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# Development of an integrated soil quality index under prolonged green manure application of oilseed radish in crop rotation

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**Abstract.** Over a 12-year study period, the effectiveness of using intermediate green manuring with oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) – applied once every two years – was evaluated under conditions of repeated application in the same field within a crop rotation system (including green manuring of crops such as grain sorghum (*Sorghum bicolo*r L.), pea (*Pisum sativum* L.), soybean (*Glycine max* (L.) Merrill), sunflower (*Helianthus annuus* L.), chickpea (*Cicer arietinum* L.) and maize (*Zea mays* L.), with three assessment checkpoints in 2014, 2019, and 2025.
The results showed that the green-manured treatment, averaged across the entire evaluation period, produced positive changes in the physical and chemical soil fertility parameters within the 0–30 cm soil layer compared with the unfertilized control. Increases were observed in humus content (by 24.65%), water absorption capacity (by 30.04%), easily hydrolyzable nitrogen (by 33.67%), available phosphorus (by 25.72%), exchangeable potassium (by 23.10%), and total porosity (by 25.04%). Decreases were recorded in bulk density (by 19.05%), particle density (by 9.95%), soil hardness (by 33.95%), and pH (by 5.60%).
Green manuring also contributed to optimizing the proportion of humic acids in the humus structure by a factor of 1.2 and to achieving a total organic carbon to total nitrogen ratio of 10.36:1, representing an 11.92% increase compared with the control. As a result, the application of green manuring was reflected in an improved integrated Soil Fertility Index, with a value of 0.692 compared with 0.499 in the non-manured control.

**Key words:** agro-physical soil properties, agrochemical soil properties, soil fertility, fertilization, soil conservation.

## INTRODUCTION

Green manuring in modern agrotechnological practice is regarded as an effective and versatile option for the bio-organic fertilization of cultivated crops. It essentially replicates the natural processes of organic matter cycling within the closed loops of biogeocenoses (Kaletnik & Lutkovska, 2020; Lutkovska & Kaletnik, 2020; Deus et al., 2022), aligning with the core principles of organic-oriented agro-industrial production and soil resource management outlined in the European Green Deal ('Green Deal') (Tokarchuk et al., 2024).

The nature of this process creates real opportunities for restoring and optimizing the natural dynamics of mineralization-humification balance within the soil profile (Das et al., 2020; Lei et al., 2022; Butenko et al., 2025), and under certain conditions and timeframes, promotes the gradual dominance of humification processes (Lee et al., 2023). Given that the green manure biomass of most crops – owing to its low C/N ratio at the typical application stage (flowering phase) – undergoes rapid hydrolysis and, under favorable temperature and moisture conditions, quick mineralization (Meena et al., 2018; Ansari et al., 2022a, 2022b), green manure fertilization practices are characterized by a substantial increase in the content of labile forms of organic matter. This, in turn, positively influences a wide range of soil indicators and properties (Israt & Parimal, 2023; Singh et al., 2023). It has been demonstrated that the positive effects of green manures are not limited to a single growing season but may persist for 2–5 years or even longer (Yadav et al., 2021; Bulgakov et al., 2023; Tsytsiura, 2023). It has also been confirmed that green manure biomass – being a valuable source of macro- and microelements, active biological components, and complex organic compounds – positively influences the soil nutrient regime (Bhogal et al., 2010; Natera et al., 2022; Butenko et al., 2025). These conclusions are further supported by studies assessing the effectiveness of green manure fertilization in comparison with widely used mineral fertilization systems across various intensities and different soil–climatic zones of the world (Sushanta et al., 2020; Ozlu et al., 2022; Indoria et al., 2025). At the same time, researchers emphasize that the overall effectiveness of green manuring largely depends on the proper selection of plant species and the timing of their incorporation (Clark, 2008). The substantial diversity among green manure crops (Green Manure Global Market Report 2024) requires their selection to be tailored to specific soil-climatic zones and even particular soil types, depending on fertility potential. Such selection should be based on evaluating the efficacy of applied green biomass in terms of its impact on nutrient balance, humus formation processes, and the resulting optimization of fertility potential across different soil property groups.

These considerations are particularly relevant for cruciferous green manure species, which dominate global agricultural practice in both monoculture and multi-species applications (Jabnoun-Khiareddine et al., 2016; Li et al., 2019; Lövgren, 2022).

In view of the above, it is relevant to investigate the long-term effectiveness of a specific green manure species in terms of its influence on a complex of soil properties in soils with medium fertility potential under conditions of unstable moisture. This corresponds well with the agricultural characteristics of most farmlands worldwide (Kopittke et al., 2019). Oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) is considered a promising candidate in this regard and is increasingly used in bio-organic fertilization systems. It possesses a favorable set of adaptive mechanisms that enable the formation of high green manuring potential in regions with adequate or unstable moisture. These include broad adaptability to abiotic environmental factors, rapid growth that allows reaching the green manure stage within 35–50 days, intensive development with deep root system penetration, and a high biochemical value of both aboveground and root biomass-comparable to classical green manure crops such as white mustard, rapeseed, charlock, and lupine (Tsytsiura (2020); Tsytsiura (2024a–2024d); Tsytsiura (2025a, 2025b)).

On the other hand, oilseed radish remains insufficiently studied with regard to its long-term and sustainable use as a green manure crop within field crop rotations involving diverse agricultural species. The aim of this study was to evaluate the efficiency and feasibility of the long-term use of oilseed radish as a summer green manure crop in crop rotation, with a focus on its effects on the development of agrochemical, agrophysical, and selected hydrological soil properties within the 0–30 cm layer, as well as on the resulting integral soil quality index.

The aim of the study was to evaluate the efficiency and feasibility of the long-term use of oilseed radish as a summer green manure crop within a crop rotation system, with a focus on its influence on the development of agrochemical, agrophysical, and selected water-related soil properties within the 0–30 cm layer, and on determining the resulting integral soil quality index.

## MATERIALS AND METHODS

The research was conducted from 2014 to 2025 at the experimental field of Vinnytsia National Agrarian University (coordinates: 49°11′31″ N, 28°22′16″ E) on grey forest soils, classified as Greyi-Luvic Phaeozems (Phaeozems Albic, Dark Gray Podzolic Soils) under WRB (IUSS Working Group WRB, 2015) and Haplic Greyzems under FAO (IUSS, 2015) –with silt loam texture. Baseline fertility indicators of the 0–30 cm soil layer at trial initiation were: humus content 2.68 %; available hydrolyzable nitrogen 81.5 mg $kg^{-1}$; extractable phosphorus 176.1 mg $kg^{-1}$; exchangeable potassium 110.8 mg $kg^{-1}$; and soil acidity $pH_{(KCl)}$ 5.8.

This experiment was part of a wider investigation into the effectiveness and suitability of oilseed radish for multi-timing siting in green manure systems (Tsytsiura, 2024b). The design compared two successive treatments: a control without green manure and a treatment with intermediate summer oilseed radish green manure, applied biennially to avoid phytotoxic buildup associated with cruciferous green manures, following recommendations from Zachariah (2011) and Duff et al. (2020). Both treatments were integrated into a crop rotation (Table 1).

The complete absence of mineral fertilizers in both studied variants (the control and the green manure treatment) was intended to isolate and evaluate the role of green manuring in maintaining soil fertility parameters relative to a zero-fertilization baseline.

Experimental plots were set up in four replicates for each variant. The recorded area of each plot was 25 m².

**Crop and green manure treatment.** The oilseed radish variety ‘Zhuravka’ was sown as a green manure crop at a rate of 2.5 million viable seeds per hectare with a row spacing of 15 cm. Sowing was performed immediately after harvesting the preceding crop using intermediate tillage (flat-cutter cultivation followed by rotary loosening with leveling) to a depth of 12–16 cm. The radish was incorporated at the flowering stage (BBCH 64–67) (according to Test Guidelines…, 2017), which is considered the optimal green manure phase (Kemper, 2024), typically occurring in the second to third ten-day period of October. The plants were mown and chopped using an FX-315 rotary mower-shredder (Canada) and then incorporated with heavy disc harrows (BDN-2.4) equipped with variable attack angles (similar to Lemken Rubin technology, Germany) to a depth of 14–16 cm. Post-incorporation tillage depth varied depending on the zone and subsequent crop, with a multi-year average tillage depth of 22.55 ± 6.31 cm.

**Table 1.** General Experimental Scheme

| Intensity of green manure application (factor A) | Soil layer, cm (factor B) | The content of the treatments by factor A |
|---|---|---|
| Absolute control (initial soil parameters) | 0–10<br>10–20<br>20–30 | The initial agrochemical and agrophysical properties of the soil were determined based on the results of soil sample analyses conducted at the beginning of the experiment (the assessment date and baseline data correspond to the year 2014). |
| Control I (5 years of crop rotation without green manuring and fertilizers) | 0–10<br>10–20<br>20–30 | The block of agrochemical and agrophysical soil properties formed in 2019 (based on the results of soil sample analyses) after a five-year rotation cycle without the use of green manure or mineral fertilizers (rotation scheme: grain sorghum (*Sorghum bicolor* L.) – spring barley (*Hordeum vulgare* L.) – pea (*Pisum sativum* L.) – spring barley (*Hordeum vulgare* L.) – soybean (*Glycine max* (L.) Merrill). |
| Green manure application I (5 years of crop rotation with three-time green manuring) | 0–10<br>10–20<br>20–30 | The block of agrochemical and agrophysical soil properties formed in 2019 (based on the results of soil sample analyses) after a five-year rotation cycle with the use of intermediate green manuring with oilseed radish (*Raphanus sativus* L. var. *oleiformi*s Pers.) (applied once every two years, rotation scheme identical to the Control I variant) under the following crops in the crop rotation: grain sorghum (*Sorghum bicolor* L.) – pea (*Pisum sativum* L.) – soybean (*Glycine max* (L.) Merrill). |
| Control II (11 years of crop rotation without green manuring and fertilizers) | 0–10<br>10–20<br>20–30 | The block of agrochemical and agrophysical soil properties formed in 2025 (based on the results of soil sample analyses) on the plots without the use of green manuring and mineral fertilizers after an eleven-year rotation cycle according to the following scheme: sorghum (*Sorghum bicolor* L.) – spring barley (*Hordeum vulgare* L.) – pea (*Pisum sativum* L.) – spring barley (*Hordeum vulgare* L.) – soybean (*Glycine max* (L.) Merrill) – spring wheat (*Triticum vulgare* Host.) – sunflower (*Helianthus annuus* L.) – winter pea (*Pisum sativum* L. (s. *amplissima*) Gov.) – chickpea (*Cicer arietinum* L.) – spring barley (*Hordeum vulgare* L.) – maize (*Zea mays* L.). |
| Green manure application II (11 years of crop rotation with six-time green manuring) | 0–10<br>10–20<br>20–30 | The block of agrochemical and agrophysical soil properties formed in 2025 (based on the results of soil sample analyses) after an eleven-year rotation cycle with the application of intermediate green manuring using oilseed radish (*Raphanus sativus* L. var. *oleiformi*s Pers.) (applied once every two years, rotation scheme identical to variant Control II) under the following crops:grain sorghum (*Sorghum bicolor* L.) – pea (*Pisum sativum* L.) – soybean (*Glycine max* (L.) Merrill) – sunflower (*Helianthus annuus* L.) – chickpea (*Cicer arietinum* L.) – maize (*Zea mays* L.) |

Note: * – Hereinafter, the year of cultivation is indicated in parentheses. The sowing dates of the agricultural crops corresponded to the following periods: for early spring crops (spring barley, spring wheat, pea, chickpea) – the second ten-day period of April; for late spring crops (soybean, sunflower, maize) – from the third ten-day period of April to the first ten-day period of May; for sorghum – the second ten-day period of June; for winter crops (winter pea) – the second ten-day period of September.

**Measurements and analysis**. Growth stages were identified using the standard BBCH scale (Test Guidelines, 2017). Above-ground biomass was sampled at the flowering stage using 1 m² quadrats (four per replicate) and weighed on a laboratory balance (WALCOM LB3002, ±0.01 g). Root biomass was quantified using the Profile

Wall and Monolith methods (Bublitz et al., 2022; Tsytsiura, 2025b). The dry matter (DM) content of both above-ground and root biomass was determined by oven drying to constant weight at 105 °C, followed by ashing at 550 °C. The green manure biomass of oilseed radish was converted to an equivalent amount of semi-composted cattle manure using a transfer coefficient of 0.6 (recommended range 0.5–0.7), based on long-term biochemical assessments (Tsytsiura, 2024b; Tsytsiura, 2025b) and data from Brown (2021) and Composts & Fertilizers (2023).

**Soil analysis.** Soil samples were collected from depths of 0–10, 10–20, and 20–30 cm using standardized disturbed sampling methods (Carter & Gregorich, 2008). Particle-size distribution (sand, silt, clay) was determined by dry sieving according to DSTU ISO 11277:2005. The 0.25–0.05, 0.05–0.01, 0.01–0.005, 0.005–0.001 mm, and < 0.001 mm fractions were quantified using the pipette method (Kachinsky modification under DSTU 4730:2007) and the Casagrande aerometric method (Prószyński modification, PN-R-4033), following the summarization approaches of Bieganowski & Ryżak (2011) based on averaged values.

Soil bulk density (BD) was determined gravimetrically using Kopecky cylinders, calculated as the mass of oven-dried soil per unit volume. Samples were dried at 105 °Cfor approximately 18–24 hours (Borek, 2019), and bulk density was expressed in g $cm^{-3}$ by dividing the dry soil mass by the cylinder volume.

