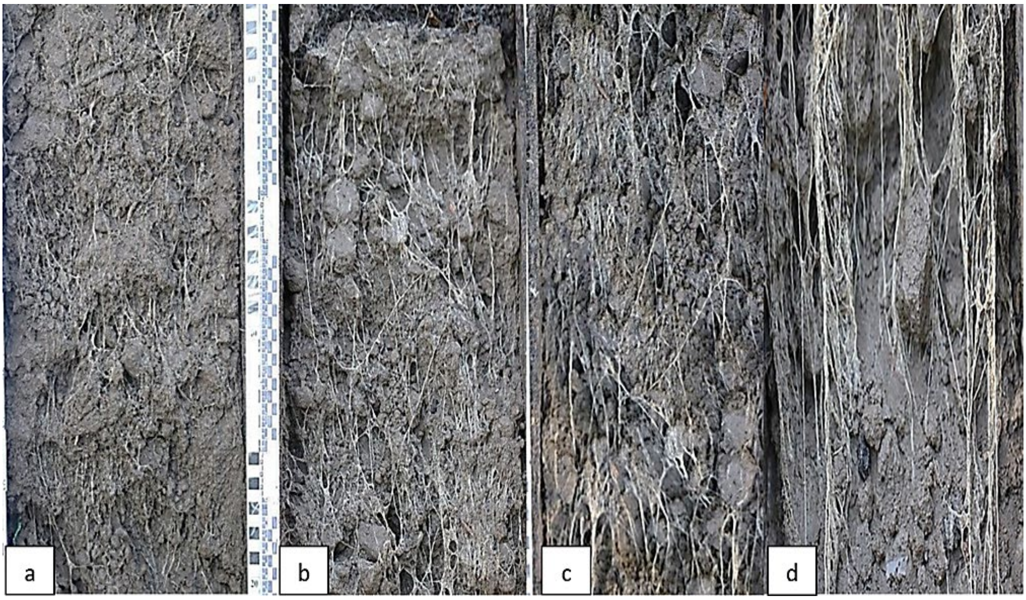

Figure 5. Morphometry and branching pattern of the oilseed radish root system at the early fruiting stage (BBCH 72–73) based on field monolith analysis (depth 0.45 m), 2024. Sequential layers represent different stages of monolith washing to a depth of: (a) 2.5 cm; (b) 10 cm; (c) 20 cm; (d) 30 cm. The black square indicates a scale of 1 cm.

The comparatively low variability of these indicators suggests a high level of developmental stability. Notably, variability in hydrothermal conditions exceeded fluctuations in taproot proportion by approximately 2.7 times, suggesting that root system formation exhibits a level of buffering against environmental extremes.

Comparable patterns of adaptive root development have been documented in previous studies, confirming the ability of oilseed radish to maintain functional stability across a wide range of moisture regimes – from sufficient to highly variable conditions (Adu, 2014; Hu et al., 2018; Kul et al., 2021). This further supports its classification as an efficient green manure crop capable of sustaining performance under diverse agroecological settings.

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This further supports its classification as an efficient green manure crop capable of sustaining performance under diverse agroecological settings. Biochemical analysis of root mass provided additional insight into its fertilisation potential. Regardless of sowing time (Table 1), the root material can be classified as relatively low in protein content (according to Hu et al., 2018; Toom et al., 2019). Under spring sowing conditions, crude protein averaged 8.10 ± 1.17% of dry matter, with total nitrogen at 1.30 ± 0.19%.

Table 1. Root chemical composition of oilseed radish (% DM) across sowing dates at BBCH 64-67 (2014–2024)

Year	Dry matter, %	Crude protein	Crude fat	Crude fibre	Crude ash	NDF	ADF	KL
Spring sowing								
2014	20.42 ± 1.03[b]	8.00 ± 0.56[b]	1.31 ± 0.26[b]	43.48 ± 1.49[b]	5.26 ± 0.77[a]	51.27 ± 1.13[c]	46.13 ± 1.43[c]	12.45 ± 0.45[b]
2015	23.12 ± 0.86[d]	8.88 ± 0.84[c]	2.59 ± 0.60[e]	53.79 ± 1.99[g]	6.93 ± 1.03[b]	58.85 ± 0.76[h]	55.75 ± 0.67[g]	14.34 ± 0.47[d]
2016	21.73 ± 1.30[c]	8.38 ± 0.60[c]	1.84 ± 0.33[c]	49.38 ± 1.15[d]	5.34 ± 0.65[a]	56.28 ± 0.31[g]	53.15 ± 4.91[e]	13.11 ± 0.34[c]
2017	22.84 ± 0.35[d]	10.50 ± 1.00[e]	2.91 ± 0.22[f]	52.77 ± 2.29[f]	7.15 ± 1.78[b]	56.92 ± 0.75[g]	54.48 ± 0.72[f]	15.78 ± 0.55[e]
2018	23.95 ± 1.94[d]	9.44 ± 1.73[d]	1.79 ± 0.19[c]	47.03 ± 2.27[c]	7.88 ± 1.11[c]	53.58 ± 0.57[d]	50.54 ± 0.68[d]	14.09 ± 0.35[d]
2019	20.68 ± 0.79[b]	7.06 ± 1.89[a]	1.18 ± 0.23[a]	41.60 ± 1.60[a]	7.22 ± 0.76[b]	48.37 ± 0.76[b]	44.41 ± 0.72[b]	11.89 ± 0.25[a]
2020	19.84 ± 0.68[a]	7.63 ± 1.53[b]	1.92 ± 0.27[d]	47.79 ± 1.64[c]	6.23 ± 0.54[b]	54.11 ± 0.70[e]	50.55 ± 0.74[d]	12.61 ± 0.22[b]
2021	19.09 ± 0.81[a]	6.56 ±1.28[a]	1.77 ± 0.27[c]	50.69 ± 2.61[e]	7.15 ± 1.17[b]	55.59 ± 0.60[f]	52.85 ± 0.60[e]	12.48 ± 0.36[a]
2022	21.47 ± 0.88[c]	6.94 ± 0.35[a]	2.43 ± 0.36[e]	55.26 ± 2.04[h]	8.24 ± 0.74[d]	58.83 ± 1.02[h]	56.62 ± 1.10[h]	12.91 ± 0.63[b]
2023	21.11 ± 0.71[b]	7.44 ± 1.02[a]	1.47 ± 0.27[b]	48.19 ± 1.83[d]	6.88 ± 0.91[b]	53.36 ± 0.99[d]	50.57 ± 0.89[d]	12.77 ± 0.26[b]
2024	20.59 ± 0.93[b]	8.25 ± 1.07[b]	1.29 ± 0.32[b]	44.75 ± 1.89[b]	7.19 ± 0.75[b]	46.91 ± 0.69[a]	42.89 ± 1.89[a]	13.85 ± 0.52[c]
Summer sowing								
2014	22.17 ± 0.62[b]	10.31 ± 1.36[d]	2.21 ± 0.50[b]	36.93 ± 1.93[c]	4.10 ± 0.40[a]	43.58 ± 0.60[a]	39.88 ± 0.66[b]	9.62 ± 0.52[b]
2015	25.18 ± 0.83[d]	6.44 ± 0.93[a]	2.91 ± 0.28[d]	42.09 ± 1.80[e]	5.59 ± 1.01[b]	47.78 ± 1.04[e]	43.84 ± 1.29[e]	10.21 ± 0.88[c]
2016	23.12 ± 1.08[c]	8.19 ± 0.73[b]	2.27 ± 0.33[b]	36.77 ± 1.87[c]	4.98 ± 0.33[a]	45.52 ± 1.08[c]	40.19 ± 1.30[b]	9.42 ± 0.30[a]
2017	21.08 ± 1.52[a]	11.88 ± 0.90[e]	2.04 ± 0.13[a]	36.35 ± 1.16[c]	7.77 ± 0.29[d]	44.59 ± 0.69[b]	39.31 ± 0.83[b]	9.06 ± 0.61[a]
2018	23.29 ± 0.78[c]	9.69 ± 0.83[c]	2.45 ± 0.17[c]	35.48 ± 1.46[b]	7.02 ± 0.37[c]	43.61 ± 1.68[a]	38.55 ± 1.71[a]	9.22 ± 0.41[a]
2019	20.15 ± 0.62[a]	8.56 ± 0.68[b]	2.78 ± 0.15[d]	36.47 ± 1.74[c]	4.88 ± 0.66[a]	45.72 ± 0.81[c]	41.92 ± 0.96[c]	10.08 ± 0.36[c]
2020	22.68 ± 1.35[b]	11.56 ± 0.45[e]	2.11 ± 0.25[a]	35.29 ± 1.55[a]	5.83 ± 0.69[b]	45.78 ± 0.43[c]	40.18 ± 0.60[b]	9.65 ± 0.15[b]
2021	23.32 ± 2.27[c]	8.94 ± 0.95[b]	2.37 ± 0.32[c]	35.81 ± 1.66[b]	4.94 ± 0.41[a]	45.85 ± 1.06[c]	38.89 ±0.92[a]	9.79 ± 0.42[b]
2022	21.91 ± 1.94[a]	12.38 ± 2.11[f]	1.91 ± 0.15[a]	34.68 ± 1.70[a]	5.41 ± 0.85[b]	44.41 ± 1.24[b]	39.92 ± 0.98[b]	10.22 ± 0.42[c]
2023	23.52 ± 0.84[c]	10.13 ± 0.78[d]	2.05 ± 0.21[a]	36.07 ± 1.24[c]	6.35 ± 0.74[c]	44.88 ± 0.72[b]	41.19 ± 0.86[c]	9.79 ± 0.21[b]
2024	23.96 ± 0.91[c]	11.68 ± 1.05[e]	1.88 ± 0.25[a]	38.79 ± 1.93[d]	5.27 ± 0.55[b]	46.55 ± 1.15[d]	42.55 ± 1.05[d]	11.07 ± 0.33[d]

