Agronomy Research **22**(2), 1026–1070, 2024
https://doi.org/10.15159/AR.24.086

Potential of oilseed radish (*Raphanus sativus* l. var. *oleiformis* Pers.) as a multi-service cover crop (MSCC)

Y. Tsytsiura*

Vinnytsia National Agrarian University, Faculty of Agronomy, Horticulture and Plant protection, Soniachna street, 3, UA21008 Vinnytsia, Ukraine
*Correspondence: yaroslavtsytsyura@ukr.net, yaroslav301974@gmail.com

Received: May 4th, 2024; Accepted: August 13th, 2024; Published: September 5th, 2024

Abstract. The possibility of oilseed radish use as multi-service cover crop (MSCC) during the ten-year period for spring and summer sowing was investigated. A comprehensive approach to assessing the formation of aboveground and root biomass by biochemical analysis with a comprehensive assessment of the factors that determine the quality, manufacturability and agricultural value of the crop was methodically applied. The actual agricultural value from the point of view of the possible use of oilseed radish as a cover, intermediate, green manure, fodder crop and an additional source for biogas production was analyzed.
A multi-year data set based on 8 indicators of the formed plant mass, 17 basic indicators of biochemical composition, and 12 derived indicators of ratios and accumulation was formed. Based on the criterion evaluation and comparison of the long-term data set with similar indicators for cruciferous species used as a multi-service cover crop, oilseed radish was classified as a crop with high adaptive bioorganic potential. This was confirmed by the application of the Multi-criteria decision aiding (MCDA) method. The use of this method proved the possibility of multi-purpose use of oilseed radish as a multi-service cover crop on soils with medium fertility potential for unstable moisture conditions. The order of increasing importance of the direction of critical use of oilseed radish in the spring sowing period was: 'Catch crop' (Consistency index 0.188) - 'Biogas' (0.226) - 'Fodder' (0.370) - 'Green manure' (0.340) - 'Cover crop' (0.431). A similar order for the summer sowing period was: 'Cover crop' (0.244) - 'Catch crop' (0.305) - 'Biogas' (0.357) - 'Fodder' (0.407) - 'Green manure' (0.415).

Key words: criteria of multipurpose use, biogas, green manure, forage intermediate crops, catch crop.

INTRODUCTION

The dynamic growth of soil degradation against the background of a general shortage of classical organic fertilizers and rising prices for mineral fertilizers lead to a constant search for technological alternatives in the agricultural sector of the economy (Kaletnik et al., 2019, 2020; Honcharuk et al., 2023, Tokarchuk et al., 2023; Honcharuk & Yemchyk, 2024). A widely recognized alternative for the formation of environmentally sustainable and balanced soil use is the use of intermediate crops for multiple purposes. Intermediate crops are used for various purposes: biologization of agrotechnologies, soil rehabilitation and conservation, a source of organic recycling fertilization systems (green manure), biomass for feed and bioenergy use (Couëdel et al., 2019; Dzvene et al., 2023). The global market for such crops has a pronounced positive growth trend. The Green Manure Global Market Report 2024 (2023) notes that the green manure market size has grown strongly in recent years. It will grow from $2.17 billion in 2023 to $2.33 billion in 2024 at a compound annual growth rate of 7.6%. The growth in the historical period can be attributed to organic farming practices, soil health awareness, crop rotation practices, government support and subsidies, crop diversification, water conservation, and reduced environmental impact. The green manure market size is expected to see strong growth in the next few years. It will grow to $3.07 billion in 2028 at a compound annual growth rate of 7.1%. The growth in the forecast period can be attributed to climate change adaptation, regenerative agriculture practices, consumer demand for sustainable agriculture, integration in precision agriculture, enhanced soil microbial activity, water quality management. Major trends in the forecast period include the integration of leguminous and cruciferous cover crops, no-till and reduced-till farming systems, innovations in cover cropping.

Based on this, the concept of multi-service cover crop (MSCC) was formulated (Justes & Richard, 2017). It involved the search, selection, and combination of crops in crop rotation that are characterized by unpretentiousness to the terms of use, high intensity and volume of accumulation of aboveground and underground biomass of appropriate biochemical quality and rates of mineralization in the soil and suitability for anaerobic fermentation processes (Couëdel et al., 2019; Lucadamo et al., 2022; Scavo et al., 2022). A significant part of the MSCC system is represented by the use of intermediate crops to prevent organic matter deficiency in soils under different fertilization options through their use as green manure (Boselli et al., 2020; Guinet et al., 2023). The relevance of green manure in the MSCC system is due to the shortage of organic fertilizers due to changes in the management of farm animals and the conversion of modern livestock complexes to schemes for processing manure waste into biogas (Pan et al., 2021), as well as the transition to minimized and zero tillage technologies (Boselli et al., 2020). In this regard, green manure has been evaluated as an effective resource for replenishing organic matter in the soil both from the point of view of optimizing the modes of its humification and accumulation of organic carbon in general (Lei et al., 2022; Lee et al., 2023). It also realized a positive impact on the complex of soil properties (Chen et al., 2020; Ansari et al., 2022; Israt & Parimal, 2023). The implementation of MSCC contributed to the agro-ecological sustainability of agro-landscapes by such factors as pollination of plants, support of wild fauna, as well as providing a more attractive aesthetic appearance due to the optimized filling of ecological niches of fauna and flora of the territories (Justes & Richard, 2017). The selection of potential candidate crops that correspond to the MSCC principles should be based on the study of basic eligibility criteria (Couëdel et al., 2019; Singh et al., 2023).

Given the relevance of these issues, the purpose of the ten-year research cycle was to determine the bioproductive potential of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) on gray forest soils from the point of view of compliance with MSCC criteria, taking into account the preliminary data of a comprehensive assessment of its morphological and bioproductive potential (Tsytsiura, 2019, 2020, 2021, 2022; 2023a, 2023b, 2023c).

MATERIALS AND METHODS

The research was carried out during 2014–2023 at the experimental field of Vinnytsia National Agrarian University (N 49°11′31″, E 28°22′16″.) on Grey and Dark Gray forest soils (Greyi-Luvic Phaeozems (Phaeozems Albic, Dark Gray Podzolic Soils) according to WRB (IUSS, 2015)) Haplic Greyzems according to FAO (IUSS, 2015)) of silty clay loamy texture (sicl) (fluctuations in the content of fractions for the horizon 0–30 cm: sand 12.03–14.32, silt 55.86–57.79 and clay 29.35–30.21). The agrochemical potential of the soil for layer 0–30 cm was determined with the standards for analytical laboratory methods (Sparks et al., 1996) and had the following average indicators for the research period: humus content: 2.68%, easily hydrolyzed nitrogen 81.5 mg kg^{-1} of soil, mobile phosphorus 176.1 mg kg^{-1} of soil, exchangeable potassium 110.8 mg kg^{-1} of soil, pH$_{KCl}$ 5.8, hydrolytic acidity 3.29 mg-equivalent 100 g^{-1} of soil. The soil fertility potential based on the presented agrochemical properties was estimated as average (according to Sanchez et al., 1982).

The variety of oilseed radish ‘Zhuravka’ was used. Sowing was carried out on an unfertilized background with a seeding rate of 2.5 million seeds ha^{-1} using the conventional row method (row spacing of 15 cm). This sowing option corresponded to the variant of fodder–green manure use of oilseed radish (Tsytsiura, 2020). Two systems of using oilseed radish as an intermediate crop for multiple purposes were investigated:

I. The system of early spring sowing (first-second decade of April) after intermediate cultivation to a depth of 8–10 cm with leveling against the background of autumn plowing at 20–22 cm. The date of phenological achievement of the optimal phase of multicomponent use of oilseed radish biomass (flowering stage (BBCH 64-67) was in the second-third decade of June.

II. The system of summer sowing (the second–third decade of July) immediately after harvesting the predecessor with intermediate combined tillage (flat cutter + rotary loosening with leveling) to a depth of 12–14 cm. The date of flowering stage (BBCH 64-67) was in the second or third decade of October.

The sowing date of the first variant was determined at the early stage of physical ripeness of the soil. For the second variant, the soil moisture indicator was used. It was based on the date of the nearest precipitation with an intensity of at least 5 mm (according to the recommendations of Florentín et al. (2010)). The optimality of the phase of leaf and stem mass use was determined taking into account the combination of maximum individual plant productivity and relevant quality indicators for effective variant of biofumigant and green manure use of oilseed radish under conditions of unstable moisture in different soil zones according to Alonso-Ayuso et al. (2014) and Duff et al. (2020).

The experimental plots were formed in quadruplicate using the method of small plot randomization (total plot area 35 m^2, accounting area 25 m^2).

To control the number of weeds, a mixture of herbicides was used in the rosette phase (BBCH 20–22) ‘Galera 334’, aqueous solution (clopyralid, 267 g L^{-1} + picloram, 67 g L^{-1}), 0.3 L ha^{-1} - against dicotyledonous weeds; ‘Select’, emulsion concentrate (clethodim, 120 g L^{-1}), 0.7 L ha^{-1} - graminicide. To control the number of cruciferous fleas (*Phyllotreta atra* F., *Phyllotreta nemorum* L., *Phyllotreta undulata* Kutsch, *Phyllotreta nigripes* F.) common in the agrocenosis of oilseed radish (Tsytsiura, 2024), the insecticide 'Bliskavka' (emulsion concentrate, alphacypermethrin 100 g L^{-1}) was applied at 0.2 L ha^{-1} in the phase of cotyledons–first true leaves (BBCH 10-12).

Stage growth was recorded using the Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie (BBCH) scale (Test Guidelines, 2017).

Accounting of aboveground plant biomass (BM). It was carried out at the full flowering stage (BBCH 64-67) in 4 randomized plots by the method of trial plots of 1 m^2 in each replication (16 plots in total) with subsequent weighing using a laboratory scale YP50002 (5 kg) with a discretion of 0.01 g. Prior to weighing and subsequent field and laboratory manipulations, any non-native plant impurities were removed from the sample. Some of the accounting plots were selected with the condition that the perimeter of the aboveground biomass accounting coincided with the system of monolithic analysis of the formed root systems.

The ground cover (GC) was monitored during the entire crop cycle for both variants of oilseed radish use. The indicator was recorded starting from the phenophase of true leaf formation (BBCH 12–13) with an interval of 5 days until the flowering phase (BBCH 64-67). To account for GC, we used the methodology of Ramirez-Garcia et al. (2012), which was based on digital pictures of the marked surface taken from a perspective at a 1.5 m height. The images were taken with a Canon EOS 750D Kit + Canon EF 50 mm f/1.8 STM processed using SigmaScan Pro 5® software. CurveExpert Professional v. 2.7.3 (Hyams Development) was used to estimate the GC dynamics according to the recommendations of Bodner et al. (2010).

Assessment of the formation of plant root biomass (RBM) of oilseed radish was carried out at a similar phenophase as for the assessment of the formation of aboveground plant biomass by the monolith method according to the recommendations of Wahlström et al. (2015). Separation of the root mass in the monolithic profile was carried out by washing on a column of sieves (laboratory sieves of woven wire mesh: 4.0 mm, 2.0 mm, 1.0 mm, 0.5 mm and 0.25 mm). The selected roots were stored in closed plastic containers at 5 °C. The washed and selected root were air-dried for 24 h and then weighed on a laboratory balance (3,100 g/0.01 g) WALCOM LB3002 (± 0.01 g).

The root system productivity coefficient was calculated according to Poorter et al. (2012) as the ratio of crude (dry) aboveground plant biomass to the mass of formed roots. The proportion of root residues in the total plant biomass was determined as the ratio of root mass to aboveground plant mass expressed in %.

Chemical analysis of leaf biomass. All laboratory chemical analyzes were carried out in quadruplicate with the determination of the basic components of biochemical analysis expressed on an absolutely dry weight basis (according to Undersander et al., 1993).

The dry matter (DM) and organic dry matter (ODM) contents were measured by drying in an oven at 105 °C and then ashing the dried sample at 550 °C. The resulting dried samples were re-weighed and ground using a Vilitek VLM-16 800 g 2,200 mL electrostatic laboratory mill.