Particle density (PD) was measured using the standard pycnometer method, widely recognized and standardized under ASTM D854 (2010) and ISO 17892-3.

These measurements were supplemented by soil hardness (SH) assessments using a Walcom FM-204TR penetrometer. For each soil horizon in every experimental replicate, five measurements were taken, and the mean value was recorded in kg $cm^{-2}$.

Capillary porosity ($P_k$), non-capillary porosity ($P_n$), and aeration porosity ($P_a$) were calculated using standard laboratory and computational procedures (Blake & Hartge, 1986; NRCS, 2004; Spasić et al., 2023). Total soil porosity ($P_g$) was computed as the sum of capillary and non-capillary porosity ($P_g = P_k + P_n$).

Water absorption capacity (WAC) of the soil was determined using a laboratory method as outlined by Bittelli (2011) and Dobriyal et al. (2012), involving saturation and subsequent drying of the soil sample. The procedure consisted of placing a known weight of oven-dried soil in a perforated container lined with filter paper, saturating the sample, and weighing it before and after drying to compute WAC using Eq. 1. Water was added until the soil became fully saturated (the surface glistened without water pooling). The soil container was then left for 2–3 hours to allow free water to drain. After this period, the saturated soil together with the container was weighed, and the mass was recorded as mwet. The sample was subsequently dried in an oven at 105 °Cfor 6–8 hours (until a constant weight was reached). After cooling in a desiccator, the sample was weighed again, and the dry mass was recorded as $m_{dry}$.

$$\mathrm{WAC} = \frac{\mathrm{m_{wet}} - \mathrm{m_{dry}}}{\mathrm{m_{dry}}} \cdot 100 \qquad (1)$$

where $m_{wet}$ – mass of saturated (wet) soil (g); $m_{dry}$ – mass of oven-dry soil (g).

Soil electrical conductivity (EC, $dS \cdot m^{-1}$) was determined conductometrically. A soil-water suspension (1:5 ratio) was prepared by mixing 10 g of air-dried soil with 50 mL of distilled water in a polypropylene container, followed by vigorous stirring for

2 minutes and subsequent settling for 1 hour to allow the soil-water mixture to equilibrate. Electrical conductivity of the upper layer of the suspension was measured using a conductivity meter (EZODO–8200 M, EZODO, Taiwan). All analyses were performed in three to five replications.

**Agrochemical analysis of soil.** Humus content was determined according to DSTU 4289:2004 (2005), a modified method of Steinbrich & Turski (1982).

Easily hydrolyzable nitrogen was assessed following the analytical protocol for agrochemical laboratories (DSTU 7863:2015 (2016)). Available phosphorus content (in the form of $P_2O_5$) was measured in accordance with DSTU 4115–2002 (2003). Exchangeable potassium (in the form of $K_2O$) was also determined using DSTU 4115–2002 (2003). Soil pH ($pH_{KCl}$) was measured potentiometrically according to DSTU ISO 10390–2007 (2009), which is identical to the international standard ISO 10390:2005. In addition to the primary agrochemical parameters listed above, the following were also assessed:

– The group and fractional composition of soil humus was determined using the Tyurin method as modified by Ponomaryova and Plotnikova, and by combustion according to B.A. Nikitin, standardized by the National Scientific Center 'Institute for Soil Science and Agrochemistry Research of NAAS of Ukraine' (DSTU 7828:2015 (2016)).

– Total nitrogen (TN) was determined using the Kjeldahl method in accordance with ISO 11261 Soil quality – Determination of total nitrogen – Modified Kjeldahl method (AOAC 955.04 (1995)).

– The soil C/N ratio was calculated as the ratio of organic carbon content (OCC, %) to total nitrogen (TN, %).

**Two indicators were used to assess the impact of green manuring:** Structure stability index (StI), Productivity index (PI) and Soil quality index (SQI).

The Structure Stability Index (StI) was calculated according to the recommendations of Pieri (1992) and Reynolds et al. (2008) using Eq. 2.

$$\mathrm{StI} = \frac{1.724 \cdot \mathrm{C_{org}}}{(\mathrm{silt} + \mathrm{clay})} \cdot 100 \tag{2}$$

where $C_{org}$ – the soil organic carbon content (%) and clay+silt – the soil's combined clay and silt content (%).Based on the conclusions Kemper & Rosenau (1986), Borek (2019): StI< 5% indicates a structurally degraded soil; 5%< StI< 7% indicates a high risk of soil structural degradation; 7%< StI< 9% indicates a low risk of soil structural degradation; and StI> 9% indicates sufficient $C_{org}$ to maintain the structural stability (it is conventionally assumed that optimal organic carbon content is 3–5%).

The Productivity Index (PI) was calculated according to the method proposed by Pierce et al. (1983), taking into account the recommendations of Mulengera & Payton (1999), using Eq. 3 in the modification by Chornyi & Vilna (Poliashenko) (2019):

$$\mathrm{PI} = \sum_{i=1}^{n} (\mathrm{H_i} \cdot \mathrm{WAC_i} \cdot \mathrm{BD_i} \cdot \mathrm{pH_i} \cdot \mathrm{E_i} \cdot \mathrm{P_i} \cdot \mathrm{K_i})^{1/7} \cdot \mathrm{RI_i} \tag{3}$$

where, in the i-th layer, all values are normalized (0–1): $H_i$ – humus content; $WAC_i$ – water absorption capacity of the soil; $BD_i$ – soil bulk density; $pH_i$ – soil solution pH; $E_i$ – soil electrical conductivity (salinity); $P_i$ – available phosphorus content ($P_2O_5$); $K_i$ – exchangeable potassium content ($K_2O$); $RI_i$ – parameter representing the proportion of roots in each soil layer under average moisture conditions, based on the analysis of the cumulative root mass distribution curve in soil, modeled as a dose-response logistic function (according to Eq. 4) (Fan et al., 2016); n – number of soil layers; i – soil layer number.

$$Y(h) = \frac{1}{1+(\frac{h}{d_a})^c} + \left[1 - \frac{1}{1+(\frac{d_{max}}{d_a})^c}\right] \cdot \frac{h}{d_{max}} \quad (4)$$

where Y(h) is the value of the cumulative root distribution curve of a given crop expressed as a fraction at the soil profile depth h (cm); $d_a$ and c are curve parameters; $d_{max}$ is the maximum root length of the crop (cm).

The indicators $H_i$, $WAC_i$, $BD_i$, $pH_i$, $E_i$, $P_i$, and $K_i$ (see Eq. 3) were normalized from 0 to 1. Normalization of the model indicators from 0 to 1 (except for the $RI_i$ parameter) was performed with adaptation to the soil cover properties of Ukraine based on detailed normalization parameters from Chornyi & Vilna (Poliashenko) (2019). The critical humus content was taken based on the optimal fertility model of grey forest soils at the level of 2.7%, according to the DSTU 4362:2004 (2005) scale.

For the calculation of the $RI_i$ indicator with adaptation to the study region, methodological approaches from Chornyi & Vilna (Poliashenko) (2019) and the reference tabular database of Fan et al. (2016) were applied, as well as the results of studies on the root system formation patterns of oilseed radish on grey forest soils (according to Tsytsiura (2025b)) using Eq. 5:

$$RI_i = Y(h)_J - Y(h)_i \quad (5)$$

where $Y(h)_j$ is the value of the function (Eq. 4) at the upper boundary of the soil layer h; $Y(h)_i$ is the value of the function (Eq. 4) at the lower boundary of the soil layer.

To obtain the average value on the date of the respective measurement, the $RI_i$ values were calculated for the corresponding crops according to the crop rotation. For the treatment variant with green manure application of oilseed radish, the $RI_i$ indicator consisted of two components: from the main crop grown during the primary vegetation period and from the oilseed radish grown in the intermediate green manure period from June to December.

The Soil Quality Index (SQI) was determined based on the collected dataset using two approaches. The first Soil Quality Index ($SQI_I$) was calculated according to a non-linear weighted model, recognized as more accurate than the linear technique (Uthappa et al., 2024), using Eq. 6, and normalization of $S_i$ was performed using Eq. 7:

$$SQI_I = \sum_{i=1}^{n} w_i \cdot S_i \quad (6)$$

where n – number of parameters, $w_i$ – the weight of the i-th parameter; $S_i$ – normalized values of the i-th parameter.

$$S_i = 1/\left[1 + \left(\frac{X}{X_0}\right)^b\right] \quad (7)$$

where X is the actual indicator value; $X_0$ is the average indicator value; b is the slope parameter, assumed to be -10.5 for indicators in the logistic form where ‘more is better’ and +10.5 for indicators where ‘less is better’.

The weights $w_i$ were derived from PCA as the ratio of the communality of the i-th indicator to the sum of communalities of all indicators (Iheshiulo et al., 2024).

The communality of factors was determined according to Zhang et al. (2025) by Eq. 8:

$$\text{Communality}_i = l_{i1}^2 + l_{i2}^2 + \cdots + l_{ik}^2 \quad (8)$$

where lij is the factor loading of variable i on component j, and k is the number of PCA components.

The second soil quality index (SQIII) was determined by the recommendations of Amacher & Perry (2007), Grzywna & Ciosmak (2021), according to Eq. 9:

$$SQI_{II} = \sum \frac{S}{n \cdot i} \quad (9)$$

where S denotes score of soil parameter, n is the number of parameters, i is maximum index.

Expert evaluation was conducted using a 5-point scale (ranging from 'very poor' – 1 point to 'very good' – 5 points) based on the generalization of ranking of the applied indicators from a range of publications. The dataset, expert evaluation of the importance of each criterion, and their corresponding weight coefficients are presented in Table 2.

**Table 2.** Criteria set for the evaluation of grey forest soils within an expert scoring system

| Criteria | Expert scoring points | | | | | Expert source |
|---|---|---|---|---|---|---|
| | 5 | 4 | 3 | 2 | 1 | |
| Humus content (H), % | > 5.0 | 4.1–5.0 | 3.1–4.0 | 2.1–3.0 | < 2.0 | Perovych et al. (2021) |
| Content of easily hydrolyzable nitrogen (N), mg $kg^{-1}$ | 140–150 | 120–140 | 110–120 | 90–110 | < 90 | |
| Content of available phosphorus ($P_2O_5$), mg $kg^{-1}$ | 120–190 | 110–120 | 100–110 | 90–100 | < 90 | |
| Content of exchangeable potassium ($K_2O$), mg $kg^{-1}$ | 140–200 | 120–140 | 100–120 | 80–100 | < 80 | |
| Soil bulk density (BD), g $cm^3$ | < 1.2 | 1.21–1.33 | 1.34–1.40 | 1.41–1.50<br>0.90–1.00 | > 1.50<br>< 0.90 | Grzywna & Ciosmak (2021) |
| Particle density (PD), g $cm^3$ | < 2.50 | 2.50–2.55 | 2.55–2.60 | 2.60–2.65 | > 2.65 | Medvedev et al. (2020) |
| pH | 6.1–7.0 | 5.5–6.0 | 5.0–5.4 | 5.0–5.3 | < 5.0 | Perovych et al. (2021) |
| Soil electrical conductivity ($E_i$), dS·$m^{-1}$ | 0.1–0.2 | 0.2–0.5 | 0.5–2.0 | 2.0–3.0 | > 3.0<br>< 0.1 | Mulengera & Payton, 1999 |
| Capillary porosity ($P_k$), % | 35–40 | 30–35 | 25–30 | 20–25 | < 20 | Medvedev et al. (2020); Yang et al. (2025) |
| Total porosity ($P_g$), % | 55–60 | 50–55 | 45–50 | 40–45 | < 40 | Amacher & Perry (2007) |
| Water absorption capacity of the soil (WAC), % | > 35 | 30–35 | 25–30 | 20–25 | < 20 | Dobriyal et al. (2012) |

Integral Soil Fertility Index (ISFI) was calculated as the geometric mean of the obtained coefficients and soil quality indices (Eq. 10) according to the optimal method of averaging coefficient and index values derived from the dataset, following Johnson & Wichern (1998):

$$ISFI = \sqrt[3]{SQI_I \cdot SOI_{II} \cdot PI} \quad (10)$$

where $SQI_I$ – the first Soil Quality Index; $SQI_{II}$ – the second soil quality index; PI – Productivity Index.

**To analyze the hydrothermal conditions** conducted based on the following indicators: average daily temperature (°C), precipitation (mm), relative humidity (%), hydrothermal coefficient (HTC) (Eq. 11), and coefficient of significance of deviations ($C_{sd}$) (Eq. 12) (Table 3).

$$HTC = \frac{\sum R}{0.1 \cdot \sum t_{>10\,°C}} \quad (11)$$

where ΣR – the sum of precipitation (mm) over a period with temperatures above 10 °C, $\Sigma t_{>10°C}$ – the sum of effective temperatures over the same period. Ranking of HTC values conditions: HTC > 1.6 – excessive humidity, HTC 1.3–1.6 – humid, HTC 1.0–1.3 – moderately dry, HTC 0.7–1.0 – dry, HTC 0.4–0.7 – very dry.

$$C_{sd} = \frac{(X_i - X_{av})}{S} \quad (12)$$

where $X_i$ – current weather element; $X_{av}$ – long-term average value; S – standard deviation; i – year index. $C_{sd}$ levels: 0 to 0.5 (or -0.5) – conditions close to normal; 1 to 2 (or -1 to -2) – significantly different from long-term averages; 2 (or < -2) – close to extreme conditions.