Note: Means sharing different lowercase letters differ significantly among treatments at level $p < 0.05$.

Under summer sowing conditions, slightly higher values were recorded, reaching 9.98 ± 1.84% and 1.60 ± 0.29%, respectively. These characteristics indicate a predominance of structural over nitrogen-rich components, which has implications for decomposition dynamics and nutrient release in soil. The increase in crude protein content under summer sowing conditions appears to be closely associated to the more stressful hydrothermal regime during this period. This is supported by a general decline in HTC values alongside a simultaneous rise in the aridity index (IDM), indicating reduced moisture availability (Fig. 1).

Such environmental conditions are known to induce adaptive physiological responses in plants, including the enhanced synthesis of stress-associated proteins (Zhou et al., 2023). In this context, the elevated protein content in root mass may reflect stress-induced metabolic adjustments. Similar responses have been reported in previous studies (Tsytsiura, 2024) where moisture limitation and temperature stress stimulated nitrogen assimilation and protein accumulation in plant tissues.

Earlier findings for aboveground mass suggest a comparable trend, which, by analogy, extends to the root system when oilseed radish is cultivated under later sowing conditions. Total organic carbon content remained relatively stable across both sowing periods, varying within a narrow range of 39.56–41.03% of dry matter (± 1.11%). This indicates that carbon accumulation in root tissues is less sensitive to hydrothermal fluctuations than nitrogen dynamics. As a result, the C/N ratio showed moderate variation, with long-term average values ranging from 26.71 to 31.01. These ratios suggest a predominance of structural carbon components and indicate relatively slow decomposition rates of root residues after incorporation into the soil. Overall, the combined changes in nitrogen and carbon fractions highlight the importance of sowing time as a factor influencing not only mass formation but also its biochemical quality and subsequent transformation in soil (Tribouillois et al., 2016; Thiébeau et al., 2021;). The transition on summer sowing conditions was associated with an overall increase in nitrogen content within plant tissues, which, under conditions of relatively stable organic carbon levels, resulted in a decrease in the C/N ratio of root residues. This change has important implications for decomposition dynamics, as lower C/N values are typically associated with more rapid microbial processing in soil (Grzebisz et al., 2023; Zhang et al., 2023).

Accordingly, root residues formed under summer sowing conditions are likely to decompose more rapidly, contributing to a better temporal alignment of mass turnover within the spring–summer green manure cycle. In the present study, the long-term average phosphorus content in root mass was relatively low to moderate, amounting to 0.43 ± 0.10% DM (spring sowing) and 0.37 ± 0.05% DM (summer sowing) (Table 2).

According to comparative evaluations (Talgre, 2013), the phosphorus-related characteristics of oilseed radish root mass occupy an intermediate position among cruciferous green manure crops. Its values are generally lower than those reported for winter rapeseed but exceed those typical for white mustard and spring rapeseed. This allows oilseed radish root residues to be regarded as a material with a relatively high capacity for phosphorus immobilisation, which is particularly relevant to soils with limited available phosphorus reserves. In addition to phosphorus, the root mass was characterised by appreciable concentrations of potassium and calcium. Over the long-term observation period, potassium content varied within the range of 2.36–2.87% DM, while calcium content remained within 0.34–0.46% DM across both sowing periods. Although these values are somewhat lower than those reported for winter rapeseed (Talgre, 2013; Askew et al., 2019; Couëdel et al., 2019; Szczepanek & Siwik-Ziomek, 2019), they remain comparable to the nutrient composition of several leguminous green manure crops (Guinet et al., 2023), indicating a relatively balanced mineral composition. From an agronomic perspective, calcium deserves special attention. Its presence in root residues suggests a potential role in regulating soil acidity, particularly in systems with low buffering capacity (Xu et al., 2023). During decomposition, calcium-containing components may contribute to the stabilisation of exchangeable acidity, thereby improving soil chemical properties. This interpretation is supported by previous findings demonstrating the positive effects of calcium release during long-term organic matter transformation (Vogel et al., 2020; Abdulraheem & Tobe, 2022).

Table 2. Additional parameters of the biochemical composition of oilseed radish root biomass (% DM) across sowing dates at BBCH 64-67 (2014–2024)

Year	Cellulose	Hemi-cellulose	TKN	TOC	P	K	Ca	S	GSL, µmoles g^{-1} DM
Spring sowing									
2014	33.68[a]	5.14[e]	1.28 ± 0.09[c]	39.22 ± 0.92[c]	0.31 ± 0.09[a]	2.08 ± 0.44[a]	0.49 ± 0.15[b]	0.52 ± 0.06[a]	16.46 ± 0.70[a]
2015	41.41[f]	3.10[b]	1.42 ± 0.13[d]	40.74 ± 0.94[d]	0.44 ± 0.11[b]	2.83 ± 0.14[b]	0.41 ± 0.08[a]	0.65 ± 0.07[b]	16.18 ± 0.49[a]
2016	40.04[e]	3.13[b]	1.34 ± 0.10[c]	39.25 ± 0.64[c]	0.55 ± 0.07[c]	3.65 ± 0.18[c]	0.53 ± 0.07[b]	0.80 ± 0.13[e]	19.19 ± 0.74[d]
2017	38.70[d]	2.44[a]	1.68 ± 0.16[e]	41.31 ± 0.69[e]	0.62 ± 0.08[d]	4.75 ± 0.28[d]	0.57 ± 0.10[c]	0.89 ± 0.03[f]	20.93 ± 1.30[e]
2018	36.45[b]	3.04[b]	1.51 ± 0.28[d]	39.84 ± 0.97[c]	0.51 ± 0.04[c]	3.01 ± 0.12[b]	0.49 ± 0.06[b]	0.77 ± 0.19[d]	20.95 ± 0.49[e]
2019	32.52[a]	3.96[c]	1.13 ± 0.30[a]	37.42 ± 0.95[a]	0.37 ± 0.08[a]	1.69 ± 0.33[a]	0.38 ± 0.07[a]	0.54 ± 0.06[a]	15.83 ± 0.73[a]
2020	37.94[c]	3.56[c]	1.22 ± 0.25[b]	40.08 ± 1.09[d]	0.45 ± 0.06[b]	3.48 ± 0.21[c]	0.41 ± 0.11[a]	0.58 ± 0.09[a]	18.82 ± 0.57[c]
2021	40.37[e]	2.74[a]	1.05 ± 0.21[a]	38.35 ± 1.78[a]	0.29 ± 0.07[a]	2.14 ± 0.14[a]	0.50 ± 0.07[b]	0.62 ± 0.06[b]	17.40 ± 0.58[b]
2022	43.71[g]	2.21[a]	1.11 ± 0.06[a]	38.77 ± 2.45[b]	0.34 ± 0.12[a]	2.42 ± 0.13[b]	0.42 ± 0.08[a]	0.62 ± 0.11[b]	18.05 ± 0.48[c]
2023	37.80[c]	2.79[a]	1.19 ± 0.16[b]	40.28 ± 1.35[d]	0.40 ± 0.07[b]	2.51 ± 0.10[b]	0.39 ± 0.04[a]	0.54 ± 0.07[a]	17.33 ± 0.42[b]
2024	36.04[b]	4.02[d]	1.32 ± 0.11[c]	39.88 ± 1.04[c]	0.43 ± 0.12[b]	3.05 ± 0.27[b]	0.47 ± 0.08[b]	0.70 ± 0.12[c]	17.59 ± 0.59[b]
Summer sowing									
2014	30.26[a]	3.70[a]	1.65 ± 0.22[c]	41.88 ± 2.39[d]	0.38 ± 0.12[a]	2.04 ± 0.14[a]	0.31 ± 0.11[b]	0.53 ± 0.05[b]	16.26 ± 0.65[a]
2015	33.63[d]	3.94[a]	1.03 ± 0.15[a]	41.96 ± 1.13[d]	0.44 ± 0.08[b]	3.01 ± 0.37[c]	0.41 ± 0.05[c]	0.77 ± 0.07[f]	15.74 ± 0.92[a]
2016	30.77[b]	5.33[c]	1.31 ± 0.12[b]	41.73 ± 2.00[c]	0.35 ± 0.07[a]	2.27 ± 0.35[b]	0.29 ± 0.06[b]	0.51 ± 0.09[b]	15.87 ± 0.86[a]
2017	30.25[a]	5.28[c]	1.90 ± 0.14[d]	40.38 ± 0.67[b]	0.32 ± 0.06[a]	2.15 ± 0.20[a]	0.31 ± 0.07[b]	0.56 ± 0.09[c]	18.74 ± 0.37[c]
2018	29.33[a]	5.06[c]	1.55 ± 0.13[c]	41.55 ± 2.20[c]	0.42 ± 0.03[b]	2.94 ± 0.46[c]	0.27 ± 0.04[a]	0.67 ± 0.08[d]	19.56 ± 0.74[d]
2019	31.84[c]	3.80[a]	1.37 ± 0.11[b]	41.84 ± 0.42[c]	0.46 ± 0.05[c]	3.22 ± 0.22[d]	0.62 ± 0.07[d]	0.70 ± 0.08[e]	18.17 ± 0.79[c]
2020	30.53[b]	5.60[d]	1.85 ± 0.07[d]	39.48 ± 1.03[b]	0.32 ± 0.21[a]	1.97 ± 0.36[a]	0.41 ± 0.05[c]	0.59 ± 0.06[c]	17.16 ± 1.83[b]
2021	29.10[a]	6.96[e]	1.43 ± 0.15[b]	41.03 ± 1.20[c]	0.37 ± 0.05[a]	2.12 ± 0.11[a]	0.37 ± 0.07[c]	0.72 ± 0.09[e]	18.78 ± 0.87[d]
2022	29.70[a]	4.49[b]	1.98 ± 0.34[e]	38.54 ± 1.09[a]	0.40 ± 0.07[b]	1.88 ± 0.13[a]	0.22 ± 0.03[a]	0.42 ± 0.08[a]	15.26 ± 0.79[a]
2023	31.40[c]	3.69[a]	1.62 ± 0.12[c]	41.38 ± 1.80[c]	0.35 ± 0.10[a]	2.34 ± 0.17[b]	0.29 ± 0.10[b]	0.64 ± 0.07[d]	18.00 ± 0.67[c]
2024	31.48[c]	4.00[a]	1.87 ± 0.17[d]	41.55 ± 1.88[c]	0.31 ± 0.08[a]	2.05 ± 0.24[a]	0.24 ± 0.08[a]	0.79 ± 0.09[f]	19.11 ± 0.96[d]