The ash content (AOAC Official Method 942.05) was based on the gravimetric loss by heating to 600 °C for a period of two hours.

Crude fiber (CFb) (AOAC Official Method 978.10) is determined gravimetrically as the residue remaining after the acid and alkaline digestions.

Dietary fiber content (DFb) was calculated as the difference between NDF-ADL (according to Quemada & Cabrera, 1995).

The crude fat content (CF) (AOAC Official Method 2003.05) was determined by using the Randall modification of the standard Soxhlet extraction.

Determination of total nitrogen content (TNC) (AOAC Official Method 978.04) by the Kjeldahl method in dry biomass was performed using the KjeLROC Kd-310 analyzer (ISO 17025). For accounting of nitrogen-containing compounds in the Kjeldahl method, a preliminary solution reduction was used (Undersander et al., 1993).

Total crude protein (CP) (AOAC Official Method 990.03 and AOAC Official Method 978.04) was calculated as the nitrogen content multiplied by the standard conversion factor of 6.25.

The content of total organic carbon (TOC) was determined using a laboratory analyzer of total organic carbon of the TOC-LCPH series according to the standard protocol for low-temperature thermocatalytic oxidation of plant material.

Neutral Detergent Fibre (NDF) was determined using AOAC Official Method 2002-04 by neutral detergent solution and heat.

Acid Detergent Fibre (ADF) was determined gravimetrically as the residue remaining after acid detergent extraction (by AOAC Official Method 973.18).

Analysis of tissue for Acid Detergent Lignin (ADL) followed the ADF-Sulfuric Lignin method (Rowland & Roberts, 1994 (AOAC Official Method 973.18) in view of Sluiter et al. (2004)).

Cellulose was considered to be represented by the difference between ADF and ADL, and hemicellulose was the difference between NDF and ADF according to the Van Soest method (Van Soest et al., 1991; FOSS, 2018).

Nitrogen-free extracts (NfE) were calculated as the difference between the content of 100% dry matter and the content of CP, CFb, CF and CA (Undersander et al., 1993).

Carbohydrates (CH) determined by the amount of NfE + CFb (according to Weende method (FOSS, 2018)).

The C/N ratio was calculated as the ratio of Total Organic Carbon (TOC) to Total Nitrogen Content (TNC) (Anzola-Rojas et al., 2014).

The crop residue quality (RQ) was calculated as the sum of its labile (100-NDF) and cellulose like (ADF-ADL) decomposable fraction (Quemada & Cabrera, 1995).

Glucosinolate content (GSL) was determined on frozen plant by high performance liquid chromatography according to standard methods (ISO 9167:2019 (2019)) in view of Arguello et al. (1999).

The content of total phosphorus and potassium in plants was determined according to Method of measurement 31-497058-019-200531-497058-019-2005.

Calcium in plant material was determined by the complexometric method (in modification of Nielsen, 2010).

Sulfur content was determined in accordance with AOAC 923.01-1923.

Comparable conversion of oilseed radish biomass by total NPK accumulation in cattle manure was carried out to the average chemical composition of manure (an orientation to manure with a dry matter content of 10–15% in comparison to similar matter content of the biomass of oilseed radish plants) at a standard concentration of N 3.2 g kg^{-1}, P 2.0 g kg^{-1}, K 3.8 g kg^{-1}) according to the statistics provided Brown (2021) and Composts & Fertilizers (2023).

Multi-criteria decision aiding (MCDA) was used for the analysis according to Ramirez-Garcia et al. (2015). The initial criteria were: ground cover (GCmax, in % at 60 days after sowing), the biomass at the end of the experiment (BM, kg m^{-2}), the C:N ratio, the N uptake (N_{upt}, g m^{-2} (calculated according to Gastal & Lemaire (2002) and Letey et al. (1982)), the residue quality (RQ, g $kg^{-1}{}_{DM}$), glucosinolate productivity (GSL, mmol m^{-2}), the fiber content (CFb, g $kg^{-1}{}_{DM}$) and the dietary fiber content (DFb, g $kg^{-1}{}_{DM}$ for the direction of use 'fodder crop'). Based on the formed system, 70 R_{ij} outcomes were obtained. The internal coefficients of importance of each factor were determined on the basis of the fundamental scale according to Saaty & Vargas (2012). The MCDA procedure was carried out in the analysis subsystem according to the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with the recommendations of Rao (2007), Ramirez-Garcia et al. (2015) and El Amine et al. (2016).

The analysis of weather conditions and the level of their variability for the period 2014–2023 was based on the hydrothermal coefficient (*HTC*) (Eq.):

$$HTC = \frac{\sum R}{0.1 \times \sum t_{>10}} \tag{1}$$

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

The De Martonne Aridity Index (I_{DM}) (according to Moral et al., 2016) was used to characterize the arid/humid conditions of a territory for a month according to Eq. (2):

$$I_{DM} = \frac{12P_m}{T_m + 10}, \tag{2}$$

where P_m and T_m are the precipitation volume and mean air temperature in the corresponding month, respectively.

According to the I_{DM} values calculated using the equation above, the climate of a region can be classified (type of climate according to the De Martonne aridity index (I_{DM}, adapted after Baltas, 2007) Arid $I_{DM} < 10$; Semi-Arid $10 \leq I_{DM} < 20$; Mediterranean $20 \leq I_{DM} < 24$; Semi-humid $24 \leq I_{DM} < 28$; Humid $28 \leq I_{DM} < 35$; Very Humid $35 \leq I_{DM} \leq 55$; Extremely humid $I_{DM} > 55$.

The evapotranspiration was calculated using Eq. (3) (according Latief et al. (2017)):

$$E = 0.0018 \times (25 + t)^2 \times (100 - a), \tag{3}$$

where *E* is the evapotranspiration of plants for a certain period, mm; *t* is the average air temperature for the period °C; *a* is the average air humidity for the analyzed period, %.

The Vysotsky-Ivanov humidification coefficient (K_h) was determined by Eq. (4) according to Latief et al. (2017):

$$K_h = \frac{P}{E}, \tag{4}$$

where K_h – moisture coefficient; *P* – amount of precipitation for the analyzed period, mm; *E* – evaporation for the analyzed period, mm. The different degrees of moisture is carried out according to gradation: $K_h > 1.0$ – territory (time period) with excessive moisture, K_h close to 1 – optimal moisture, $K_h = 1.0–0.6$ – unstable moisture, $K_h = 0.6–0.3$ – insufficient hydration.

Table 1. Estimation of the values of hydrothermal regimes of the period of vegetation of oilseed radish for the variant of spring and summer sowing, 2014–2023

Year	Precipitation, mm (IV–VI)	*t_{aver}, °C (IV–VI)	Months of the growing season								
			IV			V			VI		
			HTC	I_{DM}	K_h	*HTC*	I_{DM}	K_h	*HTC*	I_{DM}	K_h
Spring sowing											
2014	339.6	13.84	0.725	45.7	1.18	3.928	88.9	2.11	1.545	34.8	0.83
2015	142.3	14.36	0.645	37.3	0.78	0.917	20.6	0.41	0.715	16.9	0.27
2016	193.4	15.06	0.296	21.6	0.44	0.489	40.4	0.99	1.265	29.9	0.75
2017	125.1	14.07	3.919	39.2	0.75	0.777	16.8	0.34	0.504	11.9	0.22
2018	170.8	16.38	0.290	10.8	0.19	0.308	7.2	0.12	4.404	103.7	2.31
2019	398.5	15.39	0.565	33.5	0.72	4.902	111.0	3.29	1.682	41.4	0.96
2020	343.8	13.67	0.091	36.4	0.50	5.327	106.4	3.18	1.548	37.3	0.89
2021	282.8	13.26	0.233	38.8	0.96	3.125	66.7	1.64	1.679	39.8	1.00
2022	242.1	14.30	0.563	57.4	2.33	1.430	31.3	0.79	1.496	36.1	0.85
2023	239.8	14.18	1.543	91.5	3.33	0.085	1.9	0.04	1.640	38.9	0.87

Year	Precipitation, mm (VII–X)	*t_{aver}, °C (VII-X)	Months of the growing season												*t_{aver}, °C	Precipitation amount mm**
			VII			VIII			IX			X				
			HTC	I_{DM}	K_h	*HTC*	I_{DM}	K_h	*HTC*	I_{DM}	K_h	*HTC*	I_{DM}	K_h		
Summer sowing																
2014	250.8	15.4	1.312	32.7	0.77	1.049	26.0	0.51	1.252	25.7	0.56	1.770	35.8	0.93	–	–
															0.2	245.5
2015	160.8	16.6	0.321	8.1	0.14	0.124	3.1	0.05	1.184	26.8	0.63	3.039	49.4	1.25		
															9.5	256.1
2016	212.7	15.6	1.056	26.5	0.55	0.898	22.0	0.43	0.014	2.5	0.05	0.548	63.4	2.45		
															-0.6	325.7
2017	318.0	16.0	1.524	37.5	0.72	0.819	20.7	0.38	3.100	61.2	1.57	1.065	30.0	1.26		
															-0.4	323.7
2018	273.4	16.4	2.158	53.4	1.63	0.585	14.6	0.30	1.378	27.2	0.71	0.873	27.6	0.95		
															0.0	271.0
2019	161.7	16.0	1.013	24.4	0.56	0.237	5.9	0.11	0.994	20.7	0.42	0.383	27.4	0.93		
															2.9	200.5
2020	245.4	17.6	0.589	14.7	0.31	0.527	13.2	0.22	0.859	27.5	0.54	2.544	60.6	3.05		
															-0.3	356.1
2021	176.9	15.4	0.782	20.1	0.45	1.459	35.7	0.91	0.705	17.6	0.51	0.000	1.7	0.04		
															1.2	216.9
2022	436.6	16.0	0.900	22.4	0.58	1.712	43.1	1.06	4.960	98.1	2.60	3.167	51.4	1.50		
															2.2	278.0
2023	247.1	18.3	1.414	35.8	0.82	0.652	16.9	0.36	1.015	23.4	0.63	1.025	29.9	0.93	–	–

* – the mean daily average temperature (°C); ** – the amount of precipitation (mm) for the period November of the previous year – March of the following year.

A generalized assessment of the hydrothermal regimes of the oilseed radish vegetation period within the years of research presented in Table 1. According to the general classification of the hydrothermal regime of the territories (Latief et al., 2017), the study period was characterized as conditions of unstable moisture. Taking into account the optimal parameters for the growth processes of oilseed radish plants according to our previous long-term estimates (Tsytsiura, 2020) and the grouping classification by De Martonne Aridity Index (I_{DM}) and Vysotsky-Ivanov humidification coefficient (K_h), the years of research were placed in the following order of increasing favorability of growth processes for the conditions of spring sowing: 2017–2015–2016–2018–2021–2022–2023–2014–2020–2019. For the conditions of the summer sowing period, a similar series was as follows: 2015–2021–2019–2016–2023–2014–2020–2018–2017–2022.

Statistical processing. The indicators of variation statistics were determined using the generally accepted calculation method in the statistical software Statistica 10 (StatSoft - Dell Software Company, USA) and Past 4.13 software (Øyvind Hammer, Norway).

An arithmetic mean ($\overline{x}$), standard deviation ($\pm SD$) and coefficient of variation (CV) were used for statistical evaluation of the obtained average values.

Moreover, a Spearman's correlation test was used for a statistical level of $p < 0.05$ and $p < 0.01$. The data obtained were analyzed using the analysis of ANOVA (Wong, 2018). Tukey HSD Test in R (version R statistic i386 3.5.3) on the 95% family-wise confidence level were used. The coefficient of determination (R^2) and adjusted coefficient of determination (R^2_{adj}) was used for statistically assess the correlation in accordance with Snecdecor & Cochran (1991).

The Chaddock scale (1925) was used to estimate R^2 (R^2 of 0.1–0.3 indicated a weak relationship; 0.3–0.5 moderate; 0.5–0.7 significant; 0.7–0.9 high; 0.9–0.99 very high).