**Table 3.** Assessment of hydrothermal regimes (by the indicator of hydrothermal coefficient (HTC)) (Dfa/Dfb zone according to the Köppen-Geiger climate classification (Gardner et al., 2020)), 2014–2024 in comparison to the long-term period 2000–2013)

| Year | Precipitation total, mm (IV-X) | *$t_{aver}$, °C (IV-X) | Months of the growing season | | | | | | | | | | $C_{sd\ aver}$ V–IX | *$t_{aver}$, °C | Total precipitation, mm** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | V | | VI | | VII | | VIII | | IX | | | | |
| | | | $X_i$ | $C_{sd}$ | $X_i$ | $C_{sd}$ | $X_i$ | $C_{sd}$ | $X_i$ | $C_{sd}$ | $X_i$ | $C_{sd}$ | | | |
| 2014 | 590.4 | 14.62 | 3.93 | 3.39 | 1.55 | 1.00 | 1.31 | 0.24 | 1.05 | 0.46 | 1.25 | 1.10 | 1.24 | 0.2 | 245.5 |
| 2015 | 303.1 | 15.48 | 0.92 | 0.19 | 0.72 | -0.53 | 0.32 | -1.16 | 0.12 | -1.13 | 1,184 | 0.97 | -0.33 | 9.5 | 256.1 |
| 2016 | 406.1 | 15.33 | 0.49 | -0.26 | 1.27 | 0.48 | 1.06 | 0.39 | 0.90 | 0.46 | 0.01 | -1.17 | -0.02 | -0.6 | 325.7 |
| 2017 | 443.1 | 15.04 | 0.78 | 0.04 | 0.50 | -0.92 | 1.52 | 1.38 | 0.82 | 0.30 | 3.10 | 4.47 | 1.05 | -0.4 | 323.7 |
| 2018 | 444.2 | 16.39 | 0.31 | -0.45 | 4.40 | 6.28 | 2.16 | 2.71 | 0.59 | -0.19 | 1.38 | 1.33 | 1.94 | 0.0 | 271.0 |
| 2019 | 560.2 | 15.70 | 4.90 | 4.42 | 1.68 | 1.25 | 1.01 | 0.30 | 0.24 | -0.90 | 0.99 | 0.62 | 1.14 | 2.9 | 200.5 |
| 2020 | 589.2 | 15.64 | 5.33 | 4.87 | 1.55 | 1.01 | 0.59 | -0.59 | 0.53 | -0.30 | 0.86 | 0.38 | 1.07 | -0.3 | 356.1 |
| 2021 | 459.7 | 14.33 | 3.13 | 2.54 | 1.68 | 1.25 | 0.78 | -0.19 | 1.46 | 1.61 | 0.71 | 0.10 | 1.06 | 1.2 | 216.9 |
| 2022 | 678.7 | 15.15 | 1.43 | 0.74 | 1.50 | 0.91 | 0.90 | 0.06 | 1.71 | 2.13 | 4.96 | 7.86 | 2.34 | 2.2 | 278.0 |
| 2023 | 486.9 | 16.24 | 0.09 | -0.69 | 1.64 | 1.18 | 1.41 | 1.14 | 0.65 | -0.05 | 1.02 | 0.66 | 0.45 | 2.9 | 371.2 |
| 2024 | 481.9 | 17.94 | 0.58 | -0.17 | 1.66 | 1.21 | 1.19 | 0.67 | 0.77 | 1.46 | 0.45 | -0.38 | 0.41 | 1.2 | 263.8 |

*average daily temperature (°C) for the period from November of the previous year to March of the following year; **total precipitation (mm) for the period from November of the previous year to March of the following year.

A generalized assessment of the hydrothermal regimes during the oilseed radish vegetation period for the years of research is presented in Table 1. According to the general classification of territorial hydrothermal regimes (Latief et al., 2017), the study period was characterized as conditions of unstable moisture. Taking into account the optimal hydrothermal parameters for oilseed radish growth identified in our previous long-term assessments (Tsytsiura, 2023a) and the hydrothermal coefficient (HTC) grouping system, the research years were arranged in the following order of increasing favorability for the growth of oilseed radish as an intermediate summer–autumn green manure crop: 2016 → 2014 → 2024 → 2020 → 2018 → 2022.

For the main crops in the crop rotation scheme, the research years were arranged in the following order of increasing favorability of growth conditions: 2017 → 2015 → 2016 → 2018 → 2021 → 2022 → 2024 → 2023 → 2014 → 2020 → 2019.

**Statistical processing.** The indicators of variation statistics were determined using the standard calculation method described by Wong (2018), employing the statistical software Statistica 10 (StatSoft – Dell Software Company, USA).

For each analyzed physical soil parameter, the minimum and maximum values, arithmetic mean, median, standard deviation, and coefficient of variation (CV) were calculated. In addition, a Pearson correlation analysis was performed for the entire dataset. The statistical significance of the calculated correlation coefficients was assessed using Student's *t*-test at significance levels of $p < 0.05$, $p < 0.01$, and $p < 0.001$.

The evaluation of significant differences in the indicators of aboveground and root biomass formation across the years of oilseed radish green manuring was carried out using a one-way analysis of variance (ANOVA) design (6×4 – six years of green manuring in four replications), with the least significant difference (LSD) calculated at the $p < 0.05$ significance level. A preliminary assessment of normality was performed using the Kolmogorov–Smirnov test, and homogeneity of variance was verified using Levene's test.

To determine statistically significant differences by sequentially comparing each soil layer with the corresponding layer in the Absolute Control variant, Tukey's test was applied in the R software environment (v. 4.2.1). Significance was determined by comparing the corresponding soil layers of the experimental variants with the analogous layers of the Absolute Control based on the least significant difference (the *diff* indicator in the TukeyHSD test, following Lambert et al., 2010) at the $p < 0.05$ level.

To statistically evaluate the significance of differences among soil layers within a single variant (for comparisons of 0–10, 10–20, and 20–30 cm), a two-stage procedure was used. First, a one-way ANOVA was performed for each variant; this was followed by *t*-tests between pairs of soil layers (0–10 vs. 10–20; 0–10 vs. 20–30; 10–20 vs. 20–30). The Bonferroni correction was applied with a significance threshold of $p < 0.05$.

The statistical assessment of differences between the variants for the calculated soil quality coefficients was performed using *t*-tests between comparison groups.

## RESULTS AND DISCUSSION

During the period of intermediate green manure use of oilseed radish, its average green manure productivity was 24.01 t $ha^{-1}$ (4.02 t $ha^{-1}$ dry matter), according to the experimental scheme, with interannual variation ($C_V$) of 31.55% (28.53%), respectively (Table 4). The average ratio between the produced aboveground biomass and root residues was 3.52 for fresh biomass and 2.34 for dry matter.

**Table 4.** Indicators of green manure bioproductivity of oilseed radish for the summer intermediate sowing date (at the flowering stage, BBCH 64–67)

| Indicators of green manure bioproductivity | The year of green manure application | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2014 | 2016 | 2018 | 2020 | 2022 | 2024 | Mean value | $^{*}LSD_{0.5}$ |
| Aboveground biomass yield (ABY), t ha$^{-1}$ | 22.21 | 21.05 | 23.12 | 11.29 | 24.77 | 9.77 | 18.70 | 1.07 |
| Aboveground biomass yield in dry matter ($ABY_{DM}$), t ha$^{-1}$ | 3.37 | 3.36 | 3.45 | 1.82 | 3.33 | 1.55 | 2.81 | 0.29 |
| Root biomass yield (RBY), t ha$^{-1}$ | 6.59 | 5.77 | 5.52 | 3.09 | 8.03 | 2.84 | 5.31 | 0.58 |
| Root biomass yield in dry matter ($RBY_{DM}$), t ha$^{-1}$ | 1.46 | 1.33 | 1.29 | 0.70 | 1.76 | 0.68 | 1.20 | 0.17 |
| Equivalent cattle semi-rotted manure, t ha$^{-1}$ | 17.28 | 16.10 | 17.18 | 8.63 | 19.68 | 7.57 | 14.41 | 0.84 |

Evaluating the total biomass produced under a hydrothermal regime characterized by moisture instability (zone Dfa/Dfb), it can be concluded that oilseed radish should be classified as an adaptive species suitable for use as an intermediate summer green manure crop. This classification is supported by results from long-term studies of various cruciferous species (Creamer & Baldwin, 1999; Duff et al., 2020). Considering that the minimum effective threshold of total biomass required for the direct application of green manure is no less than 2 t ha$^{-1}$ of dry matter (as reported by Clark, 2008; Bhogal et al., 2010; Talgre, 2013; Singh et al., 2023), the feasibility of using oilseed radish as a bio-organic fertilizer component for non-cruciferous crops has been substantiated.

The average fertilization potential of oilseed radish used as a green manure was equivalent to 16.85 t ha$^{-1}$ of semi-composted cattle manure during 2014–2019, and 11.96 t ha$^{-1}$ during 2020–2024. The average level of green manure organic fertilization in the green manure variant over 2014–2024 was 14.41 t ha$^{-1}$, which corresponds to the average level of bio-organic fertilization (Florentín et al., 2010).

A positive effect of systematic green manuring of varying duration on changes in agrochemical soil properties was identified (Table 5). It was established that the consistent application of intermediate green manuring with oilseed radish, compared with the control, promoted a gradual accumulation of humus and organic carbon. The long-term dynamics of this indicator in the absence of green manure showed a steady negative trend, whereas in the green manure treatment a stable positive trajectory with an increasing cumulative sum was recorded.

As of the intermediate assessment in 2019, in the 0–10 cm horizon, the increase in humus content relative to the absolute control was 0.16% (5.97% in relative terms), while in the 10–20 cm and 20–30 cm horizons the increase was 0.15% (5.86%) and 0.20% (9.30%), respectively. By the 2025 assessment, a similar pattern was observed, with increases of 0.24%, 0.22%, and 0.39% acros the corresponding soil horizons.

In the variant without green manure, by 2019 the humus content had decreased by 0.07% (2.61% relative), 0.09% (3.52%), and 0.12% (5.58%) with depth. By 2025, the reduction reached 0.32%, 0.28%, and 0.17%, respectively, across the soil horizons.

The average annual rate of increase in humus content under continuous green manuring was 0.022%, 0.020%, and 0.036% per year for the respective soil horizons. In contrast, in the variant without green manuring, the corresponding annual rates showed a negative trend (decline) of –0.029%, –0.025%, and –0.015%, respectively.

The results are consistent with previous studies on the impact of green manure technologies on humus content in the soil profile. Specifically, it has been noted (Arel, 2021; Stroud et al., 2024) that for cruciferous green manure species (various types of mustard, spring and winter rapeseed), the rate of humus accumulation in evaluated soil horizons ranged from 0.014 to 0.027% per year under satisfactory hydrothermal conditions and subsequent mineralization processes. For the optimal hydrothermal regime during the period of soil implementation of the sideral mass, the indicator was found to be within the range of 0.025–0.054% per annum. The observed rates of humus accumulation associated with the utilization of oilseed radish as green manure can be elucidated from the perspective of the carbon-to-nitrogen (C/N) ratio present in its green manure plant biomass. This specific indicator, as evidenced by the findings of a long-term study on oilseed radish utilizing the green manure option, was determined to be 13.30 (Tsytsiura, 2024b). Research conducted by Toungos & Bulus (2019), Stroud et al. (2024), and Nizamutdinov et al. (2025) indicates that optimal conditions for humus accumulation are observed either in scenarios characterized by a low C/N ratio in conjunction with soils exhibiting high fertility potential, or in situations involving a high C/N ratio paired with soils of low fertility potential. Furthermore, considering the average fertility level of gray forest soils (as reported by Medvedev et al., 2020), the attained rates of humus accumulation are categorized as moderately high.

These conclusions was further supported by studies on the fractional composition of humus. A consistent increase in the proportion of humic acids ($C_{hac}$) (Table 5) within the humus structure was observed under the application of green manure. By the final assessment date, the total increase in this parameter compared to the absolute control ranged from 5.16% in the 0–10 cm soil layer to 6.00% in the 20–30 cm layer. Conversely, in the variants without green manure, a decline in the proportion of humic acids was recorded over the 12-year study period, with a maximum decrease of 3.77% in the 10–20 cm layer and a minimum decrease of 2.93% in the 20–30 cm layer.

As a result, at the endpoint of the study, the overall increase in the proportion of humic acids comparing green manure treatments to non-green manure variants was greatest in the 10–20 cm soil layer (9.13%) and lowest in the 0–10 cm layer (8.56%). The dynamics of humin content followed a similar trend, with a 12.56% higher rate of decrease in the non-green manure variants. In contrast, the proportions of fulvic acids and humin exhibited an opposite pattern, characterized by reduced dynamics of 18.7% and 65.7%, respectively.

The observed dynamics in the ratio of humic to fulvic acids within the organic carbon structure indicate a favorable predominance of organic matter accumulation over its mineralization, as well as an overall improvement in the qualitative composition of humic substances. These findings align with numerous studies (Kumada, 1987; Liu, 1997; Banach-Szott et al., 2021; Cui et al., 2023; Zhang et al., 2025a), which similarly report positive trends in the stabilization of organic carbon and, consequently, humus accumulation.