Note: Means sharing different lowercase letters differ significantly among treatments at level $p < 0.05$.

Taken together, these characteristics indicate that oilseed radish is especially suitable for use in soils prone to acidification, where lower decomposition and buffering effects are desirable.

The estimated accumulation of calcium through root residues, averaging 7.93 kg ha^{-1}, further supports this conclusion and highlights its contribution to soil chemical stabilisation. An equally important aspect of root mass quality is sulfur content, which is closely associated with glucosinolate components responsible for the biofumigation effect. These components play a key role in suppressing soil-borne pathogens, limiting weed germination, and reducing pest and nematode populations (Duff et al., 2020). While most biofumigation strategies traditionally focus on aboveground mass, the contribution of root residues remains insufficiently explored (Borpatragohain et al., 2019; Mocniak, 2023; Yan et al., 2023).

The present results indicate that sulfur and glucosinolate concentrations in root biomass are sufficiently high to ensure a pronounced biofumigation effect (Zachariah, 2011; Duff et al., 2020). Average sulfur content reached 0.65 ± 0.12% DM, while glucosinolate levels averaged 17.80 ± 1.75 μmol g^{-1} DM.

It is widely recognised that C/N ratios above 25 are indicative of slower decomposition rates of root-derived organic matter (Table 3). For most green manure crops, particularly legumes and cruciferous species incorporated at optimal growth stages, the C/N ratio of aboveground mass typically ranges between 18 and 23 (Carr et al., 2020; Li et al., 2024). In oilseed radish, however, even lower values have been reported for aboveground mass under spring sowing conditions. This contrast indicates a distinct asynchrony between the decomposition of shoot and root residues, with the latter remaining in the soil for a longer period. This decomposition pattern has important functional implications.

The prolonged transformation of root residues extends the phase of nutrient immobilisation, during which soil microbial communities actively utilize available nutrients (Diochon et al., 2016; Wang et al., 2016; Zhang & Li, 2020; Dorissant et al., 2022; Silva et al., 2023).

This process promotes the gradual formation of more stable organic components within the soil matrix and supports the development of rhizosphere biota, thereby contributing to improvements in soil quality. In comparison with other commonly used cruciferous green manure crops: white mustard and both spring and winter rapeseed (Kriaučiūnienė et al., 2012; Liu et al., 2022), oilseed radish demonstrated a more balanced relationship between aboveground and root mass in terms of C/N ratio. In these related species, the disparity between C/N values of shoots and roots is typically greater, whereas in oilseed radish it remains within a narrower and more favorable range. Specifically, the average C/N ratio of root mass in oilseed radish varied from 24.59 to 40.74, while in mustard and rapeseed it often exceeded these values over long-term observations (Liu et al., 2020; Israt & Parimal, 2023). Considering that the optimal C/N ratio for effective decomposition of green manure mass is generally reported to fall within the range of 25–30 (Nouri et al., 2022; Seres et al., 2022; Yang et al., 2022; Aboutayeb et al., 2023; Guinet et al., 2023), the root mass of oilseed radish may be considered advantageous from a technological perspective. This is associated with a more regulated decomposition rate, improved synchronization of nutrient release with plant demand, and enhanced formation of intermediate organic components within the soil system.

It was established that the enrichment of the soil profile, particularly the 10–30 cm layer, with fresh aboveground biomass and root residues characterized by a low C/N ratio and, consequently, rich in proteins, lipids, and carbohydrates, creates favorable conditions for the proliferation of pedotrophs, cellulolytic microorganisms, and nitrogen-fixing microorganisms (Lin et al., 2019). This finding is also supported by the low C/N ratio determined for oilseed radish biomass in our previous studies. Our previous research demonstrated that, under the use of oilseed radish as a green manure over a ten-year period, compared with the non-green-manured treatment, the abundance of pedotrophs increased by 35.17%, nitrogen-fixing microorganisms by 33.07%, and cellulolytic microorganisms by 39.38%. At the same time, the optimization of organic matter cycling in the soil created conditions for a 27.0% reduction in the abundance of oligotrophic microorganisms (Tsytsiura, 2025b, 2026b).

Table 3. Main biochemical characteristics of oilseed radish root mass as affected by sowing period, 2014–2024