The degree of correlations was estimated by the value of the coefficient of determination (d_{xy}) (Eq. 5) and the use of the method of correlation graph in two interpretations (G and G') (Eqs 6 and 7):

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

$$G = \sum_{|r_{ij}| \geq \alpha} |r_{ij}| \quad (6)$$

$$G' = (\sum_{|r_{ij}| \geq \alpha} |r_{ij}|)/n \quad (7)$$

where r_{ij} is the correlation coefficient between the i-th and j-th indicator. Only reliable number (n) of correlation coefficients were used in the calculation.

RESULTS AND DISCUSSION

During the ten-year period of study, the average value of the formed aboveground biomass (BM) at the spring sowing date was 24.04 t ha^{-1} with an interannual variation of 30.55% and the root biomass (RBM) was 8.70 t ha^{-1} and 44.70%.

At the summer sowing date, similar indicators were 18.34 t ha^{-1} (32.80%) and 5.50 t ha^{-1} (38.95%) (Fig. 1). The formation of these indicators in dry matter had certain differences, while maintaining the same nature of fluctuations within the years of study.

The average long-term dry matter content in aboveground biomass during the summer sowing period was 2.55% higher for aboveground biomass and 1.21% higher for root biomass compared to the spring sowing period.

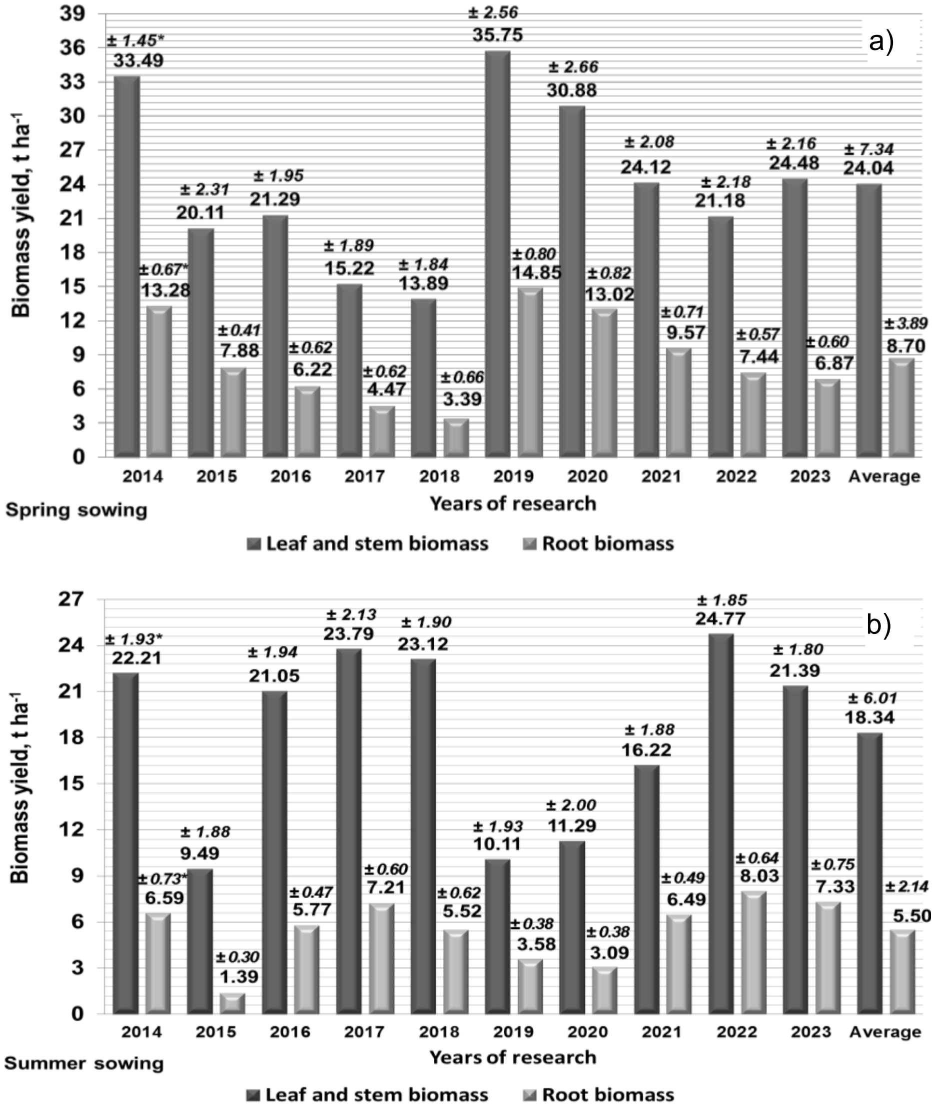

Figure 1. Formed aboveground and root biomass of oilseed radish plants for spring (a) and summer (b) sowing, t ha^{-1} ($LSD_{05\ \mathrm{spring}}$BM 1.39 $LSD_{05\ \mathrm{spring}}$RBM 1.15; $LSD_{05\ \mathrm{summer}}$BM 1.29, $LSD_{05\ \mathrm{summer}}$RBM 0.60), 2014–2023. * – Standard deviation

In terms of dry matter, the average level of aboveground biomass was 3.10 t ha^{-1} (23.59% interannual variation) and 1.82 t ha^{-1} (40.86%) for the root biomass produced in the spring sowing date, and 2.82 t ha^{-1} (27.51%) and 1.24 t ha^{-1} (38.75%) in the summer sowing date (Fig. 2). As a result, the total bioproductivity of oilseed radish (the sum of aboveground and root biomass) during the spring sowing period was 32.74 t ha^{-1} in raw weight (34.06% of interannual variability) and 4.92 t ha^{-1} in dry matter (29.47%). These indicators are 8.90 and 0.86 t ha^{-1} lower than the average for the summer sowing date.

The high level of interannual variation is explained by the reaction of oilseed radish plants and the variability of hydrothermal regimes of its vegetation period for both sowing dates during the research period (Table 1). According to the coefficient of variation (*CV*), the variability of precipitation during the evaluation period was 48.24%, average daily temperature 27.46%, *HTC* (K_h) 68.11%, I_{DM} 58.93%. Based on the statements of Latief et al. (2017), such heterogeneity of hydrothermal regimes maked it possible to assess the stress response of oilseed radish plants with high reliability from the point of view of MSCC indicators.

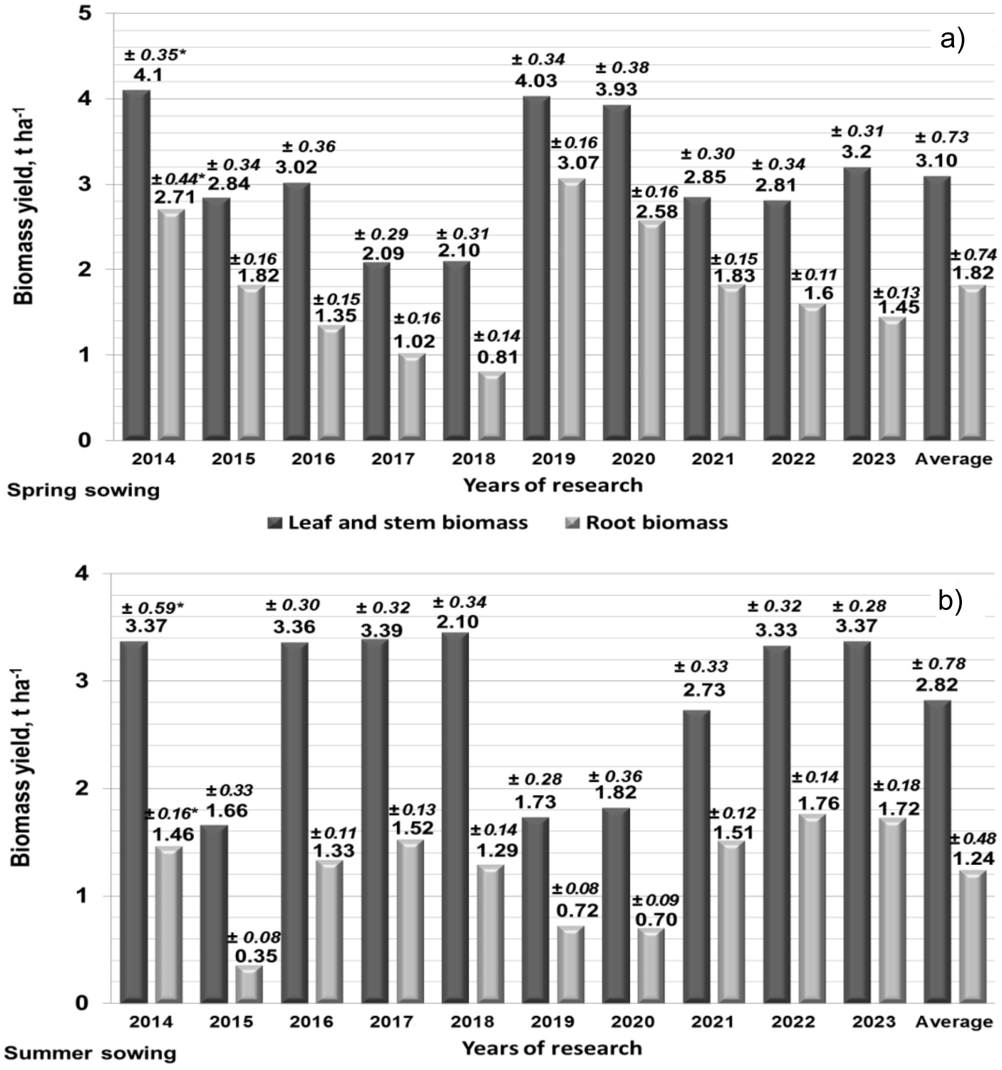

Figure 2. Formed aboveground and root biomass of oilseed radish plants in transformation to dry matter (DM) for spring (a) and summer (b) sowing, t ha^{-1} ($LSD_{05\ \mathrm{spring}}$BM 0.24 $LSD_{05\ \mathrm{spring}}$RBM 0.26; $LSD_{05\ \mathrm{summer}}$BM 0.27, $LSD_{05\ \mathrm{summer}}$RBM 0.13), 2014–2023. * – Standard deviation.

It was useful to evaluate the achieved level of bioproductivity of oilseed radish in comparison with other cruciferous species used as intermediate crops in the system of existing agrotechnological solutions.

In the study of Bhogal et al. (2019), the technological interval of oilseed radish biomass yield ranges from 15 to 45 t ha^{-1} depending on soil and climatic conditions. According to the study Quintarelli et al (2022), oilseed radish was classified as a high-yielding cover crop for conditions of sufficient moisture. A number of researchers had noted its sufficient level of adaptability for cultivation in various intermediate technological schemes with different sowing dates right up to August 15 with an average bioproductivity level above 15 t ha^{-1} (White et al., 2016; Wollford & Jarvis 2017; Lövgren, 2022). For conditions of unstable moisture, the yield of aboveground biomass of such crops as white mustard, spring rape, fodder radish (var. Tillage radish (Daikon radish) was in the range of 12–27 t ha^{-1}. For winter rape (for using its biomass in the early summer period) the yield of aboveground biomass was 25–60 t ha^{-1}. The formed underground (root) biomass for the same group of crops was 5–15 t ha^{-1} and 12–25 t ha^{-1}. A high sensitivity of these cruciferous species to the moisture regime, especially during the summer sowing period for unstable moisture conditions was most pronounced (Clark, 2008; Ramirez-Garcia et al., 2012; Ugrenović et al., 2019; Safaei et al. 2022; Ţiţei, 2022).

For conditions of sufficient moisture the achievable levels of the formed aboveground biomass of cruciferous crops was in the range of 12–30 t ha^{-1} de Ruiter et al., 2009; Pekarek et al., 2013; Sousa et al., 2019; Simeão et al., 2023). Rapid growth rates of aboveground biomass of oilseed radish in 40 days after full germination of plants and the concomitant formation of root biomass (with the share of root biomass in total phytomass 18–50%) was noted (Kemper et al., 2020). Based on these results, oilseed radish should be attributed to highly productive crops with developed adaptive mechanisms of plant biomass formation.