**Table 5.** Dataset of agrochemical soil property parameters for experimental treatment, 2014–2025

| Treatment variant | Soil layer, cm | H, % | OCC, % | $C_{hac}$, % (to OCC) | $C_{fac}$, % (to OCC) | $C_{residue}$, % (to OCC) | $C_{hac}$,: $C_{fac}$, ratio | TN, % | OCC/ TN ratio | N, mg kg$^{-1}$ | P, mg kg$^{-1}$ | K, mg kg$^{-1}$ | $pH_{KCl}$ | $E_i$, dS m$^{-1}$ | StI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2014 | | | | | | | | | | | | | | | |
| Absolute control | 0–10 | 2.68$^{a}$ | 1.555$^{a}$ | 42.37$^{a}$ | 30.04$^{a}$ | 27.59$^{a}$ | 1.410$^{a}$ | 0.151$^{a}$ | 10.29$^{a}$ | 85.3$^{a}$ | 177.5$^{a}$ | 118.8$^{a}$ | 5.82$^{a}$ | 0.285$^{a}$ | 3.099$^{a}$ |
| | 10–20 | 2.56$^{b}$ | 1.485$^{b}$ | 41.92$^{a}$ | 31.61$^{b}$ | 26.47$^{b}$ | 1.326$^{b}$ | 0.141$^{a}$ | 10.53$^{a}$ | 83.7$^{a}$ | 179.1$^{a}$ | 110.8$^{b}$ | 5.84$^{a}$ | 0.281$^{a}$ | 2.986$^{b}$ |
| | 20–30 | 2.15$^{c}$ | 1.247$^{c}$ | 40.84$^{b}$ | 32.75$^{c}$ | 26.41$^{b}$ | 1.247$^{c}$ | 0.125$^{b}$ | 9.98$^{b}$ | 77.4$^{b}$ | 171.6$^{b}$ | 105.7$^{c}$ | 5.73$^{b}$ | 0.319$^{b}$ | 2.470$^{c}$ |
| 2019 | | | | | | | | | | | | | | | |
| Control I | 0–10 | 2.61$^{a}$ | 1.514$^{a}$ | 41.21$^{a}$ | 31.18$^{a}$ | 27.61$^{a}$ | 1.322$^{a}$ | 0.147$^{a}$ | 10.30$^{a}$ | 81.3$^{a}$ | 163.7$^{a}$ | 110.4$^{a}$ | 5.71$^{a}$ | 0.234$^{a}$ | 2.964$^{a}$ |
| | 10–20 | 2.47$^{b}$ | 1.433$^{b}$ | 40.88$^{b}$ | 31.14$^{a}$ | 27.98$^{a}$ | 1.313$^{a}$ | 0.132$^{b}$ | 10.85$^{a}$ | 77.5$^{b}$ | 167.2$^{a}$ | 104.1$^{b}$ | 5.73$^{a}$ | 0.262$^{b}$ | 2.812$^{b}$ |
| | 20–30 | 2.03$^{c}$ | 1.177$^{c}$ | 39.77$^{b}$ | 32.59$^{b}$ | 27.64$^{a}$ | 1.220$^{b}$ | 0.124$^{b}$ | 9.50$^{c}$ | 71.2$^{c}$ | 161.4$^{b}$ | 95.3$^{c}$ | 5.85$^{b}$ | 0.289$^{b}$ | 2.268$^{c}$ |
| Green manure application I | 0–10 | 2.84$^{a}$ | 1.647$^{a}$ | 45.71$^{a}$ | 30.25$^{a}$ | 24.04$^{a}$ | 1.511$^{a}$ | 0.159$^{a}$ | 10.36$^{a}$ | 95.7$^{a}$ | 180.2$^{a}$ | 122.3$^{a}$ | 5.87$^{a}$ | 0.251$^{a}$ | 3.409$^{a}$ |
| | 10–20 | 2.71$^{b}$ | 1.572$^{b}$ | 45.58$^{a}$ | 30.43$^{a}$ | 23.99$^{a}$ | 1.498$^{a}$ | 0.157$^{a}$ | 10.01$^{a}$ | 86.9$^{b}$ | 187.5$^{b}$ | 117.4$^{b}$ | 5.94$^{b}$ | 0.272$^{a}$ | 3.226$^{b}$ |
| | 20–30 | 2.35$^{c}$ | 1.363$^{c}$ | 44.21$^{b}$ | 30.69$^{a}$ | 25.10$^{b}$ | 1.441$^{b}$ | 0.145$^{b}$ | 9.40$^{b}$ | 80.5$^{c}$ | 177.3$^{a}$ | 120.7$^{a}$ | 6.00$^{b}$ | 0.301$^{b}$ | 2.733$^{c}$ |
| 2025 | | | | | | | | | | | | | | | |
| Control II | 0–10 | 2.36$^{a}$ | 1.369$^{a}$ | 38.97$^{a}$ | 32.96$^{a}$ | 28.07$^{a}$ | 1.182$^{a}$ | 0.143$^{a}$ | 9.57$^{a}$ | 73.8$^{a}$ | 151.8$^{a}$ | 105.7$^{a}$ | 5.63$^{a}$ | 0.218$^{a}$ | 2.626$^{a}$ |
| | 10–20 | 2.28$^{a}$ | 1.323$^{a}$ | 38.15$^{b}$ | 33.29$^{a}$ | 28.56$^{b}$ | 1.146$^{a}$ | 0.137$^{a}$ | 9.65$^{a}$ | 68.9$^{b}$ | 152.7$^{a}$ | 102.4$^{a}$ | 5.68$^{a}$ | 0.237$^{a}$ | 2.552$^{a}$ |
| | 20–30 | 1.98$^{b}$ | 1.148$^{b}$ | 37.91$^{b}$ | 34.27$^{b}$ | 27.82$^{a}$ | 1.106$^{b}$ | 0.134$^{b}$ | 8.57$^{b}$ | 65.8$^{c}$ | 146.9$^{b}$ | 100.6$^{b}$ | 5.87$^{b}$ | 0.259$^{b}$ | 2.171$^{b}$ |
| Green manure application II | 0–10 | 2.92$^{a}$ | 1.694$^{a}$ | 47.53$^{a}$ | 28.12$^{a}$ | 24.35$^{a}$ | 1.690$^{a}$ | 0.157$^{a}$ | 10.79$^{a}$ | 102.3$^{a}$ | 184.4$^{a}$ | 127.7$^{a}$ | 5.95$^{a}$ | 0.263$^{a}$ | 3.517$^{a}$ |
| | 10–20 | 2.78$^{b}$ | 1.613$^{b}$ | 47.28$^{a}$ | 27.09$^{b}$ | 25.63$^{b}$ | 1.745$^{b}$ | 0.154$^{a}$ | 10.47$^{a}$ | 92.8$^{b}$ | 193.7$^{b}$ | 121.4$^{b}$ | 6.07$^{b}$ | 0.285$^{b}$ | 3.406$^{a}$ |
| | 20–30 | 2.54$^{c}$ | 1.473$^{c}$ | 46.84$^{a}$ | 27.32$^{b}$ | 25.84$^{b}$ | 1.714$^{a}$ | 0.150$^{a}$ | 9.82$^{b}$ | 83.6$^{c}$ | 189.4$^{c}$ | 130.9$^{a}$ | 6.12$^{b}$ | 0.307$^{c}$ | 3.052$^{b}$ |
| Threshold level (diff) in TukeyHSD *test*** | 0–10 | 0.09 | 0.05 | 1.17 | 0.27 | 0.17 | 0.108 | 0.06 | 0.11 | 1.23 | 9.59 | 6.72 | 0.11 | 0.017 | 0.104 |
| | 10–20 | 0.12 | 0.07 | 0.96 | 0.44 | 0.37 | 0.117 | 0.08 | 0.15 | 1.95 | 11.14 | 7.19 | 0.09 | 0.010 | 0.159 |
| | 20–30 | 0.11 | 0.06 | 1.03 | 1.07 | 0.52 | 0.163 | 0.08 | 0.23 | 2.58 | 12.52 | 8.91 | 0.12 | 0.019 | 0.207 |

Note: Explanation of treatment is given in the Table 1. Context of indicators: H – humus content, %; OCC – organic carbon content, %; $C_{fac}$ – total fulvic acid content, % of OCC; $C_{hac}$ – total humic acid content, % of OCC; Humin – %, of OCC; TN – total nitrogen content, %; N – content of easily hydrolyzable nitrogen, mg kg$^{-1}$; P – content of available phosphorus (in form of $P_2O_5$), mg kg$^{-1}$; K – content of exchangeable potassium (in form of $K_2O$), mg kg$^{-1}$; $pH_{KCl}$ – acidity (salt method); $E_i$ – soil electrical conductivity (salinity), dS m$^{-1}$; StI – structure stability index. Different lowercase letters in the upper register near the values of parameters in the table indicate significant differences for the experimental variants between soil layers for the same variant (for a significance level of $p < 0.05$). **The threshold difference values for the analyzed soil layers are presented in comparison with their corresponding values in the Absolute Control variant, for a statistical significance level of $p < 0.05$.

This conclusion is further supported by Silva et al. (2008), who emphasized the beneficial effects of higher humic acid concentrations. Maintaining such a ratio enhances the immobilization of decomposition products from plant and root residues, helps sustain a near-neutral soil pH, and strengthens the predominance of accumulation processes over decomposition. Furthermore, the increased proportion of humic acids in the 0–10 cm soil layer compared with the 20–30 cm layer corroborates the conclusions of Cupać et al. (2007) and Silva et al. (2022), who reported the most pronounced improvements in humus formation within the soil depth where green manure biomass is incorporated. As noted by Magdoff & Weil (2004) and Ryan (2007), this effect tends to be more substantial in crop rotations dominated by cereals and legumes–consistent with the crop rotation structure used in our experiment.

Special attention should be given to the formation of the humic-to-fulvic acid ratio ($C_{hac}$:$C_{fac}$) in treatments with oilseed radish applied as green manure. In the green manure treatment, this indicator was on average 0.39 higher across the studied soil horizons (a 29.64% increase compared with the absolute control), whereas in the treatment without green manure it was 0.18 lower (a 13.68% decrease). Thus, green manure application significantly improved organic carbon cycling within the soil profile. Considering the statements by Magdoff & Weil (2004) and Lim et al. (2012) that pronounced differences in the dynamics of fulvic acids and humin fractions reflect a balanced state between labile and non-labile humus components, such balance both facilitates organic matter accumulation and may, paradoxically, lead to relatively lower expression of soil fertility despite higher humus content. Within this context, the use of green manure enhances the proportion of labile organic components, offering additional benefits for humus formation, plant nutrition, and the mitigation of agrochemical soil degradation. Comparable trends were reported by Prajapati et al. (2023), where systematic green manuring on high-fertility soils increased the Chac:Cfac ratio to as much as 1.5.

It is also noteworthy that, against the background of a more than twofold lower rate of decline in this indicator compared with the rate of increase observed in the soil without green manure or fertilization, there was an intensification of internal humus structural transformation processes, with a potentially greater involvement of the humin fraction. Over the long term, under the continued absence of fertilization, this may lead to accelerated depletion of humus content due to enhanced mineralization of the humin component of the humus complex. Similar dynamics were reported by Roy & Kashem (2014) and Wang et al. (2024a, 2024b).

These patterns are further supported by the results for total nitrogen (TN) content (Table 5). At the final assessment date, the application of green manure increased TN content compared with the absolute control by 3.97% in the 0–10 cm soil layer, by 9.22% in the 10–20 cm layer, and by 20.0% in the 20–30 cm layer, clearly demonstrating the positive effect of green manuring on soil nitrogen accumulation. The variant without green manure displayed a heterogeneous response at the final assessment date, with a decrease of 4.10% in the 0–20 cm layer and an increase of 7.20% in the 20–30 cm layer.

Considering the identified pattern of TN redistribution in the green manure treatments between 2019 and 2025 – specifically, the increase in TN content in the 20–30 cm layer and the corresponding decrease in the 0–20 cm layer – the incorporation of green manure biomass created favorable conditions for optimizing both humification processes and nitrogen supply within the 15–30 cm depth interval. This finding corresponds well with the localization of green manure biomass in the soil and corroborates the conclusions of Nizamutdinov et al. (2025) regarding the principle of localized effects of plant tissue decomposition on the migratory distribution of released mineral and organic components.

These observations are also supported by the correlation analysis of relationships between humus fractional composition, easily hydrolyzable nitrogen content, and TN values (Table 6). A strong positive correlation (r > 0.7, $p < 0.001$) was found between soil nitrogen content and both the humic acid fraction and the $C_{fhc}$:$C_{fac}$ ratio. Conversely, negative correlations were observed for the fulvic acid and humin fractions. Similar trends were reported by Cui et al. (2023) and Stevenson (1994), emphasizing that the formation of available nitrogen forms in soils is driven primarily by the humic acid fraction, and to a lesser extent by fulvic acids and humin.

For these reasons, in the treatment using oilseed radish as a green manure crop, a substantial increase in the agrochemical parameters of the soil profile can be expected primarily at the incorporation depth. However, scientific opinions regarding this aspect of green manure practice vary. Kemper (2024), for instance, emphasizes that green manuring predominantly affects the 0–15 cm soil layer due to the intensive interaction between the green manure biomass and soil during root system development (Hudek et al., 2022), as well as its influence on agro-physical properties. Conversely, Kucerik et al. (2024) argue that the effect of green manuring on the suite of soil properties should be interpreted in conjunction with moisture fluxes within the soil profile, post-incorporation hydrothermal conditions, and the type of green manure biomass.