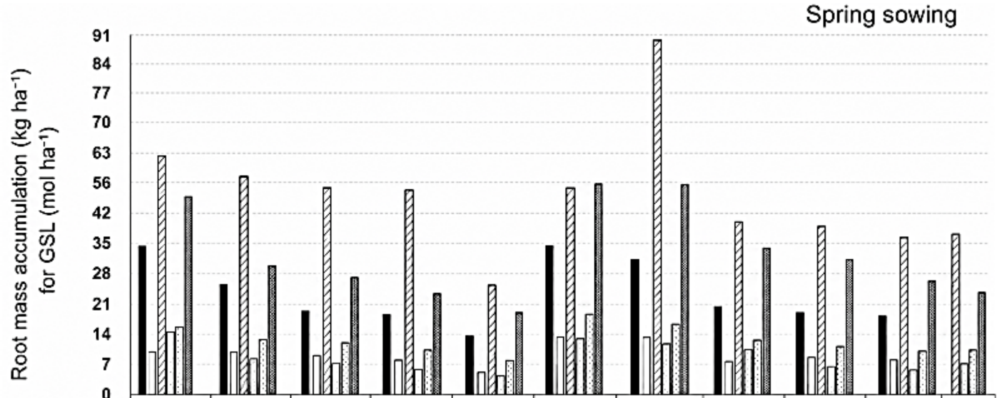
Year	C/N ratio		C/P ratio		C/S ratio	
	Spring*	Summer	Spring	Summer	Spring	Summer
2014	30.64 ± 2.11[c]	25.38 ± 4.47[c]	126.52 ± 11.70[f]	110.21 ± 5.78[c]	75.42 ± 9.37[d]	79.02 ± 5.80[e]
2015	28.69 ± 2.40[c]	40.74 ± 7.01[g]	92.59 ± 6.96[c]	95.36 ± 3.80[b]	62.68 ± 5.41[b]	54.49 ± 6.85[a]
2016	29.29 ± 1.96[c]	31.85 ± 1.38[f]	71.36 ± 3.90[a]	119.23 ± 8.08[d]	49.06 ± 8.51[a]	81.82 ± 9.54[e]
2017	24.59 ± 1.97[a]	21.25 ± 1.65[a]	66.63 ± 2.95[a]	126.19 ± 5.44[e]	46.42 ± 1.43[a]	72.11 ± 11.46[d]
2018	26.38 ± 6.59[b]	26.81 ± 3.74[d]	78.12 ± 2.63[b]	98.93 ± 2.45[b]	51.74 ± 10.16[a]	62.01 ± 9.35[b]
2019	33.12 ± 1.40[d]	30.54 ± 2.28[f]	101.14 ± 5.61[d]	90.96 ± 2.07[a]	69.30 ± 7.24[c]	59.77 ± 6.48[b]
2020	32.85 ± 5.38[d]	21.34 ± 1.10[a]	89.07 ± 5.21[c]	123.38 ± 30.61[e]	69.10 ± 12.30[c]	66.92 ± 6.46[c]
2021	36.52 ± 7.77[f]	28.69 ± 3.07[e]	132.24 ± 7.41[g]	110.89 ± 3.07[c]	61.85 ± 6.93[b]	56.99 ± 5.54[a]
2022	34.93 ± 2.50[e]	19.46 ± 3.35[a]	114.03 ± 7.13[e]	96.35 ± 5.59[b]	62.53 ± 9.18[b]	91.76 ± 19.10[f]
2023	33.85 ± 5.13[d]	25.54 ± 2.52[c]	100.70 ± 5.32[d]	118.23 ± 9.14[d]	74.59 ± 10.32[d]	64.66 ± 7.21[c]
2024	30.21 ± 3.39[c]	22.22 ± 3.55[b]	92.74 ± 8.12[c]	134.03 ± 5.89[f]	56.97 ± 8.56[b]	52.59 ± 8.59[a]

Year	KL/P ratio		KL/TKN ratio	
	Spring	Summer	Spring	Summer
2014	40.16 ± 3.64[e]	25.32 ± 3.59[b]	9.73 ± 0.78[a]	5.83 ± 1.02[b]
2015	32.59 ± 2.75[c]	23.20 ± 1.79[a]	10.10 ± 1.06[b]	9.91 ± 1.94[e]
2016	23.84 ± 1.51[a]	26.91 ± 2.49[c]	9.78 ± 0.78[a]	7.19 ± 0.79[d]
2017	25.45 ± 1.21[a]	28.31 ± 2.23[c]	9.39 ± 0.82[a]	4.77 ± 0.55[a]
2018	27.63 ± 0.91[b]	21.95 ± 0.70[a]	9.33 ± 2.36[a]	5.95 ± 0.77[b]
2019	32.14 ± 2.17[c]	21.91 ± 0.88[a]	10.52 ± 0.45[b]	7.36 ± 0.75[d]
2020	28.02 ± 1.67[b]	30.16 ± 11.95[d]	10.34 ± 2.21[b]	5.22 ± 0.31[a]
2021	43.03 ± 2.56[f]	26.46 ± 1.49[b]	11.89 ± 2.42[d]	6.85 ± 1.00[c]
2022	37.97 ± 3.77[d]	25.55 ± 2.32[b]	11.63 ± 0.66[d]	5.16 ± 1.15[a]
2023	31.93 ± 2.15[c]	27.97 ± 3.83[c]	10.73 ± 1.93[c]	6.04 ± 0.66[b]
2024	32.21 ± 2.98[c]	35.71 ± 2.19[e]	10.49 ± 1.27[b]	5.92 ± 1.09[b]

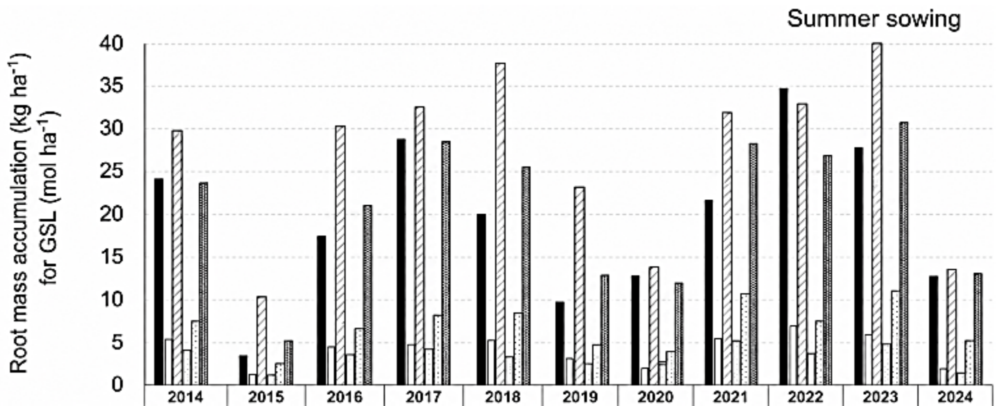
Note: *Spring, summer – date of sowing. ** Means sharing different lowercase letters differ significantly among treatments at level $p < 0.05$.

Beyond carbon-nitrogen relationships, the mineral composition of root mass further contributes to its agronomic significance. Across both sowing periods, oilseed radish roots contained appreciable levels of phosphorus, potassium, calcium, and sulfur, all of which play a key role in the restoration and maintenance of soil fertility (Table 3, Fig. 6).

The previous assessments demonstrated that the relatively high content of essential nutrients in oilseed radish root green-manure biomass contributes to a positive trend in the abundance of several functional groups of soil microorganisms. Over 10 years of systematic green manuring, the proportion of phosphate-mobilizing microorganisms increased by 29.81%, ammonifiers by 23.49%, amylolytic bacteria by 29.34%, and nitrifying microorganisms by 37.33% (Tsytsiura, 2025b).



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
N*	34.69^{b}	25.84^{c}	18.09^{c}	17.14^{c}	12.23^{a}	34.69^{b}	31.48^{f}	19.22^{d}	17.76^{c}	17.26^{c}	16.24^{b}
P	8.4^{e}	8.01^{d}	7.43^{d}	6.32^{c}	4.13^{a}	11.36^{f}	11.61^{f}	5.31^{b}	5.44^{b}	5.8^{b}	5.29^{b}
K	56.37^{e}	51.51^{d}	49.28^{d}	48.45^{d}	24.38^{a}	51.88^{e}	89.78^{f}	39.16^{c}	38.72^{c}	36.4^{b}	37.52^{b}
Ca	13.28^{f}	7.46^{c}	7.16^{c}	5.81^{b}	3.97^{a}	11.67^{e}	10.58^{d}	9.15^{d}	6.72^{c}	5.66^{b}	5.78^{b}
S	14.09^{e}	11.83^{d}	10.8^{d}	9.08^{b}	6.24^{a}	16.58^{f}	14.96^{e}	11.35^{d}	9.92^{c}	7.83^{b}	8.61^{b}
GSL	44.61^{f}	29.45^{e}	25.91^{d}	21.35^{b}	16.97^{a}	48.6^{g}	48.56^{f}	31.84^{e}	28.88^{d}	25.13^{d}	21.64^{b}



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
N	24.09^{d}	3.61^{a}	17.42^{d}	28.88^{g}	20.00^{e}	9.86^{b}	12.95^{c}	21.59^{d}	34.85^{h}	27.86^{g}	12.72^{c}
P	5.55^{d}	1.54^{a}	4.66^{c}	4.86^{c}	5.42^{d}	3.31^{b}	2.24^{a}	5.59^{d}	7.04^{e}	6.02^{d}	2.11^{a}
K	29.78^{e}	10.54^{a}	30.19^{d}	32.68^{e}	37.93^{f}	23.18^{c}	13.79^{b}	32.01^{f}	33.09^{f}	40.25^{g}	13.94^{b}
Ca	4.53^{c}	1.44^{a}	3.86^{b}	4.71^{c}	3.48^{b}	4.46^{c}	2.87^{a}	5.59^{c}	3.87^{b}	4.99^{c}	1.63^{a}
S	7.74^{c}	2.70^{a}	6.78^{c}	8.51^{d}	8.64^{d}	5.04^{b}	4.13^{b}	10.87^{e}	7.39^{c}	11.01^{e}	5.37^{b}
GSL	23.74^{c}	5.51^{a}	21.11^{c}	28.48^{e}	25.23^{d}	13.08^{b}	12.01^{b}	28.36^{e}	26.86^{d}	30.96^{f}	12.99^{b}

Figure 6. Accumulation of major nutrients in oilseed radish root biomass (kg ha^{-1}) and glucosinolates (mol ha^{-1}), 2014–2024.