On the other hand, the observed high level of variation of the hydrothermal conditions indicator showed a significant role in the realization of oilseed radish plants bioproductivity. If take into account the declared maximum productive potential of the varieties of this crop grown in Ukraine (Tsytsiura 2023c.) at the applied sowing rate up to 50 t ha^{-1} in spring and up to 35 t ha^{-1} in summer sowing, the level of realization of its potential in our studies was varied 27.8–70.0% in spring sowing and 27.1–70.8% in summer sowing. The close interval of realization of bioproductivity at radically different sowing dates was showed the presence of characteristic mechanisms of pre-adaptation to variable heterodynamic environmental conditions in the plant (Borgogno et al., 2009). Based on this oilseed radish can be recommended for the system of different terms of use in the variants of intermediate sowing between the main crops in the rotation of spring and winter groups of crops.

The level of adaptability of a plant with a focus on the formed aboveground and root biomass can be concluded by analyzing different variants of the relationship between these indicators. The efficiency of multipurpose use of field crops was determined by the productivity of its root system which used as a productivity coefficient of the share of root biomass in the formed plant biomass (Williams et al., 2013; Thorup-Kristensen & Kirkegaard, 2016). For oilseed radish, during the study period, the root system productivity coefficient for crude biomass was 2.97 (20.33%) for spring and 3.63 (33.69%) for summer sowing. In terms of dry matter, the index was 1.83 (22.82%) and 2.51 (33.53%) respectively. The inverse ratio of root mass to aboveground mass for spring sowing was 0.35 (crude biomass) and 0.57 (in dry matter) with an interannual variation of 18.67–21.24%. For the summer sowing period, the same indicators were

0.30 (22.98%), 0.43 (23.63%) respectively. This level of ratio indicated the rapid growth rates of oilseed radish plants for both parts of the plants with parity development of the aboveground mass and the presence of a sensitive stress response to deteriorating soil conditions in terms of moisture, aeration, etc (according to the statement of Bláha (2021)). The inertia of the growth of the aboveground part at termination the growth of the underground part was proved. It was confirmed by a decrease in the level of interannual variation of the ratio of root biomass to aboveground biomass with a coefficient of 1.88 for the spring sowing and 1.54 for the summer sowing. This inertia, which determined the preservation of the intensity of growth processes due to the more pronounced stress resistance of the root system (noted in cruciferous species by Ahmad et al. (2012)) allowed oilseed radish to adapt to medium-long periods of aridization and to form an aboveground plant biomass at the level of 50% compared to normal hydrothermal conditions. Such features were formed in the conditions in 2015 for both sowing dates and in 2017 with spring sowing (Table 1). At the same time, should expect an intensification of the growth rate decline with the deterioration of hydrothermal regimes of plant vegetation both from the standpoint of aboveground conditions and soil conditions (Williams et al., 2013; Agathokleous et al., 2019; Kul et al., 2021).

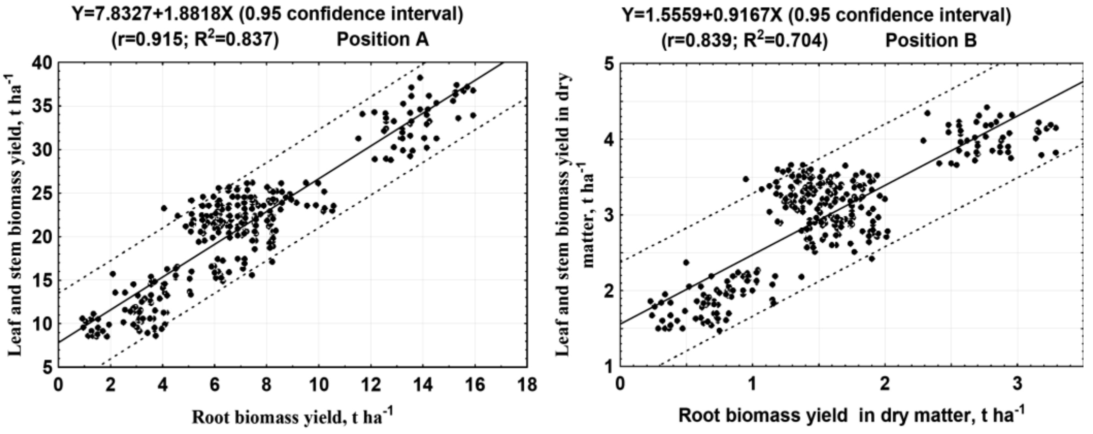

Figure 3. Relationship between aboveground biomass yield and formed root biomass in oilseed radish, 2014–2023 (in a single data system of replication–year–sowing date; position A – in raw mass, position B – in dry matter).

It was confirmed by a certain discrepancy between the abscissa and ordinate interval of the graphical display of the data set with 4 units of abscissa correspond to 15 units of ordinate in the version of the data on crude plant biomass and 2 and 3.5 units for dry matter, respectively (Fig. 3). The discrepancy in the axial graphical dynamics of the comparison explained by the difference between the dry matter content of aboveground and root biomass. Such features based on the research of Gan et al. (2009), Benjamin et al. (2014), Bacher et al. (2021) and Kou et al. (2022), confirmed the high adaptive potential of oilseed radish with the possibility of its cultivation as an intermediate crop, especially in summer sowing terms with the existing stressful hot periods characteristic. In addition, the determined parity of the aboveground part of oilseed radish plants in comparison with their root part indicates, taking into account the study of Lopez et al.

(2023), proved a high positive response of oilseed radish on additional mineral nutrition and a high level of accumulation of macro and microelements in the formed biomass.

This fact was valuable in view of the possibility of green manure application of oilseed radish as one of the components of the MSCC system.

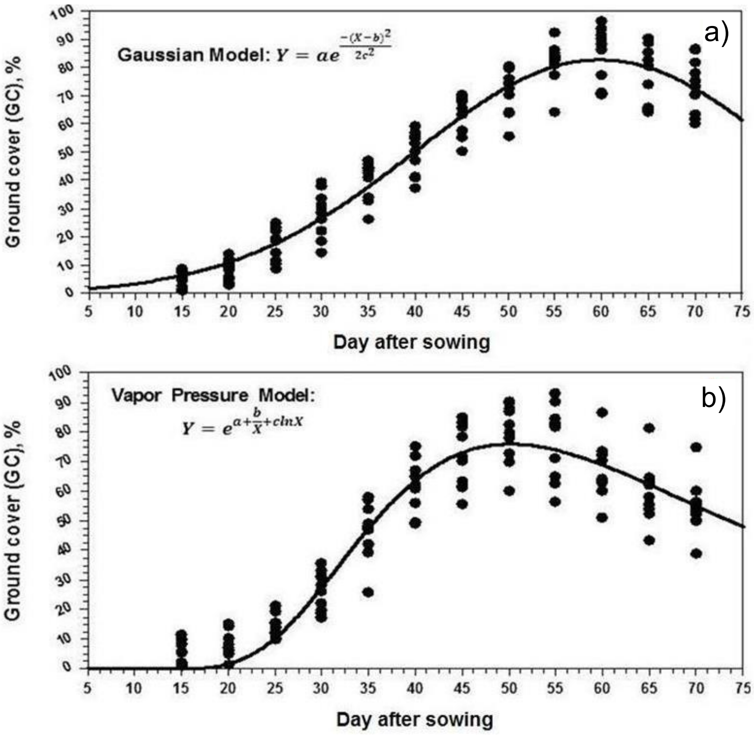

Figure 4. Graphical model with statistical evaluation parameters for the indicator 'Ground cover' (GC) in oilseed radish (vertical marks on the dates of accounting – indicator values in the experimental interval 2014–2023). The position a – variant of the spring sowing season: Coefficient Data: $a = 82.460$; $b = 59.729$; $c = 19.640$; $r = 0.967$; $R^2 = 0.936$; $R^2_{adj} = 0.919$; $S = 7.453$; $RMSE = 71.129$; $RRMSE = 7.545$; $PE = 0.843$; $p < 0.001$. The position b – variant of the summer sowing period: Coefficient Data: $a = 37.471$; $b = -335.487$; $c = -6.761$; $r = 0.956$; $R^2 = 0.915$; $R^2_{adj} = 0.902$; $S = 7.912$; $RMSE = 83.707$; $RRMSE = 9.123$; $PE = 0.796$; $p < 0.001$.

The obtained data on the bioproductive realization of oilseed radish growth processes allowed to further characterize an important component of 'ground cover' (GC) (Fig. 4) as a significant MSCC evaluation criteria. The optimal estimate of this indicator should be at least 70% for the potentially possible period before the optimal phenological date of use (Bodner et al., 2010; Tixier et al., 2010; Ramírez-García et al., 2015). For both sowing dates, an exponential dependence with certain mathematical differences from the commonly used Gompertz function with an asymptote of growth to the maximum GC index was established (Tjørve & Tjørve, 2017). Based on the analysis of the data presented and on the basis of previous studies on the patterns of formation of the leaf apparatus of oilseed radish (Tsytsiura, 2020a), the interval of intensive GC growth in the phenological interval from the beginning of flowering (BBCH 50–52) to its completion (BBCH 68–69) was determined. It should be noted a number of features of the dynamics of GC formation in oilseed radish. One of its was an intensive decrease due to leaf death on 55–75 days after sowing (which is confirmed by power expressions in the equations in Fig. 4 $X2c^{-2}$ and $2bxc^{-2}$ for spring sowing and bx^{-1} for summer sowing wich was consistent with the findings of Werker & Jaggard (1997)). The another feature was reaching the maximum level of GC on 60 days after sowing in the spring sowing 83.69% (with fluctuations in the range of 71.23–93.67 and on 50 days in the summer sowing 79.94% (60.27–90.36%).

For the summer sowing, both more intensive growth and more intensive decline in the dynamics of GC were determined. On the 70th day after sowing, the GC index was 73.77% (with an interannual variation of 22.43%) for spring and 50.74% (29.93%) for summer sowing. The duration of reaching the maximum value of the GC index in the summer sowing was significantly shorter than in the spring sowing variant. The dynamics of its decrease in the post-peak period was also significantly higher. Based on the data for the summer sowing, the optimal variant of oilseed radish use for the 'cover crop' function was in the period 45–55 days after sowing. For the spring sowing variant it was possible to prolong up to 70 days after sowing.

Table 2. Pearson's correlation coefficients of dependence of oilseed radish bioproductivity parameters on hydrothermal parameters of the growing season (for a joint system of matching sowing dates-repetitions-years (N=160))

1	2	3	4	5	6	7	8	9	10	11
1	-0.40	0.49	0.91	0.96	0.91	0.95	0.95	0.96	-0.51	0.52
2		-0.02	-0.71	-0.62	-0.71	-0.44	-0.53	-0.48	0.51	-0.54
3			0.29	0.37	0.29	0.52	0.36	0.49	-0.35	0.28
4				0.99	1.00	0.87	0.93	0.90	-0.57	0.61
5					0.99	0.91	0.96	0.94	-0.56	0.60
6						0.87	0.93	0.90	-0.57	0.61
7							0.94	0.99	-0.41	0.40
8								0.97	-0.63	0.66
9									-0.49	0.49
10										-0.96
**7.56	4.96	3.46	7.78	7.90	7.78	7.30	7.86	7.61	5.56	5.67
***0.69	0.45	0.31	0.71	0.72	0.71	0.66	0.71	0.69	0.51	0.52

$r = |0|–|0.4|$ No or weak correlation; $r = |0.4|–|0.7|$ Moderate correlation; $r = |0.7|–|1.0|$ Strong correlation. 1=Precipitation (mm); 2 = Average daily temperature (°C); 3=Air humidity (%); 4 = HTC; 5=I_{DM}; 6 = K_h; 7 = Leaf and stem biomass yield (t ha^{-1}); 8=Root biomass yield (t ha^{-1}); 9 = Total plant biomass (t ha^{-1}); 10 =Root system productivity coefficient (in dry matter); 11 = Share of root residues in total dry biomass of plants (%); ** Graf G; *** Graf G'. Significance level of $p < 0.05$, the interval $r = 0.15–0.19$, for $p < 0.01$ $r = 0.20–0.25$, for $p < 0.001$ $r > 0.25$.