In accordance with the documented efficiency of oilseed radish under specific hydrothermal regimes (Tsytsiura, 2024a, 2024b), the conditions during the study period (Table 3) were sufficiently favorable for forming the required biochemical composition, resulting in a moderate decomposition rate of the green manure biomass. This, in turn, promoted localized accumulation of organic carbon specifically within the depth interval of biomass incorporation.

The ratio of organic carbon to total nitrogen (OCC/TN) demonstrated significant differences between treatments with and without oilseed radish green manure application. In general, this ratio in soils exhibits a relatively narrow range, dictated by humus content, microbial activity, and the fractional composition of humus, typically between 7 and 18:1, with an optimum of 10–12:1 (Azis et al., 2023). This optimal range ensures a balance for microorganisms responsible for decomposing organic matter and releasing plant-available nutrients. According to our findings, long-term green manuring contributed to stabilizing the carbon-to-nitrogen ratio at approximately 10:1 during both the intermediate evaluation (2019) and the final assessment (2025).

This stabilization reflects earlier noted increases in both organic carbon and nitrogen content. Comparing the effects of green manuring across key observation dates revealed a more pronounced disparity between increases in organic carbon and total nitrogen in the respective soil layers. This was confirmed by positive incremental changes in the OCC/TN ratio ranging from 4.13% to 4.58%, with the highest value recorded in the 10–20 cm layer. Such dynamics suggest a gradual slowdown in the decomposition of oilseed radish biomass under systematic green manuring, attributed to the progressive accumulation of organic matter accompanied by a decline in its mineralization rate. Similar behavior has been widely documented for green manuring technologies used in agricultural land management (De Willigen et al., 2008; Klimkowicz-Pawlas et al., 2019; Liu, 2024; Ren et al., 2025; Zhang et al., 2025).

Considering that the OCC/TN ratio can be effectively used both to assess the decomposition rate of green manure biomass in soil and to evaluate the mineralization rate of the soil organic matter fraction (Magdoff & Weil, 2004; Dube et al., 2012; Toleikiene, 2020; Kravchenko et al., 2022), and given that values in the range of 10–15 indicate favorable conditions for moderately rapid decomposition of plant biomass at rates sufficient to ensure its retention within the plow layer or the primary root zone (Kätterer et al., 2011; Liu et al., 2020), the incorporation of oilseed radish green manure effectively optimized the overall processes of organic matter accumulation in the soil.

In contrast, in the treatment without green manuring, the OCC/TN ratio at the final observation date showed a consistent decline relative to the absolute control: by 7.01% in the 0–10 cm soil layer, by 8.34% in the 10–20 cm layer, and by 14.09% in the 20–30 cm layer. This pattern indicates clear evidence of agrochemical soil degradation under intensive agricultural use in the absence of any additional fertilization. A decreasing OCC/TN ratio creates conditions that accelerate the decomposition of soil organic matter and contribute to the onset of persistent dehumification. As a result, against the background of declining humus content accompanied by nitrogen release – where the rate of nitrogen loss is lower than that of organic carbon – the ratio assumes low values. At the same time, correlation analysis revealed a strong inverse relationship (mean $r > 0.6$, $p < 0.01$) (Table 6) between the OCC/TN ratio and key agrophysical soil parameters, including bulk density, hardness, and various porosity fractions.

Along with the increase in total nitrogen (TN) content associated with the application of oilseed radish green manure, a corresponding increase in easily hydrolyzable nitrogen (N) was also observed. This was confirmed by both the strong correlation between the indicators ($r = 0.799$, $p < 0.001$) and by the analysis of dynamic changes relative to the absolute control. By 2025, the green manure treatment showed an increase in easily hydrolyzable nitrogen across the soil profile, ranging from 19.93% in the 0–10 cm horizon to 8.01% in the 20–30 cm horizon. In contrast, the treatment without green manure showed an average decrease of 15.38% in the 0–30 cm layer, with no meaningful differentiation across soil horizons.

Furthermore, the strong correlation between TN and easily hydrolyzable nitrogen supports the conclusions of Acharya et al. (2024) regarding nitrogen cycling under single-component green manure applications. This process contributes to the previously noted shift in the humus fractional structure toward a greater proportion of humic acids and a gradual reduction in fulvic acids and humin. The markedly higher increase in easily hydrolyzable nitrogen in the 0–10 cm layer (with a reduction index of 60% when comparing the 20–30 cm and 0–10 cm layers) indicates more active nitrogen transformation processes in the upper horizons. This can be attributed to the higher concentration of plant residues combined with green manure biomass, as well as the predominance of aerobic oxidative processes, which intensify the transformation of decomposition products. Additionally, the inherently high mobility of nitrogen in soil– substantially greater than that of phosphorus or potassium—contributes to a vertical gradient of decreasing nitrogen concentration from upper to lower horizons, consistent with the findings of Hansen et al. (2022), Naz et al. (2023), Li et al. (2024), and Zhang et al. (2025).

These results are supported by the dynamics of changes in the content of mobile forms of phosphorus and potassium within the 0–30 cm soil layer, which exhibit trends similar to those observed for nitrogen. However, in the green manure treatments, the maximum phosphorus concentration shifts to the 10–20 cm horizon, while potassium peaks in the 20–30 cm horizon. This creates a gradient distribution of macronutrients in the green manure variants and can be explained by the previously discussed processes related to nutrient lability.

In contrast, in the no-green manure treatments, available forms of nitrogen, phosphorus, and potassium are predominantly concentrated in the upper soil horizons. In the absence of additional mineral fertilization, this pattern can be attributed to the accumulation of plant residues from the preceding crops. These residues serve as an additional nutrient source, partially compensating for the depletion of soil nutrient stocks during plant growth.

Under these conditions, by the final sampling date, the treatment with sustained use of oilseed radish as green manure demonstrated, on average across the 0–30 cm soil layer, a 25.75% higher concentration of mobile phosphorus and a 23.16% higher concentration of exchangeable potassium. These findings are fully consistent with results from comprehensive studies evaluating the effects of green manuring on the concentration and availability of major macro- and micronutrients (Kvakic et al., 2020; Hansen et al., 2021; Razanov et al., 2021; Abdulraheem & Tobe, 2022; Suon et al., 2023).

Considering that these studies report average increases in nitrogen, phosphorus, and potassium contents ranging from 11.8% to 45.7%, oilseed radish should be classified as a crop with a high agrochemical fertilization potential, which is also consistent with its biochemical profile under different durations of green manuring (Tsytsiura, 2024b).

The impact of green manuring on soil acidity ($pH_{KCl}$) requires separate consideration. According to the obtained data (Table 5), the systematic long-term use of oilseed radish leads to an average decrease in soil acidity by 4.30% in the 0–30 cm layer compared to the absolute control, whereas in the treatment without green manuring, soil acidity increases by 2.81%.

The relatively moderate improvement in soil pH under oilseed radish green manuring –compared with cereal or leguminous green manure species, where pH increases (i.e., acidity decreases) may reach 15–27% (Suon et al., 2023) – can be explained by: the presence of glucosinolates in the aboveground biomass of oilseed radish, which exert an acidifying effect during their decomposition (Tsytsiura, 2024b), and the accumulation of organic acids formed during the silage-type anaerobic fermentation of green manure biomass (Tsytsiura, 2025a).

The observed change in soil acidity under the application of oilseed radish can be explained by the formation of hydrogen cation groups, which, against the background of the soil's relatively low buffering capacity, leads to gradual acidification (Xu et al., 2023). A strong positive correlation was also identified between $pH_{KCl}$ values and the content of humic acids (Chac) within the accumulated organic carbon (OCC) structure ($r = 0.791$, $p < 0.01$), along with a strong negative correlation with the content of fulvic acids ($C_{fac}$) ($r = –0.748$, $p < 0.01$) (Table 6).

**Table 6.** Pearson's correlation coefficient matrix of the analyzed dataset of soil property indicators of experimental variants (*N=60*) over the period 2014–2025

| OCC | $C_{hac}$ | $C_{fac}$ | $C_{residue}$ | $C_{hac}$/ $C_{fac}$ | TN | OCC/ TN | N | P | K | $pH_{KCl}$ | $E_i$ | BD | PD | SH | $P_k$ | $P_n$ | $P_a$ | $P_g$ | WAC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.000 | 0.814 | -0.813 | -0.624 | 0.810 | 0.892 | 0.780 | 0.916 | 0.758 | 0.820 | 0.388 | -0.611 | -0.898 | -0.848 | -0.939 | 0.707 | 0.889 | 0.977 | 0.854 | 0.046 | H, % |
| | 0.814 | -0.812 | -0.623 | 0.810 | 0.892 | 0.780 | 0.915 | 0.758 | 0.820 | 0.387 | -0.611 | -0.898 | -0.848 | -0.939 | 0.707 | 0.889 | 0.977 | 0.853 | 0.045 | OCC |
| | | -0.928 | -0.861 | 0.978 | 0.771 | 0.568 | 0.894 | 0.937 | 0.915 | 0.791 | -0.567 | -0.965 | -0.982 | -0.867 | 0.904 | 0.947 | 0.821 | 0.986 | 0.555 | $C_{hac}$ |
| | | | 0.610 | -0.982 | -0.709 | -0.650 | -0.814 | -0.885 | -0.880 | -0.748 | -0.630 | 0.889 | 0.946 | 0.854 | -0.839 | -0.905 | -0.816 | -0.930 | -0.517 | $C_{fac}$ |
| | | | | -0.740 | -0.673 | -0.320 | -0.792 | -0.785 | -0.746 | -0.662 | -0.330 | 0.840 | 0.797 | 0.679 | -0.778 | -0.779 | -0.633 | -0.829 | -0.475 | $C_{residue}$ |
| | | | | | 0.745 | 0.593 | 0.855 | 0.915 | 0.910 | 0.801 | 0.354 | -0.939 | -0.981 | -0.864 | 0.888 | 0.939 | 0.818 | 0.974 | 0.575 | $C_{fhc}$/$C_{fac}$ |
| | | | | | | 0.413 | 0.799 | 0.642 | 0.843 | 0.483 | -0.476 | -0.899 | -0.781 | -0.885 | 0.737 | 0.798 | 0.891 | 0.819 | 0.098 | TN |
| | | | | | | | 0.726 | 0.639 | 0.486 | 0.103 | -0.509 | -0.561 | -0.617 | -0.660 | 0.413 | 0.672 | 0.733 | 0.583 | -0.053 | OCC/TN |
| | | | | | | | | 0.827 | 0.825 | 0.500 | 0.130 | -0.924 | -0.919 | -0.935 | 0.715 | 0.965 | 0.934 | 0.900 | 0.220 | N |
| BD | PD | SH | $P_k$ | $P_n$ | $P_a$ | $P_g$ | WAC | | 0.830 | 0.746 | 0.645 | -0.863 | -0.917 | -0.768 | 0.891 | 0.852 | 0.740 | 0.927 | 0.584 | P |
| | 0.964 | 0.927 | -0.886 | -0.954 | -0.907 | -0.981 | -0.395 | BD | | 0.711 | 0.743 | -0.931 | -0.920 | -0.879 | 0.883 | 0.859 | 0.843 | 0.927 | 0.428 | K |
| | | 0.910 | -0.880 | -0.967 | -0.868 | -0.986 | -0.502 | PD | | | 0.727 | -0.693 | -0.742 | -0.493 | 0.793 | 0.639 | 0.376 | 0.759 | 0.873 | $pH_{KCl}$ |
| | | | -0.713 | -0.943 | -0.969 | -0.887 | -0.130 | SH | | | | -0.148 | -0.215 | -0.008 | 0.391 | 0.171 | -0.079 | 0.295 | 0.753 | $E_i$ |
| | | | | 0.763 | 0.707 | 0.934 | 0.636 | $P_k$ | | | | | | | | | | | | |
| | | | | | 0.904 | 0.944 | 0.358 | $P_n$ | | | | | | | | | | | | |
| | | | | | | 0.862 | 0.048 | $P_a$ | | | | | | | | | | | | |
| | | | | | | | 0.523 | $P_g$ | | | | | | | | | | | | |

See Table 4, 5's notes for a description of the indicators. Significance levels (Student's *t-test*): $|r| = 0.255–0.330$ ($p < 0.05$); $|r| = 0.331–0.415$ ($p < 0.01$); $|r| \geq 0.415$ ($p < 0.001$).

These relationships support the findings of previous studies (Rani et al., 2021; Zhang et al., 2023a; Duan et al., 2024), which reported increased buffering capacity of the soil adsorption complex as a result of optimized humification processes and the additional accumulation of plant-derived organic matter.

It is also important to note that the observed acidity variation range aligns with results obtained for other cruciferous green manures, where changes typically fall within 0.1–0.2 pH units (Talgre, 2013; Kemper, 2024). Furthermore, the results confirm the beneficial influence of the high carbohydrate and calcium content in both the aboveground and root biomass of oilseed radish green manures, as documented in previous studies (Tsytsiura, 2024b).

The summarized interplay of mineralization and humification processes within the soil profile involving the green manure biomass of oil radish also explains the observed effects of the experimental variants on soil electrical conductivity (EC) across different soil layers. Considering that the absence of additional mineral and organic fertilization gradually leads to depletion of the soil solution in mobile cations and anions (Roy & Kashem, 2014), this naturally results in decreased electrical conductivity. The EC indicator also decreases with reduced actual and potential soil moisture content. This is supported by the correlation results between soil water absorption capacity (WAC) and EC, with a coefficient of $r = 0.753$ ($p < 0.001$). According to the presented assessments, electrical conductivity did not show a statistically significant dependence on soil bulk density (BD) and soil hardness (SH), and exhibited a weak negative correlation with particle density (PD) (Table 6).