*Means sharing different lowercase letters differ significantly among treatments at level $p < 0.05$.

Phosphorus, in particular, plays a key role in the transformation of organic matter following the incorporation of green manure into the soil. Its release and subsequent plant availability are determined not only by its concentration in the mass but also by the C/P ratio, which governs microbial immobilisation dynamics (Gu et al., 2023, 2024; Yang et al., 2024). Under typical soil conditions, elevated C/P ratios are generally associated with a temporary retention of phosphorus within the microbial mass pool (Rinasoa et al., 2022; Nguyen et al., 2024).

In combination with stable TOC levels, this resulted in C/P ratios ranging from 96.83 to 111.25, with peak values reaching 132.24. Such ratios suggest a tendency toward partial phosphorus immobilisation during the early stages of decomposition (Norberg & Aronsson, 2020; Hansen et al., 2021, 2022; Cavadini & Kladivko, 2025), followed by its gradual release, which may contribute to more sustained nutrient availability in the soil over time.

These values exceed commonly accepted thresholds for effective biofumigation, suggesting that root residues can serve as an additional in situ source of biologically active components on aboveground mass (Tsytsiura, 2022; 2024; 2025a; Tsytsiura & Sampietro, 2024). When combined with data on aboveground mass, the overall biofumigation potential of oilseed radish becomes even more evident. This corresponds to a biofumigation potential of 41.20 mol ha^{-1} (aboveground mass) and 31.17 mol ha^{-1} (root residues), totaling 72.37 mol ha^{-1} under spring sowing conditions. Under summer sowing conditions, the corresponding values were 54.90 and 20.76 mol ha^{-1}, respectively, totaling 75.66 mol ha^{-1}. These values fall within the effective range of 30–105 mol ha^{-1} for cruciferous green manure crops (Duff et al., 2020). Under more favorable spring conditions, accumulation was relatively higher in roots, whereas under summer stress conditions, a greater proportion was found in aboveground tissues. The ratio of aboveground to root glucosinolate content in oilseed radish was 0.75 under spring and 1.12 summer sowing conditions.

This indicated that under increased environmental stress (lower HTC, higher aridity), oilseed radish tended to accumulate sulfur-rich components more intensively in aboveground tissues. The increased synthesis of sulfur-rich glucosinolate components under stress conditions reflects an adaptive physiological response (Yi et al., 2016). This redistribution likely reflects an adaptive physiological response to environmental constraints.

Although the mechanisms governing glucosinolate redistribution between plant organs are not yet fully clarified (Blažević et al., 2020), the patterns observed in this study indicate a clear adaptive response. Under favorable spring conditions, the accumulation of these components is more strongly expressed in the root system. In contrast, under less favorable summer conditions, characterised by increased environmental stress and accelerated plant development, glucosinolate synthesis becomes more pronounced in aboveground tissues. Such a shift in the internal distribution of sulfur-rich components can be interpreted as a regulatory adjustment aimed at optimizing plant adaptation to changing environmental conditions. Similar tendencies have been documented in both wild and cultivated forms of radish (Malik et al., 2010; Park et al., 2022; Ben Ammar et al., 2023), confirming the consistency of this response across different genetic backgrounds and growing environments.

The ratio between carbon and sulfur (C/S) above 100 provided additional insight into decomposition processes. In the present study, root mass exhibited relatively low C/S values (61.79–67.47), compared to higher values observed in aboveground mass (90.52–99.83 (Tsytsiura, 2024)). This confirmed that root residues decompose more slowly, reinforcing earlier conclusions based on C/N and C/P ratios. Such multi-stage decomposition dynamics are beneficial for maintaining a prolonged release of nutrients in soil.

As a result, under conditions of unstable moisture and moderate soil fertility, oilseed radish contributed the following average nutrient inputs through root residues: nitrogen 22.24 kg ha^{-1} (max 34.69), phosphorus 7.19 kg ha^{-1} (max 11.61), potassium 41.59 kg ha^{-1} (max 89.79), calcium 7.93 kg ha^{-1} (max 13.28), and sulfur 11.03 kg ha^{-1} (max 16.58). Under summer sowing conditions, the corresponding values were lower but still significant. The results clearly indicate that oilseed radish functions as a dual-purpose green manure crop, ensuring the supply of nutrients from both aboveground and belowground mass. This is further supported by the distribution of mineral components, reflected in crude ash content. In root residues, ash values remained relatively low (6.86% DM under spring and 5.65% DM under summer sowing conditions) compared to aboveground mass, where they were substantially higher. The elevated C/N ratio of root mass contributes to lower decomposition, ensuring a more gradual and prolonged release of nutrients into the soil. Another important characteristic of root residues is their relatively high crude fat content, which varied from 1.86% DM ($Cv = 30.65\%$) under spring sowing conditions to 2.27% DM ($Cv = 14.98\%$) under summer sowing conditions. Although quantitatively modest, this fraction plays a specific functional role in decomposition processes. Lipid-derived components can influence microbial activity by stimulating particular metabolic pathways and modifying the overall dynamics of organic matter transformation. In addition, the presence of crude fat may enhance the biofumigation effect by limiting the mobility of glucosinolate degradation products, thereby prolonging their biological activity in soil. As a result, they contribute to the diversification and activation of soil microbiota (Shu et al., 2022). In addition, crude fat indirectly affects the biofumigation potential of green manure. By limiting the mobility of glucosinolate hydrolysis products – particularly isothiocyanates – it can prolong their persistence in the soil environment and enhance their biological activity (Duff et al., 2020; Abdel-Massih et al., 2023). This interaction suggests that lipid components play a supporting role in regulating the pathways of organic matter transformation and the expression of biofumigation effects in oilseed radish-based systems. Long-term evaluations of aboveground mass of oil seed radish (Tsytsiura, 2024) indicated that crude fat content remained consistently higher in shoots than in root tissues. Under spring sowing, its average level reached 3.98% DM, increasing to 4.91% DM under summer conditions. Accordingly, the ratio of crude fat between aboveground mass and root residues remained relatively stable, at approximately 2.14:1 in spring and 2.16:1 in summer. Such consistency suggests that the allocation of lipid components between plant organs is governed by a regulated physiological mechanism rather than random variation. This pattern appears to be maintained even under contrasting hydrothermal conditions, indicating a coordinated plant response to environmental stress. In particular, the parallel accumulation of lipids and stress-associated proteins reflects an integrated adaptive strategy aimed at maintaining metabolic stability. These observations were consistent with previously reported trends (Ahmad, 2017), where root systems generally contain lower concentrations of lipids compared to aboveground plant parts throughout different stages of development. Together, these findings support the view that lipid distribution in oilseed radish was both functionally structured and environmentally responsive.