The correlation analysis confirmed the above conclusions about the role of hydrothermal conditions in the possible level of achievement of the total bioproductivity of oilseed radish plants (Table 2). According to the value of the correlation graph of the first type (Graf G), the formation of both aboveground and underground (root) biomass of oilseed radish plants had the highest total dependence of modular numerical values of correlation coefficients from the position of plant weight characteristics (interval Graf G 7.30–7.61). Among the hydrothermal factors of the growing season, hydrometeorological coefficients such as HTC, I_{DM}, K_h were maximum (average Graf $G > 7.70$). The amount of precipitation played a more significant role in the system of formation of the total bioproductivity of plants than the level of average daily temperature (ratio coefficient 1.52) and relative humidity (ratio coefficient 2.18). According to the values of the correlation graph of the second type (Graf G'), the coefficient of determination was 51.84% for the Aridity Index (I_{DM}), 50.41% for the hydrothermal coefficient (HTC) and the humidification coefficient (K_h), 47.6% for the amount of precipitation, 20.3% for the average daily temperature and 9.6% for the relative humidity. The determining factor in the formation of the total bioproductivity of oilseed radish plants was the total moisture supply during of its vegetation period and the processes of change of this indicator in relation to evaporation, temperature dynamics and the rate of its growth. The determined lower dependence on the average daily temperature gave grounds to assert its adaptive resistance to low temperatures and the possibility of initiating growth processes in the early and ultra-early periods of the sowing dates. The direction of the dependence showed that the level of total biomass of oilseed radish plants with a high level of predicted probability will increase with increasing precipitation (d_{yx} = 92.2%) and high values of hydrothermal coefficients and ratios (d_{yx} = 81.0–88.4%). It should be noted that oilseed radish had certain advantages in terms of climate adaptation indicators in comparison obtained dependencies with the model parameters wich were included in the predictive models of biomass formation for spring and winter rape, white mustard in variants of its multiple use (Dorsainvil et al., 2005; Jing et al., 2016; Asgari et al., 2021).

The ability to intensive growth processes of oilseed radish plants at lower temperatures had already been noted. Over the 10-year period of research, the average daily air temperature was 14.5 °C for the period April–June (Table 1). Such level of temperature for white mustard and spring rape will already contribute to a decrease in the rate of growth processes and the size of the formed generative part of plants (Ahmad, 2017). The higher levels of dependence for relational quantities (ratios, coefficients) in comparison with the basic climatic parameters on oilseed radish was proved a more complex hierarchy of dependencies between the bioproductivity of oilseed radish plants and the climatic parameters of its growing season. Oilseed radish had a rather flexible adaptive mechanism that distinguished it from other cruciferous plants in terms of the possibility of using it in the MSCC system. This was also confirmed by research Akbarzadeh & Katsikas (2021).

From the point of view of assessing the value of the respective crop for its use in green manure, reclamation (rehabilitation of degraded soils) and biogas potential, it was important to assess the biochemical composition of the formed biomass. The results of such studies was presented in Tables 3 and 4. To estimate and determine the average biochemical portfolio of oilseed radish, gradations of estimates of a number of cruciferous crops were applied in the studies of Ayres & Clements (2002), Azam et al. (2013), Villalobos & Brummer (2013), Winkler (2017), Bell et al. (2020), Keim et al. (2020), Castillo-Umaña et al. (2020), Bakker et al. (2021), Omokanye et al. (2021), Sánchez et al. (2023). Based on these studies, the formed aboveground biomass of oilseed radish plants attributed as a high-protein (CP = 12–23%$_{\text{DM}}$) with an increase in summer sowing variant. The average perennial ratio content CP between summer and spring sowing 1.23. The high fat content (CF > 3.0%$_{\text{DM}}$) also actualized the leaf and stem mass of oilseed radish as a fodder crop. The high ash content (CA > 12%$_{\text{DM}}$) against the background of high phosphorus, potassium, calcium and sulfur (based on the conclusions of Abe (1984), Justes & Richard, 2017) allowed to attribute the leaf mass simultaneously for fodder and green manure purposes.

Table 3. Chemical composition of oilseed radish leaf and stem mass in spring sowing for flowering stage (BBCH 64-67), 2014–2023

Year	Organic dry matter (ODM) (%$_{DM}$)*		Crude protein (CP) (%$_{DM}$)		Crude fat (CF) (%$_{DM}$)		Crude fibre (CFb) (%$_{DM}$)		Crude ash (CA) (%$_{DM}$)		NDF (%$_{DM}$)		ADF (%$_{DM}$)		ADL (%$_{DM}$)	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	87.29	2.50	17.55	2.78	3.02	0.24	19.22	0.64	12.71	0.59	36.91	0.52	24.12	0.42	5.85	0.12
2015	85.41	1.82	15.08	1.91	5.55	0.40	23.07	0.65	14.59	0.45	40.12	0.29	31.24	0.59	4.77	0.14
2016	86.72	1.74	14.29	1.29	3.89	0.16	21.75	0.42	13.28	0.57	36.88	0.42	25.09	0.51	3.89	0.21
2017	84.89	2.47	15.91	1.85	5.09	0.49	23.24	0.30	15.11	0.19	38.09	0.35	28.57	0.57	4.05	0.12
2018	85.95	1.88	15.12	0.56	4.53	0.10	21.52	1.00	14.05	0.27	36.17	0.28	26.62	0.39	3.35	0.09
2019	87.48	1.59	19.17	0.84	3.01	0.31	19.17	0.87	12.52	0.76	34.02	0.19	22.19	0.25	3.58	0.11
2020	87.12	2.13	14.19	1.25	3.28	0.12	20.97	0.83	12.88	0.24	35.39	0.44	24.97	0.39	3.37	0.15
2021	87.39	1.72	12.75	0.83	3.59	0.45	21.83	0.43	12.61	0.34	36.41	0.25	25.17	0.47	4.02	0.07
2022	87.73	0.81	14.56	1.27	3.87	0.66	22.19	0.58	12.27	0.81	37.58	0.57	25.91	0.21	3.81	0.18
2023	86.32	1.49	17.02	1.01	3.94	0.20	22.29	0.87	13.68	0.54	35.89	0.39	24.11	0.33	3.96	0.13
$\bar{X}$	86.63	0.96	15.56	1.89	3.98	0.85	21.53	1.40	13.37	0.96	36.75	1.65	25.80	2.54	4.07	0.75
***R_{min}	1.17–1.33	–	0.55–1.08	–	0.47–0.58	–	0.81–1.09	–	0.63–0.82	–	0.81–0.97	–	0.88–1.05	–	0.13–0.21	–
LSD_{05}	1.29	–	0.87	–	0.52	–	1.00	–	0.75	–	0.90	–	0.93	–	0.16	–

Year	Cellulose (%$_{DM}$)	Hemicellulose (%$_{DM}$)	TNC (%$_{DM}$)		TOC (%$_{DM}$)		Phosphorus (%$_{DM}$)		Potassium (%$_{DM}$)		Calcium (%$_{DM}$)		Sulfur (%$_{DM}$)		GSL µmol g^{-1} DM	
	$\bar{x}$	$\bar{x}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	18.27	12.79	2.81	0.44	38.25	0.57	0.54	0.06	2.71	0.11	1.07	0.14	0.32	0.06	12.08	0.45
2015	26.47	8.88	2.41	0.31	40.22	0.81	0.62	0.05	3.96	0.19	0.97	0.12	0.42	0.09	13.52	0.43
2016	21.20	11.79	2.29	0.21	39.14	0.48	0.77	0.17	4.74	0.24	1.00	0.10	0.50	0.10	14.51	0.37
2017	24.52	9.52	2.55	0.30	41.12	0.65	0.85	0.08	5.72	0.38	1.15	0.15	0.59	0.11	16.08	0.87
2018	23.27	9.55	2.42	0.09	39.77	0.78	0.69	0.07	3.74	0.20	1.03	0.08	0.52	0.06	15.56	0.57
2019	18.61	11.83	3.07	0.13	37.14	1.14	0.52	0.05	2.25	0.11	0.81	0.18	0.35	0.12	11.89	0.44
2020	21.60	10.42	2.27	0.20	40.09	0.43	0.63	0.08	4.08	0.16	0.92	0.07	0.35	0.05	12.44	0.60
2021	21.15	11.24	2.04	0.13	37.95	0.73	0.48	0.09	2.87	0.37	0.93	0.17	0.39	0.05	12.77	0.40
2022	22.10	11.67	2.33	0.20	38.44	0.46	0.51	0.03	3.03	0.10	0.89	0.10	0.41	0.08	13.84	0.52
2023	20.15	11.78	2.72	0.16	38.89	0.42	0.61	0.06	3.19	0.31	0.82	0.07	0.34	0.09	12.97	0.59
$\bar{X}$	21.73	10.95	2.49	0.30	39.10	1.21	0.62	0.12	3.63	1.04	0.96	0.11	0.42	0.09	13.57	1.44
R_{min}	–	–	0.20–0.39	–	0.89–1.05	–	0.09–0.14	–	0.25–0.39	–	0.15–0.20	–	0.10–0.14	–	0.19–0.36	–
LSD_{05}	–	–	0.34	–	0.98	–	0.12	–	0.34	–	0.18	–	0.12	–	0.23	–

*The indicator of transformation between %DM and g kg^{-1}_{DM} = %DM x 10.**SD – standard deviation; ***Tukey's test (R_{min} for $p_{adj} < 0.05$).

Table 4. Chemical composition of oilseed radish leaf and stem mass in summer sowing for flowering stage (BBCH 64-67), 2014–2023

Year	Organic drymatter (ODM) ($\%_{DM}$)*		Crude protein (CP) ($\%_{DM}$)		Crude fat (CF) ($\%_{DM}$)		Crude fibre (CFb) ($\%_{DM}$)		Crudeash (CA) ($\%_{DM}$)		NDF ($\%_{DM}$)		ADF ($\%_{DM}$)		ADL ($\%_{DM}$)	
	$\bar{x}$	**SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	85.08	0.99	17.44	1.31	4.17	0.82	23.32	0.82	14.92	0.90	42.31	0.52	29.89	0.42	6.12	0.12
2015	83.79	0.87	14.88	1.61	5.82	0.62	26.72	0.70	16.21	0.72	46.12	0.29	33.17	0.59	6.61	0.14
2016	84.08	1.78	18.38	2.15	4.40	0.40	23.89	0.61	15.92	0.33	42.87	0.42	30.05	0.51	6.18	0.21
2017	85.36	3.32	19.88	2.00	4.29	0.33	22.97	0.75	14.64	0.60	41.92	0.35	29.19	0.57	5.74	0.12
2018	84.80	1.71	20.75	2.42	4.78	1.09	23.69	0.99	15.20	0.63	42.30	0.28	29.68	0.39	5.92	0.09
2019	83.21	1.13	16.13	1.65	5.02	0.48	25.33	1.03	16.79	0.35	44.35	0.19	31.87	0.25	6.48	0.11
2020	84.63	0.74	20.44	1.39	4.55	0.79	24.17	0.85	15.37	1.11	44.11	0.44	31.05	0.39	6.25	0.15
2021	83.56	1.93	19.31	1.52	4.72	0.28	24.85	0.64	16.44	0.86	44.55	0.25	31.27	0.47	6.29	0.07
2022	85.03	0.67	22.94	3.26	4.08	0.65	22.51	0.79	14.97	0.44	42.37	0.57	28.97	0.21	5.52	0.18
2023	84.42	0.54	21.44	3.13	4.27	0.32	23.92	0.64	15.58	0.92	43.09	0.39	30.34	0.33	6.09	0.13
$\bar{X}$	84.40	0.71	19.16	2.48	4.61	0.52	24.14	1.23	15.60	0.71	43.40	1.34	30.55	1.30	6.12	0.33
***R_{min}	0.81–0.96	–	1.05–1.28	–	0.82–0.96	–	0.92–1.19	–	0.88–1.12	–	0.99–1.36	–	1.53–1.81	–	0.32–0.48	–
LSD_{05}	0.92	–	1.14	–	0.91	–	1.14	–	1.05	–	1.24	–	1.64	–	0.37	–