These aspects of EC formation are partly explained by the inverse correlations of the aforementioned agro-physical soil parameters ($r = -0.493$ to $-0.920$, $p < 0.01$) with the contents of nitrogen, phosphorus, and potassium, as well as the previously noted relationship with WAC. On the other hand, degradation processes that cause overall soil structure breakdown increase soil density, potentially raising EC but also simultaneously reducing soil moisture capacity and cation-anion exchange capacity, which ultimately lowers electrical conductivity.

Due to these correlation relationships and considering the fact that increasing organic carbon content in the soil profile leads to a decrease in EC ($r = -0.611$, $p < 0.001$), the overall soil electrical conductivity in the 0–30 cm layer in the green manure variant (2025 measurement) was 3.35% lower compared to the absolute control (2014). However, when comparing EC at the 2025 assessment between the variants without and with green manuring, the variant with green manure showed 29.71% higher electrical conductivity. Similar conclusions were drawn in the studies of Suon et al. (2023).

The results of the presented studies confirmed consistent processes of overall soil profile degradation in the absence of organic replenishment and without any additional mineral fertilization. This led to steady declines in the total humus content of the soil profile and, consequently, caused a general reduction in soil aggregation and a denser, more destructured profile.

The above generalizations have shaped a positive agro-technological image of oilseed radish as a cruciferous green manure species for the intermediate green manuring variant, which was confirmed by the resultant Structure Stability Index (StI) (Table 5). The index values across the experimental variants ranged from 2.450 to 3.648 (with an average experimental variant value of 3.069). According to the statements by Kemper & Rosenau (1986) and Borek (2019), soils with StI < 5% are classified as structurally degraded (overall, the use of oilseed radish as a green manure, by the final assessment dates and in comparison with the Control II treatment, resulted in an improvement of the indicator, yielding a growth index of 1.36).

Thus, due to intensive previous agricultural use, the soil cover of the experimental plots already exhibited a reduced fertility potential at the beginning of the trial. Long-term application of green manuring significantly increased the StI by 23.74% in the 0–10 cm soil layer, by 22.59% in the 10–20 cm layer, and by 27.22% in the 20–30 cm layer. This pattern clearly confirms the highest effectiveness of green manuring at depths corresponding to the incorporation zone of the green manure biomass.

In the treatment without green manuring, the opposite trend was observed relative to the absolute control (2014): a decline in StI by 11.40% in the 0–10 cm layer, and by 10.72% and 5.38% in the 10–20 cm and 20–30 cm layers, respectively. From the standpoint of applying the StI indicator to assess soil degradation intensity, the strongest deterioration of structural, physical, and agrochemical properties under intensive use of grey forest soils without fertilization was concentrated in the upper part of the arable horizon (0–10 cm). According to Xu et al. (2025), this creates a high risk of surface crusting and significantly impairs soil profile aeration – key indicators of active degradation processes.

However, when comparing the data for 2019 and 2025 for the treatment without green manuring, a gradual downward shift in the depth at which degradation effects intensified was observed, indicating the progressive penetration of adverse changes into deeper soil layers. The overall changes in the Structure Stability Index (StI) were supported by the assessment of the experimental treatments' influence on the formation of soil agrophysical and water-related properties within the 0–30 cm layer (Table 7). Changes in the agrophysical parameters were evaluated through the dynamics of the main textural fractions of the soil's mechanical composition. Although mechanical composition is generally regarded as a stable property – primarily determined by parent material and pedogenesis, and only marginally influenced by green manuring (Plisko, 2019; Medvedev et al., 2020) – a noticeable trend toward shifts in the major textural components was identified.

Specifically, compared with the control at the final assessment date (2025), the 0–30 cm soil layer exhibited an average decrease in the sand fraction (0.05–2.00 mm) by 10.92%, the silt fraction (0.002–0.05 mm) by 1.49%, and the clay fraction (< 0.002 mm) by 6.01% (Table 7). These findings were consistent with the evaluation of the stability of the < 0.25 mm fraction in terms of its contribution to soil aggregate formation (Ciric et al., 2012; Melo et al., 2022; Dai et al., 2024; Nsabimana et al., 2024). It should also be noted that the observed trends align with and positively correlate with existing models describing the formation of soil structural–aggregate and mechanical composition under systematic green manuring.

The threshold difference values for the analyzed soil layers are presented in comparison with their corresponding values in the Absolute Control treatment, at a statistical significance level of $p < 0.05$.

**Table 7.** Dataset of agrophysical and selected soil water property parameters as influenced by experimental treatments (for the comparable period 2014–2025)*

| Treatment variant | Soil layer, cm | Fraction share, % sand | silt | clay | BD, g cm$^{-3}$ | PD, g cm$^{-3}$ | SH, kg cm$^{-2}$ | $P_k$, % | $P_n$, % | $P_a$, % | $P_g$, % | WAC, % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2014 | | | | | | | | | | | | |
| Absolute control | 0–10 | 23.84$^{a}$ | 63.97$^{a}$ | 22.52$^{a}$ | 1.32$^{a}$ | 2.55$^{a}$ | 13.51$^{a}$ | 26.36$^{a}$ | 20.44$^{a}$ | 21.54$^{a}$ | 46.80$^{a}$ | 23.87$^{a}$ |
| | 10–20 | 23.51$^{a}$ | 62.37$^{b}$ | 23.36$^{a}$ | 1.36$^{b}$ | 2.57$^{a}$ | 16.17$^{b}$ | 26.78$^{a}$ | 19.78$^{b}$ | 18.64$^{b}$ | 46.56$^{a}$ | 26.62$^{b}$ |
| | 20–30 | 21.97$^{a}$ | 63.95$^{a}$ | 23.09$^{a}$ | 1.45$^{c}$ | 2.62$^{b}$ | 19.56$^{c}$ | 25.35$^{b}$ | 18.53$^{b}$ | 14.98$^{c}$ | 43.88$^{b}$ | 28.47$^{c}$ |
| 2019 | | | | | | | | | | | | |
| Control I ** | 0–10 | 28.66$^{b}$ | 63.48$^{a}$ | 24.59$^{b}$ | 1.37$^{a}$ | 2.61$^{a}$ | 15.29$^{a}$ | 24.74$^{a}$ | 19.74$^{a}$ | 20.43$^{a}$ | 44.48$^{a}$ | 21.54$^{a}$ |
| | 10–20 | 29.06$^{b}$ | 63.54$^{a}$ | 24.31$^{b}$ | 1.41$^{b}$ | 2.63$^{a}$ | 18.39$^{b}$ | 25.29$^{a}$ | 19.15$^{a}$ | 17.17$^{b}$ | 44.44$^{a}$ | 24.51$^{b}$ |
| | 20–30 | 27.73$^{b}$ | 64.52$^{c}$ | 24.99$^{b}$ | 1.49$^{c}$ | 2.65$^{a}$ | 19.44$^{b}$ | 23.28$^{b}$ | 18.47$^{a}$ | 12.22$^{c}$ | 41.75$^{b}$ | 27.11$^{c}$ |
| Green manure application I*** | 0–10 | 19.20$^{c}$ | 61.11$^{d}$ | 22.21$^{a}$ | 1.18$^{a}$ | 2.48$^{a}$ | 11.24$^{a}$ | 27.22$^{a}$ | 23.17$^{a}$ | 23.61$^{a}$ | 50.39$^{a}$ | 24.29$^{a}$ |
| | 10–20 | 18.56$^{c}$ | 61.41$^{d}$ | 22.60$^{a}$ | 1.22$^{b}$ | 2.51$^{a}$ | 14.87$^{b}$ | 29.14$^{b}$ | 21.17$^{b}$ | 20.48$^{b}$ | 50.31$^{a}$ | 28.15$^{b}$ |
| | 20–30 | 19.97$^{d}$ | 63.01$^{b}$ | 22.98$^{a}$ | 1.29$^{c}$ | 2.54$^{b}$ | 16.24$^{b}$ | 28.84$^{b}$ | 19.63$^{c}$ | 18.07$^{b}$ | 48.47$^{b}$ | 30.53$^{c}$ |
| 2025 | | | | | | | | | | | | |
| Control II **** | 0–10 | 30.46$^{e}$ | 63.59$^{a}$ | 26.29$^{c}$ | 1.42$^{a}$ | 2.65$^{a}$ | 16.18$^{a}$ | 24.72$^{a}$ | 18.41$^{a}$ | 18.23$^{a}$ | 43.13$^{a}$ | 20.37$^{a}$ |
| | 10–20 | 29.85$^{e}$ | 64.02$^{a}$ | 25.33$^{b}$ | 1.45$^{a}$ | 2.67$^{a}$ | 19.81$^{b}$ | 25.19$^{a}$ | 17.12$^{b}$ | 15.47$^{b}$ | 42.31$^{a}$ | 23.86$^{b}$ |
| | 20–30 | 27.26$^{b}$ | 64.65$^{c}$ | 26.56$^{c}$ | 1.49$^{b}$ | 2.72$^{b}$ | 21.96$^{c}$ | 23.92$^{b}$ | 16.85$^{b}$ | 11.15$^{c}$ | 40.77$^{b}$ | 28.79$^{c}$ |
| Green manure application II***** | 0–10 | 18.65$^{c}$ | 62.59$^{b}$ | 20.44$^{d}$ | 1.14$^{a}$ | 2.39$^{a}$ | 10.12$^{a}$ | 28.18$^{a}$ | 24.59$^{a}$ | 25.59$^{a}$ | 52.77$^{a}$ | 27.63$^{a}$ |
| | 10–20 | 18.38$^{c}$ | 62.42$^{b}$ | 19.20$^{e}$ | 1.17$^{a}$ | 2.41$^{a}$ | 12.24$^{b}$ | 29.89$^{b}$ | 23.55$^{b}$ | 23.48$^{b}$ | 53.44$^{b}$ | 33.59$^{b}$ |
| | 20–30 | 17.78$^{f}$ | 63.79$^{a}$ | 19.43$^{e}$ | 1.22$^{b}$ | 2.44$^{a}$ | 13.21$^{b}$ | 29.48$^{b}$ | 22.08$^{b}$ | 20.22$^{c}$ | 51.56$^{c}$ | 32.93$^{b}$ |
| Threshold level (diff) in TukeyHSD test** | 0–10 | 2.87 | 0.15 | 0.19 | 0.04 | 0.04 | 1.17 | 1.23 | 0.72 | 0.81 | 1.14 | 1.78 |
| | 10–20 | 3.12 | 0.31 | 0.57 | 0.04 | 0.03 | 1.52 | 1.19 | 0.79 | 1.24 | 1.18 | 1.89 |
| | 20–30 | 4.25 | 0.39 | 0.45 | 0.07 | 0.05 | 1.74 | 1.62 | 0.67 | 1.51 | 1.57 | 2.05 |

Note: The explanation of treatments is provided in Table 1. Indicator definitions: sand – soil particle fraction (0.05–2.0 mm); silt – soil particle fraction (0.002–0.05 mm); clay – soil particle fraction (< 0.002 mm); BD – soil bulk density, g cm$^{-3}$; PD – particle density, g cm$^{-3}$; SH – soil hardness, kg cm$^{-2}$; Pk – capillary porosity of the soil, %; Pn – non-capillary porosity of the soil, %; Pa – aeration porosity of the soil, %; Pg – total porosity of the soil, %; WAC – water absorption capacity of the soil, %.

Different lowercase letters in superscript next to the parameter values in the table indicate significant differences among experimental treatments between soil layers within the same treatment ($p < 0.05$).

These models have been described in a number of publications for various soil-climatic zones (Abiven et al., 2008; Segoli et al., 2013; Tuo et al., 2017; Bulygin et al., 2020; Zhou et al., 2020; Lawal et al., 2022; Choudhary et al., 2023; Krishnan & Sivakumar, 2024; Chen et al., 2025) from the standpoint of enhanced aggregation involving intermediate fractions sized < 0.05 mm, alongside intensified internal profile reworking of the finest fractions, which creates certain structural shifts in the main fractions that ultimately determine the mechanical composition of the soil. At the same time, the overall classifying group of mechanical composition component ratios is preserved, particularly for the represented soil type – clay loam. In these models, it has been noted that under intensive agricultural use without any fertilization, especially organic fertilization, which leads to a negative trend in humus content, soil aggregate dispersion is observed, along with a simultaneous increase in soil fractions larger than 10 mm and smaller than 0.25 mm.

The fractional ratio shifts in the long-term evaluation towards fractions smaller than 2 mm, and at the microaggregate level, there is a significant increase in fractions smaller than 0.05 mm. This dynamic leads to intensive soil compaction, a decrease in all forms of porosity, with the resulting effect being a gradual increase in soil hardness (SH), which is consistent with findings by Yang et al. (2025).

These processes were consistently identified in the experimental variants through indicators such as bulk density (BD), particle density (PD), soil hardness (SH), and specific types of soil porosity ($P_k$, $P_n$, $P_a$). Based on the comparison of the variants with and without green manure by the final assessment date (2025), a decrease in BD by 19.05%, PD by 9.95%, and SH by 33.95% was determined, alongside an increase in $P_k$ by 18.63%, $P_n$ by 34.06%, and $P_a$ by 57.83%. The greatest changes, either increasing or decreasing, were observed in the soil horizon from 10 to 30 cm. Under the same conditions, compared to the absolute control variant (baseline indicators from 2014), an opposite trend was noted: increases in BD by 5.65%, PD by 3.88%, and SH by 18.18%, accompanied by decreases in $P_k$ by 5.93%, $P_n$ by 10.82%, and $P_a$ by 19.31%. In these cases, the primary structural changes in the variant without green manure were observed in the 0–20 cm soil layer. Regarding the total porosity indicator ($P_g$), its value was determined by the specifics of forming component types of porosity, based on the calculation ratio of capillary and non-capillary soil porosity.