An essential criterion in assessing the green manure value of root residues is the composition of structural carbohydrates, particularly crude fibre and its associated fractions, including cellulose, hemicellulose, neutral detergent fibre (NDF), acid detergent fibre (ADF), and Klason lignin. These components largely govern both the rate and temporal pattern of mass mineralisation in soil. The content of crude fibre and cellulose exceeded 30% of dry matter, indicating a tendency towards slower and more prolonged decomposition in soil. In contrast, aboveground mass contained lower proportions of these components (approximately 21–24% DM), resulting in differences in the rate and synchrony of organic matter transformation between plant fractions. The decomposition of fibre-rich material is closely linked to soil biological activity and is often accompanied by increased CO_2 emissions, reflecting intensified microbial metabolism (Vahdat et al., 2011; Lu et al., 2019; Sousa et al., 2019; Salume et al., 2020; Shu et al., 2022; Wang et al., 2022). The overall content of structural carbohydrates and the level of tissue lignification act as key regulators of decomposition duration, determining how long organic residues persist in the soil environment (Haddad et al., 2023; Rumi et al., 2024; Zhang et al., 2023a). When the content of crude fibre and cellulose exceeds approximately 30% of dry matter, decomposition typically follows a two-phase pattern. The initial phase involves relatively rapid mass loss due to the breakdown of more labile fractions, while the subsequent phase is characterised by slower degradation of structurally complex components. Under such conditions, total mass reduction may reach 60–80% over a period of 70–100 days, depending on hydrothermal conditions (Datta et al., 2024). Importantly, this type of decomposition not only prolongs the presence of organic residues in soil but also promotes the development and activity of microbial communities responsible for organic matter transformation. As a result, structural carbohydrates play a dual role, simultaneously regulating the tempo of mineralisation and enhancing the biological functioning of the soil system (Tosi et al., 2022; Rezende et al., 2023). In the present study, root mass of oilseed radish under both sowing periods was characterised by a pronounced dominance of structural carbohydrates, with crude fibre and cellulose contents consistently exceeding the 30% DM threshold. Under spring sowing, average values reached 48.61% DM for crude fibre and 38.06% DM for cellulose (Cv = 8.90% and 8.62%), whereas under summer conditions these indicators decreased to 36.79% DM and 30.75% DM (Cv = 5.70% and 15.32%), respectively. Such levels indicate a tendency toward slower mineralisation, particularly within the central root fractions distributed in the soil profile. By contrast, aboveground mass contained substantially lower amounts of these components, with crude fibre and cellulose remaining within the range of approximately 21–24% DM across both sowing periods (Tsytsiura, 2024). This contrast reflects clear differentiation in decomposition dynamics between plant fractions. Based on the proportional relationships between crude fibre and cellulose in shoots and roots (1:0.43–0.45 in spring sowing and 1:0.62–0.67 in summer sowing), it can be inferred that root-derived mass decomposes approximately 1.3–1.7 times more slowly than aboveground residues.

Additional insight is provided by the distribution of carbohydrate fractions within the mass. In root tissues, the relative proportion of hemicellulose to cellulose remained low (1:0.086 in spring sowing and 1:0.153 in summer sowing), whereas in aboveground mass this ratio was markedly higher (1:0.504 and 1:0.526, respectively). This structural difference suggests that root residues contain a greater share of more recalcitrant components, which slow down decomposition processes. As a result, the breakdown of root mass follows a sequential pattern. The initial phase is associated with the rapid degradation of more labile fractions, particularly hemicellulose, while the subsequent phase is dominated by the gradual decomposition of cellulose-rich components (López-Mondéjar et al., 2016; Chang et al., 2024). In contrast, aboveground mass, characterised by a higher proportion of easily degradable components, undergoes more rapid mineralisation.

Further evidence for this pattern is provided by the close correspondence between NDF and ADF fractions in root tissues (1:1.07 in spring sowing and 1:1.12 in summer sowing), where their ratio approached unity and both exceeded 40% DM. Such a structural configuration is known (Liu et al., 2020; Seres et al., 2022; Wang et al., 2022; Dorissant et al., 2022) to support a multi-stage decomposition process, beginning with an intensive phase lasting approximately 20–30 days under favorable hydrothermal conditions, followed by a progressive slow down governed by the more resistant ADF fraction.

Previous studies (Frei, 2013; Shu et al., 2022) have shown that the presence of lignified structures in plant tissues fundamentally alters decomposition pathways. When lignin content – expressed as acid detergent lignin or, in this case, Klason lignin – is sufficiently high, mass breakdown tends to proceed via a so-called skeletonization mechanism. This process is characterised by the rapid loss of non-lignified fractions, while more resistant, lignin-associated structural components persist and are decomposed at later stages.

The results obtained in this study indicate that oilseed radish root residues fall within the category of relatively highly lignified plant materials (according to the classification of lignin content in plant mass (Frei, 2013)). Average Klason lignin content reached 13.30% DM under spring sowing and 9.83% DM under summer sowing, with comparatively low interannual variability (Cv = 8.42% and 5.70%, respectively). These values suggest substantial structural stabilisation within root tissues. Given that the thickened taproot represents the dominant fraction of total root mass, these findings imply that its decomposition is largely governed by skeletonization processes (Fig. 7). In practical terms, this indicates that while more labile components are mineralized relatively quickly, the lignified structural framework remains in the soil for an extended period, contributing to longer-term organic matter accumulation and stabilisation.

At the early stage following application (10 days; Fig. 7, a–c), initial signs of decomposition were observed, primarily associated with the breakdown of labile organic components and hemicellulosic fractions. This phase was accompanied by visible changes in root color and the appearance of characteristic signs of tissue sloughing and decay. At this stage, initial differentiation of root structures into phloem and xylem components became apparent. The first indications of structural differentiation between phloem and xylem tissues became evident. After 30 days (Fig. 7, d–f), the root system exhibited more pronounced structural modification. Decomposition was mainly localized in the outer layers, while the internal structure remained comparatively intact. A clear contrast developed between the central, less dense (amorphous) region and the more compact peripheral tissues, reflecting the uneven progression of degradation processes. At the intermediate stage (50 days; Fig. 7, g–i), decomposition intensified, leading to fragmentation of both external and internal structures. This phase was characterised by a distinct darkening of root tissues – from gray to nearly black – and the onset of mechanical disintegration of xylem elements, indicating the transition toward more advanced stages of structural breakdown. Further development of the decomposition process is illustrated in Fig. 7, j–o (70 days), where progressive skeletal fragmentation can be observed. This stage involves the separation of lignified structural elements and the gradual transformation of root tissues into amorphous aggregates composed of resistant cellulose-lignin complexes. Such transformations reflect the dominance of skeletonization processes during the later stages of root residue decomposition. Taking into account the identified features of decomposition of the taproot component of the oilseed radish root system, it was observed that within 20–40 days after incorporation – depending on soil temperature and moisture conditions – the overall morphological integrity of the root was largely preserved. Intensive degradation of its internal anatomical structures occurred (Fig. 7, q), indicating a heterogeneous pattern of decomposition among different tissue types.

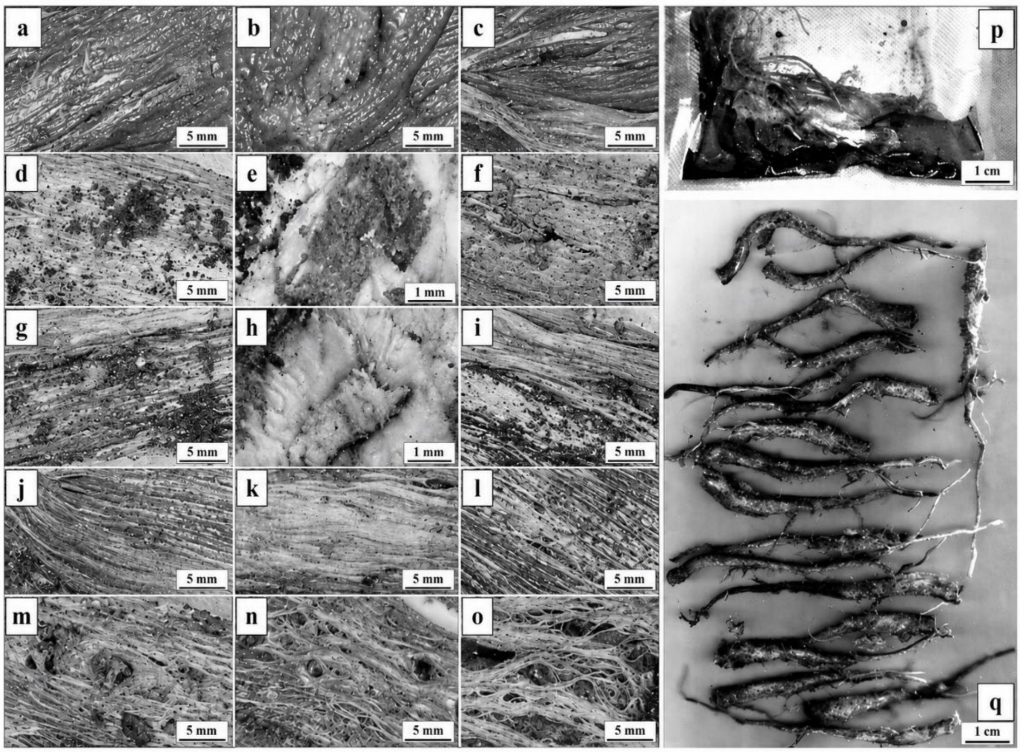


Figure 7. Decomposition dynamics of the central (core) root structures of oilseed radish in soil under spring sowing conditions (incorporation in mid-June), 2024.

Note: figure annotations are described in the text.

During the same period, roots of lateral branches of the 2nd–4th orders underwent significantly more rapid transformation, reaching complete decomposition with the formation of amorphous organic matter, including remnants of outer tissues. This process was confirmed under controlled laboratory conditions using the litter-bag method (Fig. 7, p), which allowed for a more detailed assessment of the decomposition dynamics of individual root fractions.