Year	Cellulose ($\%_{DM}$)	Hemicellulose ($\%_{DM}$)	TNC ($\%_{DM}$)		TOC ($\%_{DM}$)		Phosphorus ($\%_{DM}$)		Potassium ($\%_{DM}$)		Calcium ($\%_{DM}$)		Sulfur ($\%_{DM}$)		GSL mmol g^{-1} DM	
	$\bar{x}$	$\bar{x}$	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	23.77	12.42	2.79	0.21	41.03	1.34	0.57	0.09	3.52	0.36	1.07	0.17	0.41	0.11	18.55	1.04
2015	26.56	12.95	2.38	0.26	39.82	1.31	0.71	0.10	4.71	0.20	1.13	0.26	0.68	0.06	21.58	1.56
2016	23.87	12.82	2.94	0.34	40.59	1.78	0.67	0.07	3.89	0.14	1.09	0.29	0.39	0.04	18.19	1.09
2017	23.45	12.73	3.18	0.32	38.51	0.79	0.59	0.09	3.33	0.46	0.92	0.18	0.35	0.06	17.92	0.60
2018	23.76	12.62	3.32	0.39	38.09	1.71	0.65	0.07	4.35	0.16	0.85	0.09	0.53	0.04	21.02	0.53
2019	25.39	12.48	2.58	0.26	40.87	0.82	0.78	0.07	4.98	0.15	1.28	0.23	0.56	0.17	21.19	0.56
2020	24.80	13.06	3.27	0.22	38.44	0.85	0.54	0.06	3.39	0.23	1.09	0.15	0.47	0.05	19.75	0.52
2021	24.98	13.28	3.09	0.24	41.29	0.76	0.64	0.09	3.57	0.34	1.05	0.09	0.59	0.07	21.53	0.70
2022	23.45	13.40	3.67	0.52	38.98	1.73	0.52	0.03	3.05	0.20	0.67	0.18	0.31	0.09	17.17	0.63
2023	24.25	12.75	3.43	0.50	39.15	0.89	0.59	0.08	3.82	0.40	0.95	0.11	0.49	0.09	20.09	0.47
$\bar{X}$	24.43	12.85	3.07	0.40	39.68	1.20	0.63	0.08	3.86	0.63	1.01	0.17	0.48	0.12	19.70	1.64
***R_{min}	–	–	0.41–0.53	–	1.73–1.95	–	0.07–0.15	–	0.32–0.44	–	0.21–0.32	–	0.08–0.15	–	0.31–0.54	–
LSD_{05}	–	–	0.49	–	1.82	–	0.11	–	0.41	–	0.27	–	0.12	–	0.43	–

*The indicator of transformation between %DM and g kg^{-1}_{DM} = %DM x 10. ***SD* – standard deviation; ***Tukey's test (R_{min} for $p_{adj} < 0.05$).

On the basis of this, it was also established possibility of the recycling of nutrients through the system of its return to the soil as green fertilizers in the form of oilseed radish biomass. The relatively high cellulose content at the flowering stage in spring (> 18%$_{DM}$) and summer sowing (> 23%$_{DM}$) against the background of the previously noted features of accelerated plant development ('biological aging') confirmed a steady trend of reducing the quality biochemical parameters of plant mass in later phases of the growing. This was confirmed by comparing the content of not only cellulose but also the constituent derivatives NDF, ADF and ADL. This is also confirmed in a number of studies on other cruciferous plant species (Azam et al., 2013; Herrmann et al., 2016; Bell et al., 2020). It was also indicated by a 1.5-fold increase in lignin content in plant mass (in the form of ADL) when comparing summer and spring sowing dates. Such a stable trend allowed to determine the peculiarities of oilseed radish biomass formation at different sowing dates. For the spring sowing, against the background of lower average daily temperatures and slow growth rates, the process of protein complex formation under the lower stressful temperature conditions, which (according to the studies of Sharma & Dubey (2019), Zhou et al. (2023)), contributed to the formation of plant tissues with a higher level of organic matter and water content with lower fiber, cellulose, protein and ash content. For the summer sowing, when plants formed at significantly higher levels of average daily temperature and more stressful conditions of hydrothermal vegetation regime (Table 1), biochemical processes had the reverse nature. A similar system of correlations was noted for white mustard at different periods of its use (Ţiţei (2022)) and some representatives of the radish genus (Ayres & Clements, 2002). This is also confirmed by the results of comparing the main biochemical components for the spring sowing with similar long-term averages of the summer one. The obtained coefficients of this ratio in the interval of research years for ODM 1.03–1.11, CP 0.77–0.85, CF 0.74–0.88, CFb 0.79–0.89, ADL 0.59–0.71, Cellulose 0.81–0.89, Hemicellulose 0.73–0.85, TNC 0.74–0.85, TOC 0.91–0.99, P 0.89–0.98, K 0.85–0.94, Ca 0.87–0.95, S 0.79–0.90, GSL 0.82–0.88. As a result, in view of a number of studies (Clark 2008; Hansen et al., 2021, 2022; Jauhiainen 2022; Launay et al., 2022; Fajobi et al., 2023; Lallement et al., 2023; Lymperatou et al., 2023; Manyi-Lohn & Lues, 2023), the leaf mass of oilseed radish of different sowing dates will have different criterion evaluation in the MSCC system.

At the same time, due to the increasing stress of general environmental factors, the overall variability of the obtained average values in terms of years of research was also increasing. The coefficient of variation of the average for the general data set for the summer sowing of oilseed radish had an average growth coefficient of 1.21 compared to the indicators of the spring sowing. Such features lead to an increase in the variable component in assessing the effectiveness of the use of the obtained oilseed radish biomass for the criterion goals of the MSCC system.

It should also be noted that based on studies oilseed radish in the management system as a cover crops for different purposes (Herrmann et al., 2016; Blume et al., 2020; Gamba et al., 2021; Hansen et al. 2021; Lövgren, 2022; Olofsson & Ernfors, 2022; Kemper et al., 2023), the results of biochemical evaluation presented in Tables 3–4 have certain differences. The CP content at the spring sowing was 0.9–1.5% $_{DM}$ lower than at the summer sowing and did not reach 25–27%$_{DM}$ noted in the above studies. The content of lignin, cellulose and its derivatives was 3.8–7.7%$_{DM}$ higher than in the estimates of Herrmann et al. (2016) and Hansen et al. (2021). The total organic carbon (TOC) content had a relatively stable value with fluctuations in the range of 38–42%$_{DM}$, although in the study by Hansen et al. (2021) its had a narrower interval of 39–40%$_{DM}$. In the study of Gamba et al. (2021) its level of 35–44%$_{DM}$ was noted. The detail of the content of the main elements (nitrogen, phosphorus and potassium) was estimated for two seasons with different weather conditions in the study by Hansen et al. 2021. In comparison with the data of this study, for oilseed radish on gray forest soils under conditions of unstable moisture, the phosphorus content was found 0.13–0.33%$_{DM}$ higher, the potassium content was 0.72–1.12%$_{DM}$ lower, and the calcium content was 0.15–0.24%$_{DM}$ higher. The nitrogen content was less by 0.18–0.35%$_{DM}$. In comparison with other cruciferous plant species were determined: CP content by 3.4–8.7%$_{DM}$ lower, CF content by 1.3–2.4%$_{DM}$ higher, CFb content by 1.9–6.1%$_{DM}$ lower, CA content by 1.7–2.2%$_{DM}$ lower, ADL content by 0.7–2.5%$_{DM}$ lower, potassium content by 1.8–3.7%$_{DM}$ higher, phosphorus content by 0.12–0.22%$_{DM}$ lower and sulfur content by 0.27–0.35%$_{DM}$ lower (Swarcewicz et al., 2013; Li et al., 2019; Abdallah et al., 2020;, Liu et al., 2020; Tian & Deng, 2020; Wang et al., 2022; Jacob et al., 2022; Rajković et al., 2022; Ţiţei, 2022; Oliveira & Słomka, 2021; Shitophyta et al., 2023; Israt & Parimal, 2023).

The content of glucosinolates (GSL) is important in the MSCC criterion system in such areas as 'cover crop', 'catch crop', 'green manure'. Glucosinolates provide the effect of biofumigation through the formation of active components as a result of the decomposition of the leaf and stem mass of cruciferous species that has been worked into the soil. Biofumigation contributes to reduce the germination of weed seeds, soil fungicidal effect against a number of harmful pathogens and reduction of soil pests, in particular, various species of nematodes due to soil transformation of glucosinolates into isothiocyanates (ITC) (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Śmiechowska et al., 2010; Edwards & Ploeg, 2014; Sarıkamıs et al., 2017; Blažević et al., 2020; Yan et al., 2023; Redha et al., 2023).

The presence of glucosinolates at certain concentration levels is desirable for intermediate cover crops, especially in summer sowing, to control a number of entomophages and diseases, which guarantees the necessary level of plant survival and the appropriate technological planting density and bioproductivity (McDowell et al., 2008; Zachariah, 2011; Bohinc et al., 2013; Bhandari et al., 2015; Perniola et al., 2019; Andini, 2020; Ait Kaci Ahmed et al., 2022; Abdel-Massih et al., 2023; Tsytsiura, 2024).

At the same time, the high concentration of glucosinolates significantly narrowed the use of crop in the MSCC system as a 'fodder crop', reducing the feed value of the plant and can cause poor compatibility and a number of disorders in animals (Prieto et al., 2019).

High concentration of glycosinolates also reduced the efficiency of such a direction as 'biogas crop' due to the inhibition of the intensity of anaerobic fermentation of the resulting leaf-stem mass (Cleemput, 2011; Al Seadi et al., 2013; Herrmann et al., 2016; Tsytsiura 2023b). The content of glucosinolates is also important for cruciferous crops used as 'catch crops'. It has been established that these compounds was involved in the formation of plant stress responses to abiotic factors. Its intensive growth had a high levels of significant correlation with the increase in the overall stress of the growing season by climatic parameters. It is especially important for intermediate crops that are often grown in the summer–autumn period with increasingly stressful environmental conditions (Chowdhury, 2022; Lei et al., 2022; Zhang et al., 2022).

Long-term assessment of the direct and derived glucosinolate potential of cruciferous plants proved high interspecific variability of their content as well as high variability of concentration in the aboveground parts of the plant depending on the phenological phase of development and abiotic environmental conditions (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Bellostas et al., 2004; Ciska et al., 2008; Velasco et al., 2008; Edwards & Ploeg, 2014; Bhandari et al., 2015; Yi et al., 2016; Ricardo et al., 2018; Liu et al., 2020; Wu et al., 2021; Mocniak et al., 2023; Iwar et al., 2024). The total content of glucosinolates and different cruciferous plant species ranged from 1.97 to 140.9 μmol $g^{-1}{}_{DM}$ with a maximum concentration in seeds and generative parts and a minimum in the early stages of vegetation in leaves and roots. It was noted (Velasco et al., 2008) that the concentration of glucosinolates among the cruciferous groups was maximum for leafy cruciferous plants (up to 26 μmol $g^{-1}{}_{DM}$), lower values were noted for the group of fodder cruciferous plants (up to 24 μmol $g^{-1}{}_{DM}$). The classical oilseed cruciferous plants had the lowest level of this indicator (12–16 μmol $g^{-1}{}_{DM}$). In the study by Bhandari et al. (2015), The lowest GSL conyent were observed in radish genus across all tissues examined (18–40 μmol $g^{-1}{}_{DM}$).