The described patterns of influence on the overall set of soil properties resulting from the use of oilseed radish as a green manure are positively aligned with findings reported in numerous studies (Edlinger et al., 2023; Kumar et al., 2023; Lee et al., 2023; Zhang et al., 2023; Li et al., 2024; Wu et al., 2024; Yang et al., 2025; Park & Lee, 2025). These results are also confirmed by correlation analysis (Table 6), which showed a strong inverse relationship between soil porosity parameters and key density indicators across the entire dataset at a level of $r > -0.850$ ($p < 0.001$). Similarly, an inverse correlation was found between the same soil density parameters and humus content with a correlation coefficient of approximately $r \approx -0.900$ ($p < 0.001$). Considering that the indicated features of the formation of basic agro-physical soil parameters were directly determinative in creating potential pore spaces for water movement and retention (according to Rasheed et al., 2022), the applied treatments logically influenced the fundamental constant of soil water properties – the water absorption capacity of the soil (WAC). It was determined that systematic use of green manuring over the period

2014–2024 contributed to an increase in this indicator compared to the control without green manure by 35.64% in the 0–10 cm soil layer, and respectively by 40.78% and 14.38% in the 10–20 cm and 20–30 cm soil layers. These values were on average 11% higher than those obtained in soils with heavier mechanical composition (according to dos Santos et al., 2021) and 8.7% lower than those found in soils with lighter mechanical composition (according to Plisko, 2019) under green manure fertilization variants. This effect is associated with the specific root system development of oilseed radish during its summer (intermediate) green manure use (Tsytsiura, 2025b), which, due to intensive branching and rapid deepening, strongly influences the formation of the soil profile structure, its aeration, and, through the decomposition of root residues in the soil, serves as an additional effective source of organic matter.

The determined level of correlation determination, with over 70% of correlation coefficients exceeding r > 0.600 (Table 6) (according to Chaudhry et al., 2024), allows for the application of PCA (Principal Component Analysis) approaches to define integral soil quality assessment coefficients. The calculated components of the PCA, following the standard applied procedure, are presented in Table 8. After evaluating the variance plot of components and the cumulative variance indicators, with a requirement to represent no less than 80% cumulative variance, a two-component analysis was applied.

**Table 8.** Principal Component Analysis Parameters of Soil (PAs) (based on dataset 2014–2025)

| Soil parameter | Principal component 1 (PC1) | Principal component 2 (PC2) | Communalities | Weight of the i-th parameter ($w_i$) | Soil parameter | Principal component 1 (PC1) | Principal component 2 (PC2) | Communalities | Weight of the i-th parameter ($w_i$) |
|---|---|---|---|---|---|---|---|---|---|
| H, % | 0.899 | -0.414 | 0.980 | 0.052 | $pH_{Kcl}$ | -0.725 | -0.598 | 0.884 | 0.047 |
| OCC | 0.899 | -0.414 | 0.980 | 0.052 | $E_i$ | 0.274 | 0.821 | 0.749 | 0.040 |
| $C_{fhc}$ | 0.981 | 0.148 | 0.984 | 0.052 | BD | 0.984 | -0.029 | 0.968 | 0.051 |
| $C_{fac}$ | 0.936 | 0.073 | 0.882 | 0.047 | PD | 0.981 | 0.075 | 0.968 | 0.051 |
| $C_{residue}$ | 0.813 | 0.213 | 0.706 | 0.037 | SH | 0.928 | -0.260 | 0.930 | 0.049 |
| $C_{fhc}$ : $C_{fac}$ | 0.984 | 0.116 | 0.981 | 0.052 | $P_k$ | 0.902 | 0.257 | 0.879 | 0.047 |
| TN | 0.861 | -0.327 | 0.848 | 0.045 | $P_n$ | -0.975 | 0.083 | 0.958 | 0.051 |
| OCC : TN | 0.631 | -0.393 | 0.552 | 0.029 | $P_a$ | 0.908 | -0.382 | 0.969 | 0.051 |
| N | 0.949 | -0.178 | 0.932 | 0.049 | $P_g$ | 0.990 | 0.087 | 0.988 | 0.052 |
| P | 0.926 | 0.228 | 0.910 | 0.048 | WAC | 0.392 | 0.884 | 0.936 | 0.050 |
| K | 0.950 | 0.032 | 0.904 | 0.048 | | | | | |
| Eigenvalue | | | | | | 15.999 | 2.888 | | |
| Percent variance | | | | | | 6.189 | 3.752 | | |
| Cumulative percent variance | | | | | | 6.189 | 9.942 | | |

Note: Context of indicators: H – humus content, %; OCC – organic carbon content, %; $C_{fac}$ – total fulvic acid content, % of OCC; $C_{hac}$ – total humic acid content, % of OCC; Humin – content of humin fraction, % of OCC; TN – total nitrogen content, %; N – easily hydrolyzable nitrogen, mg kg$^{-1}$; P – available phosphorus (as $P_2O_5$), mg kg$^{-1}$; K – exchangeable potassium (as $K_2O$), mg kg$^{-1}$; pHKCl – soil acidity (salt method); $E_i$ – soil electrical conductivity (salinity), dS m$^{-1}$; StI – structure stability index; BD – soil bulk density, g cm$^{-3}$; PD – particle density, g cm$^{-3}$; SH – soil hardness, kg cm$^{-2}$; Pk – capillary porosity, %; $P_n$ – non-capillary porosity, %; $P_a$ – aeration porosity, %; $P_g$ – total porosity, %; WAC – water absorption capacity of the soil, %.

This fully corresponded to the approaches for assessing the Soil Quality Index and the standard requirements for such procedures (He et al., 2023). The obtained communalities and weighting parameters of soil properties ($w_i$) showed close absolute values, confirming the appropriateness of the selected soil property dataset for calculating the Soil Quality Index.

This aligns with the principles of initial dataset selection according to Estrada-Herrera et al. (2017) and Simfukwe et al. (2021). The initial dataset used for the calculation of the second Soil Quality Index ($SQ_{II}$) and the Productivity Index (PI) is fully presented in Table 9.

**Table 9.** Data set for the calculation of the RI parameter based on actual average values of the data set within the experimental variants, 2010–2025

| Rotation year | Crops* | $d_a$ | c | $d_{max}$ | $RI_{0–10}$ | $RI_{10–20}$ | $RI_{20–30}$ | Accumulated $RI_{0–30}$ |
|---|---|---|---|---|---|---|---|---|
| 2010 | Soybean | 11.6 | -0.626 | 172.1 | 0.486 | 0.147 | 0.039 | 0.672 |
| 2011 | Soybean | 11.6 | -0.626 | 172.1 | 0.486 | 0.147 | 0.039 | 0.672 |
| 2012 | Winter wheat (*Triticum aestivum* L.) | 17.2 | -1.286 | 150.4 | 0.336 | 0.272 | 0.075 | 0.683 |
| 2013 | Annual lupine (*Lupinus albus* L.) | 16.2 | -1.115 | 104.8 | 0.379 | 0.263 | 0.054 | 0.696 |
| 2014 | Sorghum | 14.5 | -1.165 | 128.1 | 0.399 | 0.205 | 0.113 | 0.789 |
| | Oilseed radish** | 9.9 | -0.473 | 42.8*** | 0.579 | 0.198 | 0.084 | |
| 2015 | Spring barley | 11.8 | -1.06 | 146.1 | 0.461 | 0.225 | 0.056 | 0.742 |
| 2016 | Pea | 18.9 | -1.394 | 111.3 | 0.299 | 0.307 | 0.071 | 0.756 |
| | Oilseed radish | 9.9 | -0.473 | 46.9** | 0.570 | 0.190 | 0.075 | |
| 2017 | Spring barley | 11.8 | -1.06 | 146.1 | 0.461 | 0.225 | 0.056 | 0.742 |
| 2018 | Soybean | 11.6 | -0.626 | 172.1 | 0.486 | 0.147 | 0.039 | 0.775 |
| | Oilseed radish | 9.9 | -0.473 | 40.9** | 0.584 | 0.203 | 0.090 | |
| 2019 | Spring wheat | 17.2 | -1.286 | 150.4 | 0.336 | 0.272 | 0.075 | 0.683 |
| 2020 | Sunflower | 10 | -0.671 | 133.3 | 0.511 | 0.161 | 0.038 | 0.787 |
| | Oilseed radish | 9.9 | -0.473 | 42.5** | 0.580 | 0.199 | 0.085 | |
| 2021 | Pea | 18.9 | -1.394 | 111.3 | 0.299 | 0.307 | 0.071 | 0.677 |
| 2022 | Chickpea | 11.9 | -0.98 | 92.9 | 0.470 | 0.235 | 0.045 | 0.814 |
| | Oilseed radish | 9.9 | -0.473 | 40.9** | 0.584 | 0.203 | 0.090 | |
| 2023 | Spring barley | 11.8 | -1.06 | 146.1 | 0.461 | 0.225 | 0.056 | 0.742 |
| 2024 | Maize | 14.9 | -1.151 | 118.3 | 0.394 | 0.260 | 0.058 | 0.753 |
| | Oilseed radish | 9.9 | -0.473 | 55.8** | 0.556 | 0.176 | 0.061 | |

The Latin names of other crops cultivated in the rotational scheme of the experiment are presented in Table 1. ** Oilseed radish used as an intermediate green manure. *** Parameter based on a long-term study of the root systems of oilseed radish under its green-manure use (Tsytsiura, 2025b). The period 2010–2013 was used for calculating the RI indicator for the absolute control variant (2014). The parameters da and c of the cumulative root distribution curve for a given crop, expressed as a fraction at a specific soil profile depth, and dmax, the maximum root length of the crop (cm), were taken from the dataset of Fan et al. (2016). $R1_{0–10}$, $RI_{10–20}$, and $RI_{20–30}$ represent the proportion of roots in the 0–10, 10–20, and 20–30 cm soil layers, respectively. $RI_{0–30}$ is the accumulated RI parameter for the 0–30 cm soil layer.

According to the determined root influence parameter in the analyzed soil layer (RI), oilseed radish, with its short growing period as a summer green manure, exhibits a relatively high cumulative effect, amounting to at least 47–58% of the accumulation share observed for cereal and leguminous crops used in the crop rotation system over the period 2010–2024.

This confirmed the long-term critical evaluation of the root system of oilseed radish from the perspective of its use as a green manure (Tsytsiura, 2025b) and the agro-technological value of the root biomass of this crop within overall green manure systems for conditions of unstable moisture on soils with low to medium fertility levels. As a consequence of the noted features, the average indicator of additional accumulation of root residues in the 0–30 cm soil layer over the entire assessment period was at the level of 11.13% and ranged from 9.87% to 20.45% compared to a similar single-component variant without green manure cultivation of certain agricultural crops. This ensured, alongside the identified positive influence on the complex of agro-physical and agro-chemical soil properties, the differentiation of the resulting Productivity Index (PI). In particular, its value at the final assessment date in the variant with green manure application was 24.86% higher compared to the absolute control variant (2014) and 34.87% higher compared to the variant without green manure on the same assessment date.

Meanwhile, the Productivity Index (PI) in the variants without green manure decreased by 7.43% compared to the absolute control (Table 10).

It should be noted that the obtained PI values correspond to the lower threshold of the medium soil fertility potential range within the 0.5–0.8 gradation (according to Chornyi & Vilna (Poliashenko), 2019), except for the variant without green manure, where according to the latest assessment data, this indicator fell into the low fertility category (0.3–0.5). Thus, under intensive agricultural use without fertilization over a long time frame in conditions of unstable moisture, gray forest soils show a stable trend of declining inherent fertility potential. The rate of this decline during 2014–2025 (with the baseline from 2014 data) was -0.0036 PI per year. Conversely, for the variant with sustainable green manure use of oilseed radish, the indicator was +0.0122 PI per year. Similar patterns were identified for the $SQI_{II}$ indicator as well. Comparison of the actual soil property group parameters within the experimental variants (Table 5, 7) with the expert evaluation criteria parameters (Table 2) allowed the calculation of the total score of soil parameters (S) (Table 10).

The determined values of this calculation additionally confirmed the feasibility and effectiveness of the green manure variant using oilseed radish as the green manure crop. Compared to the Absolute control variant (2014), the total score of soil parameter was lower in the variants without green manure by 14.29% for the 0–10 cm and 10–20 cm soil layers, and by 9.38% for the 20–30 cm soil layer.