The observed patterns of anatomical transformation in the taproot are consistent with its biochemical composition and provide a basis for a more precise interpretation of organic matter turnover processes within the soil profile. Additional support for these findings was obtained through the analysis of two key indicators commonly used to evaluate plant residue decomposition: the KL/TKN and KL/P ratios. It is well established (Stewart et al., 2015; Lin et al., 2019; Hall et al., 2020; Bonanomi et al., 2021; Rieznik et al., 2021) that lower values of these ratios are associated with higher decomposition intensity. The results are consistent with the previously identified relationships involving C/N and C/P ratios, confirming the critical role of the balance between structural components and nutrient elements in regulating the decomposition rate of oilseed radish root residues. Previous studies indicate that the most intensive decomposition of plant residues occurs when the KL/TKN ratio is within the range of approximately 3–4 (Stewart et al., 2015). Similarly, for the KL/P ratio, the highest rates of mass mineralisation are typically observed at values below 15 (Diochon et al., 2016). The corresponding ratios for oilseed radish root residues were consistently higher. Under spring sowing conditions, the KL/TKN ratio averaged 10.36 (Cv = 8.02%), while under summer sowing conditions it decreased to 6.38 (Cv = 22.41%). For the KL/P ratio, the respective values were 32.27 (Cv = 2.91%) and 26.68 (Cv = 11.67%) (Table 3). These values indicate that the decomposition of oilseed radish root mass under green manure conditions proceeds at a moderate intensity and follows a clearly expressed multi-stage pattern of mineralisation within the soil profile. Comparative analysis of these ratios suggests that, under similar hydrothermal conditions, root mass formed during summer sowing may decompose more efficiently due to relatively lower KL/TKN and KL/P values. These observations are consistent with previously reported trends for cruciferous crop residues (Askew et al., 2019; Liu et al., 2020; Wang et al., 2022), where decomposition rates are strongly influenced by the balance between lignin content and nutrient availability. Analysis of interannual variability (CV), together with the statistical significance of the year factor and its interaction with sowing time in the analysis of variance (Fig. 8), further demonstrated that the studied indicators were markedly affected by hydrothermal conditions during the growing season preceding green-manure biomass incorporation. The two-way ANOVA results show that sowing time, year, and their interaction had significant effects on most of the biochemical and structural characteristics of oilseed radish root biomass. The statistical significance is expressed as $-log_{10}(P)$, with asterisks indicating the corresponding significance levels.

The sowing time effect was particularly pronounced for ADF, cellulose, KL, KL/P ratio, and NDF, indicating that the structural and carbohydrate composition of the root biomass was strongly influenced by the conditions under which the crop was established. Significant effects of sowing time were also observed for CF, CFb, CP, CA, TKN, TOC, and the C/N, C/P, and C/S ratios.

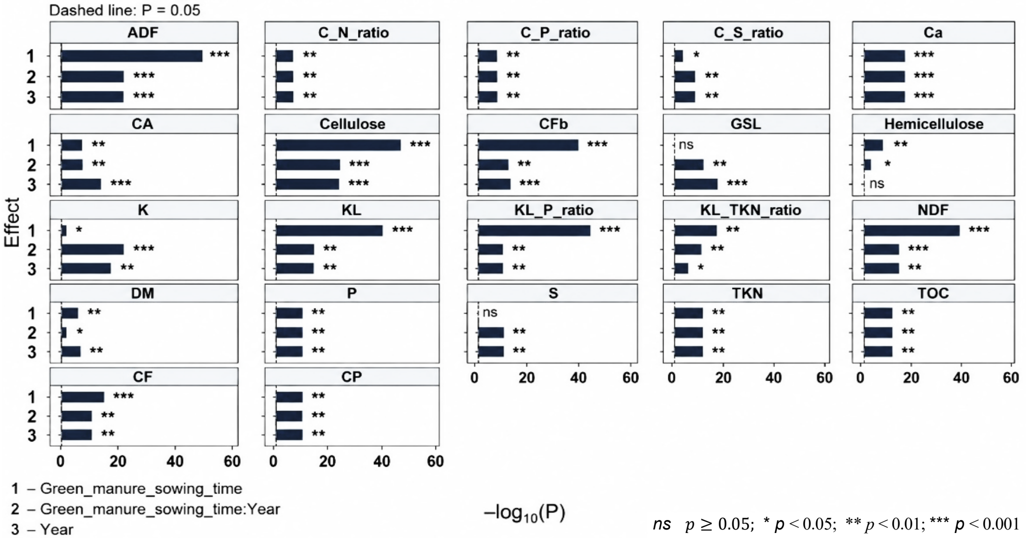


Figure 8. Statistical significance of ANOVA effects in the factorial experimental design, 2014–2024.

The year of assessment had a significant effect on almost all of the variables examined. The strongest year-related effects were observed for ADF, cellulose, KL, NDF, and several nutrient ratios, indicating considerable year-to-year variation in the formation and biochemical composition of the root biomass.

The sowing time × year interaction was also significant for most variables. This indicates that the effect of sowing time was not constant across the study period but varied between years. This interaction was particularly evident for structural components of the root biomass, mineral elements, and their respective ratios.

Some variables showed a weaker response to sowing time. In particular, the effect of sowing time on GSL and S was not statistically significant (*ns*), although the year and/or interaction effects remained significant. Hemicellulose also showed a weaker differentiation among the effects of the factors considered.

Overall, the results indicate that both year and sowing time were important determinants of variation in the biochemical composition of oilseed radish root biomass, while the significant interaction between these factors demonstrates that their effects cannot be considered independently. Therefore, assessment of the green-manure value of the root biomass should consider not only the average effect of sowing time but also year-to-year variability and the specific response of individual biochemical characteristics to growing-season conditions.

This relationship was further supported by correlation analysis, the results of which are summarized in Fig. 9.

An integrated assessment based on the coefficient of determination (d_{xy}) together with the cumulative magnitude of correlation coefficients (expressed as the correlation graph, G) made it possible to differentiate the relative influence of hydrothermal variables on the biochemical profile of oilseed radish root residues. The factors formed a consistent gradient of increasing influence: air humidity (G = 3.84), followed by HTC (G = 5.72), I_{DM} (G = 5.97), K_h (G = 6.40), average daily temperature (G = 7.64), and, finally, precipitation (G = 8.35), which exhibited the strongest overall effect. Within this hierarchy, precipitation emerged as the key environmental regulator shaping the biochemical composition of root mass. Its impact was manifested not only directly, but also indirectly through its contribution to derived hydrothermal indices such as HTC, I_{DM}, and K_h.

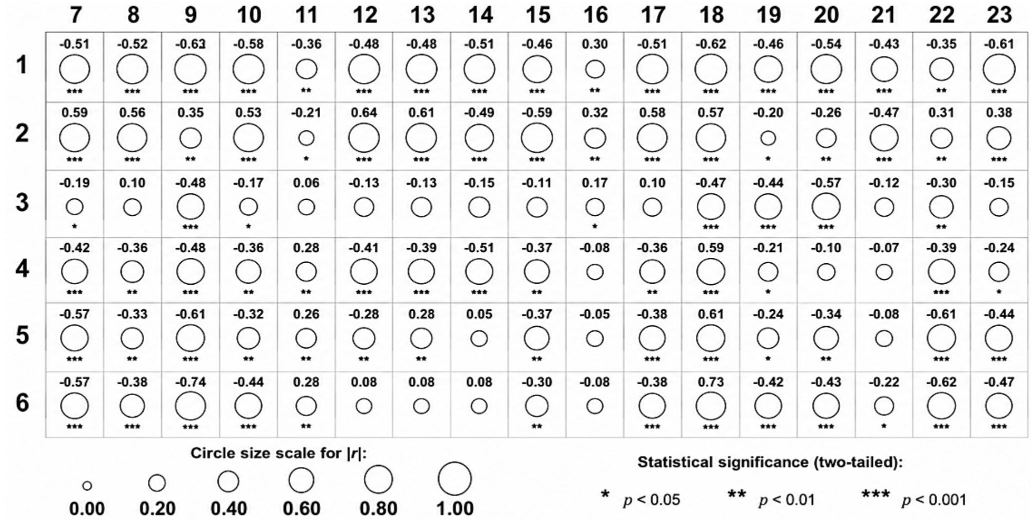


Figure 9. Pearson's correlation coefficients between oilseed radish root green manure value parameters and weather conditions (pooled dataset including sowing dates, replicates, and years for $N = 88$ ($df = 86$)), 2014–2024.