The long-term average GSL content in the aboveground biomass of oilseed radish was 13.57 μmol $g^{-1}{}_{DM}$ (*CV* 8.32%) in spring and 19.70 μmol $g^{-1}{}_{DM}$ (*CV* 10.58%) in summer sowing. It was confirmed the increase in its concentration with an increase in the overall stress of the growing season. In various studies on oilseed radish at the flowering stage, the level of glucosinolates was in the range of 9–41 μmol $g^{-1}{}_{DM}$ and was 1.2–1.5 times higher in inflorescences compared to leaves and stem (Gimsing & Kirkegaard, 2006; Bohinc et al., 2013; Duff et al., 2020). For white mustard the average GSL content (on average per plant) for the flowering phase was in the range of 11–56 μmol $g^{-1}{}_{DM}$ (Sang et al., 1984; Kirkegaard & Sarwar, 1998; Bohinc et al., 2013; Ciska et al., 2008; Tian & Deng, 2020). For spring rape GSL content was 9–44 μmol $g^{-1}{}_{DM}$ (Sang et al., 1984; Birch et al., 1992). For winter rape this indicator was at the level of 8–51 μmol $g^{-1}{}_{DM}$ (Sang et al., 1984; Milford & Evans, 1991; Kirkegaard & Sarwar, 1998; Ciska et al., 2008; Yasumoto et al., 2010; Bohinc et al., 2013; Salisbury et al., 2018). The long-term data of the GSL content in oilseed radish (Table 3–4) allowed to classify it as a cruciferous crops with high biofumigation potential for both spring and summer use.

The biofumigation potential of oilseed radish was also confirmed by the value of glucosinolate productivity for both sowing dates (Table 5). The obtained values was in the range of 32.7–49.5 mol ha^{-1} (with an interannual *CV* of 15.1%) for spring sowing and 36.0–72.5 mol ha^{-1} (24.9%) for summer sowing. This result was positively correlated with the study of Duff et al. (2020). It was noted the effective level of GSL content for achieving multiple goals of soil biofumigation by green manure in the case of spring and summer sowing, depending on the type of cruciferous plants in the range of 30–105 mol ha^{-1}. The interval of 60–105 mol ha^{-1} was achieved by using different types of mustard (White mustard (*Sinapis alba*), Ethiopian mustard (*Brassica carinata*), Indian mustard (*Brassica juncea*), Fodder mustard (*Brassica napus*), Black mustard (*Brassica nigra*)) in pure sowings or in various mixtures with radishes (such species-specific trademarks as 'Tillage Radish', 'Terranova Radish', 'Black Jack Radish').

Table 5. The main indicators of quality of oilseed radish aboveground biomass for different terms of sowing, 2014–2023

Year	C/N ratio				C/P ratio				C/S ratio				Carbohydrates (CH) (%$_{DM}$)			
	[*]SprS		SumS		SprS		SumS		SprS		SumS		SprS		SumS	
	$\bar{x}$	[**]SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	13.94	2.80	14.77	1.18	71.41	7.27	73.59	13.45	122.24	19.90	106.69	34.14	66.71	3.37	64.43	1.33
2015	16.86	1.81	16.86	1.60	65.12	4.58	57.06	9.16	98.68	18.50	58.94	5.65	64.80	2.05	65.01	1.98
2016	17.20	1.67	13.99	2.18	53.27	14.66	61.25	8.23	80.55	15.57	105.36	15.79	68.52	1.90	62.44	1.95
2017	16.28	1.83	12.21	1.35	48.70	4.49	66.25	9.09	71.71	14.05	112.41	18.62	63.86	2.49	62.45	2.22
2018	16.45	0.71	11.58	1.41	58.20	7.29	59.08	6.73	77.13	7.97	72.27	7.92	66.30	0.83	60.60	1.90
2019	12.12	0.86	15.97	1.73	72.13	8.98	52.73	4.93	115.31	35.43	80.62	33.69	65.28	1.71	63.31	1.97
2020	17.75	1.37	11.81	1.03	64.30	7.13	71.70	6.70	116.73	19.14	82.29	6.68	69.65	1.37	61.08	1.45
2021	18.67	1.44	13.42	1.06	80.82	12.41	65.64	10.32	98.56	14.00	70.80	9.22	71.05	0.81	60.88	1.57
2022	16.59	1.48	10.84	2.11	75.56	4.00	75.03	2.14	96.60	18.90	134.31	40.91	69.30	1.00	59.18	2.97
2023	14.34	0.96	11.58	1.51	64.24	6.67	67.15	8.31	120.76	31.85	82.23	17.63	65.38	1.71	59.93	3.24
$\bar{X}$	16.02	2.36	13.30	2.40	65.37	12.13	64.95	10.23	99.83	25.78	90.59	29.80	67.08	2.83	61.93	2.63
LSD_{05}	2.30	–	2.05	–	5.79	–	3.89	–	12.81	–	10.55	–	2.71	–	3.08	–

Year	Residue quality (RQ) (%$_{DM}$)				Accumulation in aboveground biomass (kg ha^{-1})											
					Nitrogen[***]				Phosphorus				Potassium			
	SprS		SumS		SprS		SumS		SprS		SumS		SprS		SumS	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
2014	81.36	0.82	81.46	0.88	114.6	15.27	93.94	11.22	22.14	2.70	19.50	5.27	111.15	9.64	118.21	12.98
2015	86.35	0.84	80.44	0.72	68.34	8.05	39.51	4.58	17.62	1.71	11.88	2.50	112.56	9.22	78.38	7.71
2016	84.32	0.98	81.00	1.33	69.32	8.38	98.71	14.96	23.19	4.95	22.32	0.16	143.27	10.32	130.87	15.65
2017	86.43	0.65	81.53	1.84	53.28	6.04	108.00	12.61	17.76	1.65	20.04	3.26	119.68	10.73	113.53	20.25
2018	87.10	1.15	81.46	0.78	51.08	9.02	114.45	14.26	14.58	3.01	22.42	2.64	78.54	10.69	150.09	11.32
2019	84.59	0.88	81.04	0.78	123.8	10.91	44.75	5.09	21.05	3.56	13.56	1.81	90.61	5.69	86.49	7.42
2020	86.21	1.08	80.69	0.68	89.21	8.25	59.46	6.82	24.79	3.46	9.77	0.74	160.26	4.34	61.51	5.40
2021	84.74	1.33	80.43	0.52	58.03	4.48	84.48	10.67	13.88	4.07	17.56	3.53	81.32	8.28	97.64	13.52
2022	84.52	1.07	81.08	0.71	65.62	7.09	122.58	21.80	14.35	1.12	17.28	1.17	85.26	4.59	101.62	10.79
2023	84.26	1.39	81.16	0.98	87.14	5.89	115.51	17.38	19.50	1.36	19.79	1.68	101.96	6.37	129.07	18.97
$\bar{X}$	84.99	1.83	81.03	0.95	78.04	25.40	88.14	31.25	18.88	4.57	17.41	4.80	108.46	25.52	106.74	22.25
LSD_{05}	1.50	–	2.17	–	8.69		9.73		4.33		3.86		8.77		10.72	

Year		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	$\bar{X}$	LSD_{05}
Ca accumulation (kg ha^{-1})	SprS	44.05	27.48	30.27	24.04	21.75	32.28	36.17	26.79	25.05	26.31	29.42	3.69
	SumS	36.27	18.69	36.90	31.04	29.24	22.09	19.72	28.81	22.10	32.03	27.69	4.27
S accumulation (kg ha^{-1})	SprS	13.18	11.89	15.15	12.31	11.00	14.29	13.78	11.10	11.52	10.82	12.50	2.34
	SumS	14.09	11.32	13.02	11.87	18.24	9.75	8.51	16.19	10.36	16.53	12.99	3.82
GSL productivity (mol ha^{-1})	SprS	49.5	38.4	43.8	33.6	32.7	47.9	48.9	36.4	38.9	41.5	41.2	0.17
	SumS	62.5	35.8	61.1	60.8	72.5	36.7	36.0	58.8	57.2	67.7	54.9	0.35
Equivalent cattle manure, t ha^{-1}	SprS	23.0	18.9	22.8	18.9	13.7	21.7	26.1	13.9	15.2	19.6	23.0	–
	SumS	22.0	12.6	24.3	23.1	28.1	14.2	12.5	19.2	23.1	25.6	22.0	–

[*]SprS – Spring sowing; SumS – Summer sowing. [**]SD – standard deviation; [***] transformation from kg ha^{-1} to g m^{-2} by dividing the value by 10.

At the achieved level of glucosinolate accumulation, the studied species of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) can be effectively used at both sowing dates in the soil rehabilitation system through the process of green manure biofumigation. The issue of combining oilseed radish with other cruciferous species under conditions of unstable moisture should be further investigated in the future.

It was noted (Couëdel et al., 2019) that the biochemical assessment of the leaf mass of plants used as cover crops for multipurpose use requires a system of appropriate ratios that determine the processes of decomposition, mineralization, accumulation and the predicted intensity of anaerobic fermentation. These ratios was widely used by the scientific community and proposed in the analysis of Hansen et al. (2021), Thiébeau et al. (2021), Hansen et al. (2022), Quintarelli et al. (2022), Allam et al. (2023), Yousefi et al. (2024). The results of this assessment was presented in Table 5.

According to a number of studies (Kriaučiūnienė et al., 2012; Jahanzad et al., 2016; Sousa et al., 2019; Liu et al., 2020; Toleikiene et al., 2020; Dorissant et al., 2022; Silva et al., 2023), the C/N ratio is decisive in the decomposition rate of green manure. The biomass of oilseed radish at the interval value of C/N ratio 8.73–20.11 with interannual variation of 12.3% for spring sowing and 15.4% for summer sowing (Table 5) was fully compliant to the criteria of 'fodder crop' and 'green manure'. It was predicted to ensure rapid decomposition of its raw biomass in the soil, especially under conditions of sufficient moisture supply against the background of high average daily temperatures. These values also indicated a significant proportion of leaves and inflorescences in the total biomass of oilseed radish, especially at the summer sowing date. Such conclusions was confirmed by the findings of Kriaučiūnienė et al. (2012) on the decomposition rates of different parts of cruciferous plant species. It should also be noted that in the case of summer sowing of oilseed radish, according to a number of studies (Wadman & de Haan, 1997; Hadas et al., 2004; Flores-Sánchez et al., 2016; Drost et al., 2019; Salume et al., 2020) decomposition rates will have predictably slower due to the significantly lower temperature during the period of direct use of biomass in the form of green manure (Table 1). The optimal value of C/N ratio, which provides a positive ratio between the rate of decomposition and subsequent humus accumulation and immobilization of mineral nutrients, was range from 13 to 25 depending. Actually, this indicator depends from the weather conditions, soil type and the nature of the use of the corresponding cover crop (Wadman & de Haan, 1997). It was also positively correlates with C/N ratio in classical cattle manure 16.6–25.0 (Pan et al., 2021). The biomass of oilseed radish formed during spring sowing had a higher degree of compliance with these intervals for green manure use. Its use can be optimized by using oilseed radish in mixed crops with cereals and legumes, as well as using additional plant materials for combined green manure (e.g. straw) (according to the recommendations of Couëdel et al. (2019) and Hansen et al. (2021)).

The determined long-term average C/N ratio also allowed to classify oilseed radish as a candidate for the 'fodder crop' in the MSCC system.

The value of the C/N indicator was considered from the standpoint of increased protein content, i.e. higher total nitrogen content with optimization of fiber and non-nitrogenous compounds (lower carbon content). As a result, the optimal value of the C/N ratio was in the range of 8–15 (Li & Zhou, 2002).