**Table 10.** Normalized criteria for calculating the Productivity Index (PI) and summary parameters of the second soil quality index ($SQI_{II}$) within the experimental variants, 2010–2025

| [a] Treatment variant | Soil layer, cm | $H_i$ | $WAC_i$ | $BD_i$ | $pH_i$ | $E_i$ | $P_i$ | $K_i$ | [c] $RI_{av}$ | [d] Productivity index (PI) 0–30 cm | Total score of soil parameter (S) | $SQI_{II}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [b] $H_i$=h/2.7 if h≤2.7 and 1 if h≥2.7 (DSTU 4362:2004 (2005)) | $WAC_i$= WAC/35 if WAC≤30 1 if WAC≥35 (Mulengera & Payton, 1999) | $BD_i$=1-5.00×(BD-1.20)$^2$ if BD≤1.65 0.1 if BD≥1.65 (Chornyi & Vilna, 2019)) | $pH_i$=-0.067×(pH)$^2$+0.875×pH-1.863 (Chornyi & Vilna, 2019) | $E_i$=1.00-0.07E (Mulengera & Payton, 1999) | $P_i$=P/45 if P≤45 1 if P≥45 (Chornyi & Vilna, 2019)) | $K_i$=K/300 if K≤300 1 if K≥300 Chornyi & Vilna, 2019)) | | | | |
| 2014 | | | | | | | | | | | | |
| Absolute control | 0–10 | 0.993 | 0.597 | 0.93 | 0.960 | 0.980 | 1.000 | 0.396 | 0.422 | 0.539 | 35 | 0.636 |
| | 10–20 | 0.948 | 0.666 | 0.87 | 0.962 | 0.980 | 1.000 | 0.369 | 0.207 | | 35 | 0.636 |
| | 20–30 | 0.796 | 0.712 | 0.69 | 0.951 | 0.978 | 1.000 | 0.352 | 0.052 | | 32 | 0.582 |
| 2019 | | | | | | | | | | | | |
| Control I | 0–10 | 0.967 | 0.539 | 0.86 | 0.949 | 0.984 | 1.000 | 0.368 | 0.421 | 0.528 | 31 | 0.564 |
| | 10–20 | 0.915 | 0.613 | 0.78 | 0.951 | 0.982 | 1.000 | 0.347 | 0.222 | | 31 | 0.564 |
| | 20–30 | 0.752 | 0.678 | 0.58 | 0.963 | 0.980 | 1.000 | 0.318 | 0.067 | | 30 | 0.545 |
| Green manure application I | 0–10 | 1.052 | 0.607 | 1.00 | 0.965 | 0.982 | 1.000 | 0.408 | 0.499 | 0.643 | 38 | 0.691 |
| | 10–20 | 1.004 | 0.704 | 1.00 | 0.970 | 0.981 | 1.000 | 0.391 | 0.210 | | 37 | 0.673 |
| | 20–30 | 0.870 | 0.763 | 0.96 | 0.975 | 0.979 | 1.000 | 0.402 | 0.075 | | 39 | 0.709 |
| 2025 | | | | | | | | | | | | |
| Control II | 0–10 | 0.874 | 0.509 | 0.76 | 0.940 | 0.985 | 1.000 | 0.352 | 0.417 | 0.499 | 30 | 0.545 |
| | 10–20 | 0.844 | 0.597 | 0.69 | 0.945 | 0.983 | 1.000 | 0.341 | 0.227 | | 30 | 0.545 |
| | 20–30 | 0.733 | 0.720 | 0.58 | 0.965 | 0.982 | 1.000 | 0.335 | 0.054 | | 29 | 0.527 |
| Green manure application II | 0–10 | 1.081 | 0.691 | 0.98 | 0.971 | 0.982 | 1.000 | 0.426 | 0.493 | 0.673 | 41 | 0.745 |
| | 10–20 | 1.030 | 0.840 | 1.00 | 0.980 | 0.980 | 1.000 | 0.405 | 0.218 | | 42 | 0.764 |
| | 20–30 | 0.941 | 0.823 | 1.00 | 0.983 | 0.979 | 1.000 | 0.436 | 0.068 | | 41 | 0.745 |

[a]Explanation of variants is given in the Table 1. [b] Criteria for transformation into normalized indicators; [c] Average parameter representing the proportion of roots ($RI_{av}$) for the respective variants over the periods (2010–2013, 2014–2019, 2020–2024); [d] Presented as the sum for each soil horizon (according to Pierce et al. (1983)); $H_i$ – humus content; $WAC_i$ – water absorption capacity of the soil; $BD_i$ – soil bulk density; $pH_i$ – soil solution pH; $E_i$ – soil electrical conductivity (salinity); $P_i$ – available phosphorus content ($P_2O_5$); $K_i$ – exchangeable potassium content ($K_2O$); $RI_i$ – parameter representing the proportion of roots in each soil layer; $SQ_{II}$ – the second soil quality index. For the corresponding crop with green manure, the calculation of the average indicator for two components was applied according to Pierce et al. (1983).

Conversely, for the variant with sustained use of oilseed radish as green manure, the corresponding values across the studied soil layers were 17.14%, 20.00%, and 28.13%, respectively. Comparing the variants with and without green manure as of 2025, an increase of 36.67%, 40.00%, and 41.38% was observed, respectively. This pattern of distribution within the variants logically influenced the $SQI_{II}$ indicator values, which showed a similar trend across the experimental variants (Table 10). It should be noted that the obtained values for the $SQI_{I}$, $SQI_{II}$, and PI indicators differed in magnitude (Fig. 1).

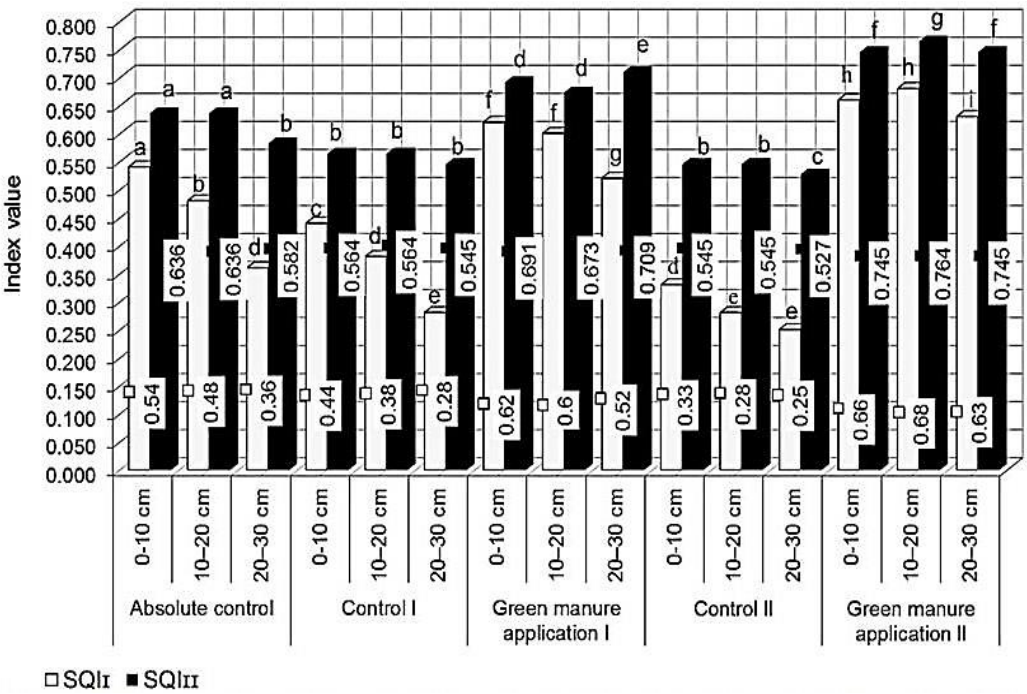


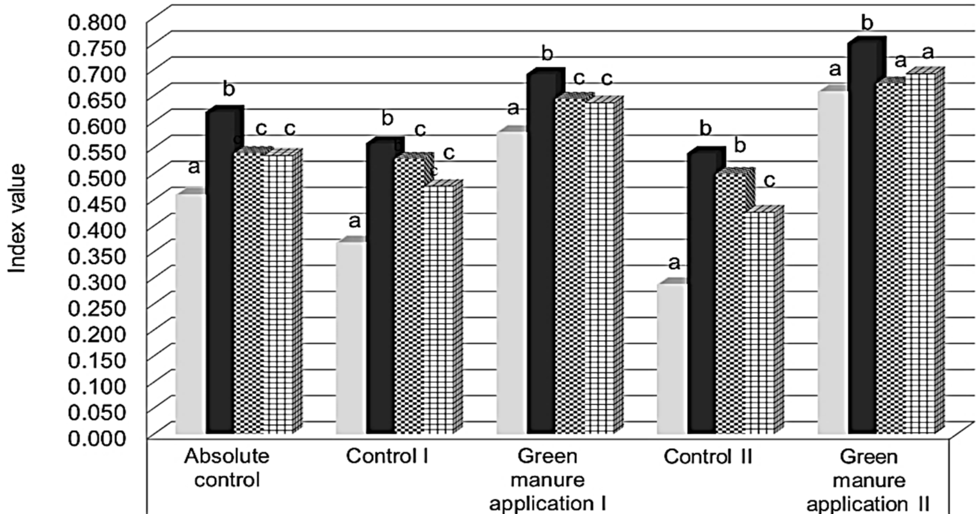

**Figure 1.** Soil quality indices ($SQI_{I}$ and $SQI_{II}$) based on the analyzed soil parameter dataset, 2014–2025.

Note: Explanation of variants is given in the Table 1. $SQ_{I}$ – the first Soil Quality Index; $SQ_{II}$ – the second soil quality index. Different letters within the same column indicate significant differences at the 5% significance level according to the LSD test (comparisons conducted separately for $SQI_{I}$ and $SQI_{II}$ parameters).

Specifically, based on the average values within the recorded variants, the applied soil quality assessment criteria were ranked in ascending order as follows: $SQI_{I}$ (0.470) – PI (0.576) – $SQI_{II}$ (0.631). From the standpoint of assessment reliability, it has been noted (Obade & Gaya, 2021; AbdelRahman et al., 2022; Bhaduri et al., 2022; Kusumawati et al., 2022; Chaudhry et al., 2024; Coelho et al., 2024; Sakin et al., 2024) that preference is given to the SQII indicator. This is because the SQI variant, due to its reliance on expert evaluation, contains a certain degree of subjectivity in the gradational assessment, as well as several nuances related to soil type, soil-climatic zone, and even the methods used for determining individual indicators – all of which influence the quality and reliability of the assessment.

Similar considerations apply to the Productivity Index (PI), since the RI component in the formula follows a standardized (unified) approach with fixed criteria for root system distribution according to Fan et al. (2016), while the first part of the PI calculation also incorporates an element of expert-based normalization.

Given these arguments, a decision was made to define an integrated soil quality indicator – the Integral Soil Fertility Index (ISFI) – and to evaluate its values under different soil management treatments (Fig. 2).




| | Absolute control | Control I | Green manure application I | Control II | Green manure application II |
|---|---|---|---|---|---|
| SQIɪ (0–30 cm) | 0.459 | 0.367 | 0.579 | 0.287 | 0.657 |
| SQIɪɪ (0–30 cm) | 0.618 | 0.558 | 0.691 | 0.539 | 0.751 |
| PI (0–30 cm) | 0.539 | 0.528 | 0.643 | 0.499 | 0.673 |
| ISFI (0–30 cm) | 0.535 | 0.476 | 0.636 | 0.426 | 0.692 |

**Figure 2.** Evaluated experimental variants based on applied soil quality and productivity indices with identification of the mean indicator (data set for the period 2010–2025).

Note: Explanations of the experimental variants are provided in Table 1. SQI – the first Soil Quality Index; SQII – the second Soil Quality Index; ISFI – Integral Soil Fertility Index; PI – Productivity Index. Different lowercase letters in the table indicate significant differences among treatments within the same variant ($p < 0.05$).

This integrative approach corresponds to the specifics of applying multiple methodological frameworks for soil index assessment (as outlined by Chaudhry et al., 2024) and allows for their comprehensive consideration when developing a highly reliable indicator. The results obtained through this methodology, taking into account the aforementioned generalizations, consistently demonstrate the markedly higher effectiveness of using oilseed radish as green manure in preserving and enhancing the complex of agrophysical and agrochemical properties of gray forest soils. In this treatment, the highest ISFI value – 0.692 – was recorded at the final assessment stage, representing an increase of 29.35% compared with the absolute control and 62.44% compared with the treatment without green manure.

These findings provide scientifically substantiated grounds for the effective and rational use of oilseed radish as a green manure component and a fully viable alternative to traditional cover crops within bio-organic fertilization systems used in crop rotations.

The introduction of this species contributes to the phytoremediation of soils with moderate fertility potential and significantly reduces their degradation rates under temperate continental agro-landscape conditions with both sufficient and variable moisture regimes.

## CONCLUSIONS

A high soil-rehabilitation and soil-improving potential of oilseed radish used as an intermediate green manure in crop rotations with non-cruciferous crops has been identified for the 0–30 cm soil layer. This is evidenced by a stable annual positive dynamic in the key agrochemical parameters (humus content +0.0026%, organic carbon +0.0026%, total nitrogen +0.0011%, soil C/N ratio +0.0087, easily hydrolyzable nitrogen +0.979 mg $kg^{-1}$, available phosphorus +1.191 mg $kg^{-1}$, exchangeable potassium +1.355 mg $kg^{-1}$, soil pH +0.023, and electrical conductivity −0.0011 dS·$m^{-1}$); agrophysical parameters (bulk density −0.019 g $cm^{-3}$, particle density −0.015 g $cm^{-3}$, soil hardness −0.323 kg $cm^{-2}$, total porosity +0.622%, capillary porosity +0.275%, non-capillary porosity +0.348%, and aeration porosity +0.429%); as well as hydrological characteristics (water absorption capacity +0.460%).

The observed dynamic improvements across these groups of soil properties resulted in a significantly higher Integral Soil Fertility Index (ISFI), reaching 0.692 – representing a notable increase compared to the non-green-manured treatment at the final assessment date, which had an index value of 1.62.

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