Note: *cp – correlation pairs. Correlation strength was interpreted as follows: $|r| < 0.4$ – weak or no correlation; $0.4 \leq |r| < 0.7$ – moderate correlation; $|r| \geq 0.7$ – strong correlation. Variables: (1) precipitation (mm); (2) average daily temperature (°C); (3) air humidity (%); (4) hydrothermal coefficient (HTC); (5) De Martonne aridity index (I_{DM}); (6) Vysotsky–Ivanov moisture coefficient (K_h); (7) dry matter; (8) crude protein; (9) crude fat; (10) crude fibre; (11) crude ash; (12) neutral detergent fibre; (13) acid detergent fibre; (14) Klason lignin; (15) cellulose; (16) hemicellulose; (17) total nitrogen; (18) total organic carbon; (19) phosphorus; (20) potassium; (21) calcium; (22) sulfur; (23) glucosinolates (μmol g^{-1} DM). Parametrs 7–22 in % DM.

The analysis revealed that most associations between precipitation and the major biochemical constituents were negative, indicating a suppressive effect of increasing moisture on their accumulation. On average, these relationships corresponded to a determination level of 25.3%. The most pronounced inverse dependencies were observed for crude fat (CF; d_{xy} = 39.70%), total organic carbon (TOC; d_{xy} = 38.44%), and glucosinolate content (GSL; d_{xy} = 37.21%). In contrast, hemicellulose represented the only component showing a positive response to increased precipitation, although the strength of this relationship remained relatively low (d_{xy} = 9.00%).

An increase in mean daily air temperature was accompanied by a noticeable rise in the concentration of several biochemical components in oilseed radish root residues, particularly crude protein, crude fat, and crude fibre. The strength of these associations, as reflected by coefficients of determination, varied from 12.25% to 31.36%. Similar tendencies were recorded for hemicellulose, total organic carbon, and total nitrogen, suggesting that warmer conditions favor the accumulation of both metabolically active and structural organic substances. Conversely, elevated temperatures were associated with a decline in cellulose-related fractions, including neutral detergent fibre (NDF), acid detergent fibre (ADF), and Klason lignin, with determination coefficients varying between 24.01% and 40.96%. A comparable negative trend was observed for mineral elements, as the contents of phosphorus, potassium, and calcium decreased with rising temperature, although these relationships were relatively moderate in strength (4–18%).

When the combined influence of hydrothermal conditions prior to mass incorporation was considered across both sowing periods, more favorable moisture–temperature regimes were generally linked to a reduction in the overall biochemical potential of root residues. This effect can be explained by the predominance of inverse relationships affecting both organic fractions and mineral constituents, as well as glucosinolate content. Among the hydrothermal indicators evaluated, the moisture coefficient (K_h) demonstrated the highest explanatory power, exceeding the predictive capacity of HTC and I_{DM} by approximately 18% on average. This indicates that K_h serves as a more robust integrative parameter for assessing the biochemical potential of green manure mass under variable environmental conditions.

The patterns observed are consistent with earlier findings (Adu, 2014; Tiemann et al., 2015; Hu et al., 2018; dos Santos Nascimento et al., 2021; Ben Ammar, 2023), which demonstrated that the formation of biochemical composition differs fundamentally between aboveground and belowground plant organs. Such differentiation is largely associated with the buffering capacity of the soil profile, which moderates the impact of external environmental factors.

As a result, the biochemical properties of root residues are determined not only by atmospheric conditions, including temperature and moisture, but also by soil-related processes such as heat transfer and water redistribution, which together influence the final composition of root-derived organic matter. Furthermore, the observed decrease in the concentration of both organic and mineral components in root mass under conditions of increased precipitation and more favorable temperature regimes may be attributed to physiological adjustments of the root system to enhanced moisture availability. In such environments, intensified water uptake leads to a dilution of cellular contents, thereby reducing the proportion of dry matter and, consequently, lowering the concentration of essential biochemical constituents. This interpretation is further supported by earlier findings (Poorter et al., 2012; Maan et al., 2023) demonstrating that root tissues typically retain higher water content than aboveground plant parts under adequate moisture supply. Such allocation patterns contribute to maintaining active growth processes in the aerial mass, while simultaneously modifying the biochemical density of root residues.

The observed trends were further corroborated by regression analysis (Table 5), which enabled a more detailed evaluation of the joint influence of major hydrothermal factors. The analysis showed that the interaction between precipitation and mean daily air temperature significantly affected the key biochemical ratios used for characterizing green manure quality. Multiple correlation analysis ($p < 0.01$) showed that concurrent increases in moisture availability and temperature were associated with a decrease in the C/N ratio of root mass, with an adjusted coefficient of determination of 38.44%. A similar pattern emerged when hydrothermal conditions were described using composite indices. In particular, lower I_{DM} values in combination with higher K_h were linked to a reduction in the same ratio (dxy = 27.04%). Consistent relationships were also identified for the C/P and C/S ratios, with determination coefficients ranging from 28.09% to 43.56%, confirming the sensitivity of these integrative biochemical indicators to fluctuations in temperature and moisture regimes. According to the regression models, the accumulation of total glucosinolates (GSL) in root residues tended to increase under conditions of limited precipitation combined with higher average daily temperatures, with a coefficient of determination of 32.49%.

Table 5. Results of regression analysis describing the dependence of oilseed radish root residue biochemical characteristics on hydrothermal conditions of the growing season (2014–2024, averaged data)

Ratio parameters	Regression equation	Model coefficients		Statistical evaluation				
		x	*y*	Multiple *R*	Adjusted R^2	*F-value*	*df* (1, 2)	*p-value*
C/N	$59.023-0.190x-0.500y$	Precipitation (mm)	Average daily temperature (°C)	0.72	0.62	7.47	2.19	< 0.01
C/P	$104.537-0.108x-0.329y$			0.67	0.53	3.69	2.19	< 0.05
C/S	$51.256-0.09x+0.676y$			0.79	0.66	8.59	2.19	< 0.01
KL/TKN	$25.337-0.170x-0.670y$			0.78	0.66	9.06	2.19	< 0.01
KL/P	$39.620+0.0240x-0.250y$			0.59	0.43	2.90	2.19	< 0.05
GSL	$19.034-0.047x+0.150y$			0.71	0.57	4.86	2.19	< 0.01
C/N	$26.856+0.023x-0.109y$	I_{DM}	K_h	0.66	0.52	3.19	2.19	< 0.05
C/P	$93.802-0.053x+0.733y$			0.71	0.60	7.32	2.19	< 0.01
C/S	$48.897-0.03x+0.340y$			0.72	0.62	7.78	2.19	< 0.01
KL/TKN	$6.511-0.092x-0.155y$			0.62	0.53	4.93	2.19	< 0.01
KL/P	$21.964-0.140x+0.641y$			0.64	0.50	3.30	2.19	< 0.05
GSL	$18.943-0.010x+0.270y$			0.68	0.51	4.54	2.19	< 0.01

Structural components associated with lignin (quantified as Klason lignin, KL) exhibited a distinct pattern when analysed in relation to nutrient elements. Specifically, the ratios of KL to nitrogen and phosphorus decreased under conditions characterised by higher moisture availability and elevated temperatures.

In contrast, under reduced precipitation combined with increased thermal input, the decline was more pronounced primarily in relation to phosphorus content. The strength of these relationships, expressed through coefficients of determination, varied within the range of 18.49% to 43.56%. These observations were additionally validated through regression modelling incorporating hydrothermal indices (I_{DM} and K_h), which confirmed the statistical significance of the identified relationships at the level of $p < 0.01$.

CONCLUSIONS

A prolonged assessment of oilseed radish root residues as an additional component of green manure confirmed their considerable agronomic relevance under both spring and summer sowing regimes. Dry matter productivity reached 3.06 t ha^{-1} under spring sowing conditions and 2.71 t ha^{-1} under summer sowing conditions. The biochemical profile of the residues, together with key stoichiometric ratios (C/N, C/P, C/S, KL/TKN, KL/P) that regulate decomposition dynamics in soil, indicates that this type of mass belongs to a category characterised by relatively slow mineralisation and a prolonged release of nutrients. When considered as a source of bioorganic inputs, root residues obtained under spring sowing conditions were capable of supplying the soil with up to approximately 34.7 kg ha^{-1} of nitrogen, 11.6 kg ha^{-1} of phosphorus, 89.8 kg ha^{-1} of potassium, 11.7 kg ha^{-1} of calcium, and 16.6 kg ha^{-1} of sulfur, while also exhibiting a biofumigation capacity of up to 48.6 mol ha^{-1}. Under summer sowing conditions, the fertilising potential of the root mass was notably reduced, being on average 34.73% lower compared to the spring variant.

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