It has been noted that the optimal C/N ratio for anaerobic biomass dehydration in biogas production technologies was in the range of 20–30 with an interval of possible technological deviations from 10 to 40 (Guarino et al., 2016; Herrmann et al., 2016; Dębowski et al., 2022; Manyi-Loh. & Lues, 2023; Tsytsiura, 2023a). At low values of the C/N ratio, the concentration of the ammonium form of nitrogen increased significantly and the microbial process of anaerobic fermentation was inhibited (Cerón-Vivas et al., 2019; Choi et al., 2020). Based on this, the most appropriate option for oilseed radish would be the use of pre-prepared biomass both through silage and through co-fermentation of fresh mass with other plant or organic resources as well as the use of cofermentation and inoculum (Carvalho et al., 2011; Wang et al., 2012; Herrmann et al., 2016; Oliveira & Słomka, 2021). It was proved that silage fermentation of oilseed radish leaf and stem mass allowed to increase the C/N ratio by 3–6 units depending on the phenological phase of plants during the formation of silage mass and the use of inoculum. It was helped to optimize the accumulation curve of the generated biomethane and intensified the digestion process (Tsytsiura, 2023c). It should be noted that C/N ratio for other cruciferous crops used in MSCC variants at the flowering stage was in the range of 12–23 for spring sowing and 10–18 for summer sowing (Herrmann et al., 2016; Li et al., 2019; Blume et al., 2020; Keim et al., 2020; Liu et al., 2020; Hansen et al., 2021; Ţiţei, 2022). Such results confirmed the high potential of oilseed radish in the MSCC criterion system in comparison with the already widely used cruciferous crops.

It was also important to evaluate the C/P ratio, which was characterized the relationship between soil immobilization of mobile phosphorus forms and the efficiency of its replenishment by biomass introduced into the soil. This ratio affects the nature of the microbiological decomposition of green manure, especially in soils depleted in mobile phosphorus forms (Ngatia et al., 2014; Nobile et al., 2019). The optimal option for green manure application of the formed biomass was a high phosphorus content and low C/P ratio (Rinasoa et al., 2022). This ensured the maintenance of intensive rates of biomass decomposition in the soil with a positive balance of phosphorus release (Amy et al., 2024). According to this criterion, the leaf and stem mass of oilseed radish responded the required disparity between the phosphorus content and its ratio to organic carbon with a long-term average value about 70 with an interannual variation of 15.3% for spring and 11.34% for summer sowing. At the same time, the difference between the average long-term value for both sowing dates was not significant. It is interesting to note that in cereal green manure, this ratio was 115–140. In legumes green manure was 110–125 (Hansen et al., 2021). Based on this the oilseed radish will be effective for green manuring of soils poor in mobile phosphorus and in options for restoring a positive phosphorus balance in soils under organic fertilization systems.

Important for assessing the biofumigation potential of plants was the C/S ratio. It was a relative indicator of the presence of glucosinolates in plant biomass, since the biochemical composition of some chemical compounds belonging to this group of substances is sulfur-containing (De Kok et al., 2012; Pekarek et al., 2013; Galaup, 2018; Couëdel et al., 2019; Duff et al., 2020). It has been established that an effective green manure option with an overall biofumigation effect is possible at a C/S ratio of no more 120 (Kirkegaard & Sarwar, 1998; Zachariah, 2011). For oilseed radish this indicator was in the range of 71–122 for spring sowing and 59–134 for summer sowing. That was corresponded to the requirements of an effective biofumigation process for green manure use of the formed biomass. During the summer sowing period, this indicator had a 1.36 times higher level of interannual variation than during the spring sowing period (25.6%) and significantly lower than its long-term average value by 9.24 units. This character of the formation of the indicator was explained by the lower proportion of the generative part and the larger proportion of leaves, which, given the data on the content of glucosinolates in different parts of cruciferous plants and naturally reduces the content of sulfur-containing compounds in the formed biomass (Bohinc et al., 2013; Perniola et al., 2019). This was confirmed by comparing the maximum C/S value of 134.31 for the conditions of summer sowing in 2022, for which the highest amount of precipitation of 436.6 mm at moderate temperature was recorded in this period (Table 1).

The criterion value of the leaf-stem aboveground mass of oilseed radish in the MSCC system was also confirmed by the level of carbohydrates (CH), which determined the dynamics of mass decomposition in terms of released substances and its subsequent positive effect on the microbiological activity of the soil and the promotion of its self-aggregation (Liu et al., 2020; Israt & Parimal, 2023). From this point of view, CH content in oilseed radish mass in the range of 55–60%$_{\mathrm{DM}}$ characterized it as suitable for effective green manure utilization. It had also proved that carbohydrates are energy-providing feed components composed of carbon, hydrogen, and oxygen. They should make up about 75%$_{\mathrm{DM}}$ of an animal's diet (Navarro et al., 2019). According to this indicator, the biomass of oilseed radish with a carbonate content of up to 50–70%$_{\mathrm{DM}}$ needs to be improved in terms of the desired compatible use. For this effective will be the use cereals and legumes, which is confirmed in a number of studies (Ayres & Clements, 2002; Mbambalala et al., 2023; Sánchez et al., 2023).

It is argued that biomass, particularly agricultural residues and biomass rich in structural carbohydrates, offers significant potential for sustainable biogas production (Venslauskas et al., 2024). At the same time, for most crops with high biogas production potential, the CH content should reach 65–75%$_{\mathrm{DM}}$ (Herrmann et al., 2016). Based on these statements, the biomass of oilseed radish formed by the plant during the spring sowing period with an average long-term carbonate content of 67.08%$_{\mathrm{DM}}$ was technologically more suitable for biogas production than the same during the summer sowing period, which is consistented with the results of our previous studies (Tsytsiura, 2023a).

To evaluate the possibility of effective use of oilseed radish leaf mass in the form of mulching with spreading of the chopped mass on the soil surface (Duff et al. 2020; Nithisha et al. 2022), the residue quality (RQ) index in the traditional variation (Quemada & Cabrera, 1995) was adapted. The obtained long-term average RQ index was 84.99%$_{\mathrm{DM}}$ for spring and 81.03%$_{\mathrm{DM}}$ for summer sowing. This was close to the value of the indicator for other cruciferous plant species (Bajgai et al., 2014, Thiébeau et al., 2021; Sharma et al., 2022). It was also proved the potential use of oilseed radish biomass for green mulching in the system of creating a protective mulching layer in the variants of bioconservation agriculture. This type of technological solution for oilseed radish mass is predicted to be more efficient when using plant biomass grown in the spring sowing period.

The study of the indicators of accumulation of the main nutrients in the formed biomass of oilseed radish was comparabled to their concentration noted in Tables 3–4. The average long-term ratio of content and accumulation in the aboveground biomass of

N:P:K:Ca:S was established in the following expression (with indication of the range of values) 1.00 (0.65–1.59):0.24 (0.18–0.40):1.39 (1.04–2.05):0.38 (0.28–0.56):0.16 (0.14–0.19) for spring sowing and 1.00 (0.51–1.39):0.20 (0.11–0.25):1.21 (0.70–1.70):0.31 (0.21–0.42):0.15 (0.10–0.21) for the summer sowing. To compare the intensity of accumulation of individual elements (based on the generalization of De Kok et al., 2012; Szczepanek & Siwik-Ziomek, 2019; Franzen, 2023; Yahbi et al., 2024) this ratio of N:P:K:Ca:S for rapeseed was in the range of 0.9–1.7:0.4–0.7:1.4–2.2:0.45–0.75:0.18–0.55. The same ratio for different mustard species was 0.8–1.2:0.3–0.6:1.2–1.6:0.40–0.65:0.24–0.60. For other types of cruciferous plants used in the system of intermediate green manure (for example*, Barbarea vulgaris* L.) this ratio was in the range of 0.6–1.1:0.2–0.6:1.1–1.3:0.25–0.50:0.18–0.32. In summary, the oilseed radish was characterized by similar features in the accumulation of basic nutrients as for widely used rapeseed and mustard in the MSCC system.

Based on the determined ratios, the intensity of growth processes for the formation of oilseed radish leaf and stem mass will be predicted to be high with sufficient soil supply of available forms of nitrogen and potassium. As for phosphorus, (according to the findings of Weih et al. (2018)), the critical period of consumption of this element for oilseed radpsh will be at the early stages of the growing.

At the same time, in terms of the direction and use of 'catch crop' in the MSCC system, according to the 'N uptake' indicator, oilseed radish showed significantly lower levels of nitrogen removal over the ten-year evaluation period compared to the predicted levels of this indicator for already noted widely used crops such as rapeseed and mustard. The determined nature of accumulation also showed a high positive response of oilseed radish to additional mineral nutrition, especially during the period of active growth of vegetative mass, which according corresponded to 30–35 days after sowing for spring and 25 days after sowing for summer sowing (Fig. 4).

According to the accumulation of phosphorus and calcium in comparison with niche cruciferous crops, oilseed radish was classified as a species with intensive accumulation of these elements (based on the gradation of Wallace & Mueller, 1980).

Based on the above, the established high levels of productivity of oilseed radish at lower levels of consumption of the main elements to ensure this productivity allowed to recommend it for the system of saturating multi-term crops in the links of typical crop rotations with the criterion of 'catch crop' and 'green manure'. This statement is consistented with the findings of Grzebisz et al. (2022, 2023). This was also confirmed by the results of equivalent transformation of the formed aboveground mass of oilseed radish in terms of the content of organic and dry matter in cattle manure. Such conversion, which provided an average perennial rate of more than 20 t ha^{-1} and taking into account the study by Carr et al. (2020), proved the effectiveness of using oilseed radish at both sowing dates in the system of bioorganic fertilization technologies.

It is important to note that the characterized basic indicators and correlations (according to Ramírez-García et al. (2015)) that determine the belonging to different niche areas in the MSCC system for oilseed radish formed a regression system of dependencies. The most significant are presented in Table 6. It was found that the quality of plant residues (RQ) decreased with both an increase in precipitation and an increase in temperature. This was explained by the intensification of vegetative growth processes with a slowdown in qualitative biochemical transformations characteristic of natural physiological aging. At the same time, an increase in temperature will ensure an increase in the content of lignin derivatives and an increase in precipitation will cause a general decrease in the components of NDF and ADL. In interaction, this will form plant residues with rapid rates of aerobic decay and reduce its quality in terms of bio-cycling of its components. This character was consistented with the determined dependencies between RQ and hydrothermal ratios – the aridity coefficient I_{DM} and the moisture coefficient K_h. Similar results were obtained in the studies of Bajgai et al. (2014).

Table 6. Multiple regression dependence between hydrothermal conditions of vegetation and indicators of value of aboveground mass of oilseed radish according to the criteria of multi-service cover crop (MSCC) (average data for 2014–2023)

Qualitative indicator	Equation of dependence	Parameters of the equation		Statistical evaluation of components				
		x	y	Multiple R	$R^2_{(adj.)}$	F	$df1$, $df2$	p
RQ	$RQ = 92.503-0.00995x-0.4975y$	Precipitation (mm)	Average daily temperature (°C)	0.873	0.735	27.334	2.170	< 0.001
C/N	$C/N = 24.5149-0.0189x-0.4478y$			0.788	0.576	13.891	2.170	< 0.001
N_{upt}	$N_{upt} = -7.040+0.1394x+1.3556y$			0.850	0.689	22.058	2.170	< 0.001
CFb	$CFb = 21.851-0.0152x-0.1937y$			0.862	0.713	24.599	2.170	< 0.001
GC	$GC = 84.205+0.0934x-1.343y$			0.821	0.636	17.625	2.170	< 0.001
GSL	$GSL = 12.918-0.0147x+0.1731y$			0.806	0.609	15.773	2.170	< 0.001
RQ	$RQ = 84.268-1.5649x+10.285y$	I_{DM}	K_h	0.738	0.545	10.188	2.170	< 0.05
C/N	$C/N = 17.569-2.151x+13.344y$			0.854	0.729	22.823	2.170	< 0.001
N_{upt}	$N_{upt} = 13.420+9.622x-54.875y$			0.921	0.831	47.785	2.170	< 0.001
CFb	$CFb = 25.222-0.1074x-0.7081y$			0.815	0.625	16.785	2.170	< 0.001
GC	$GC = 62.557-1.1471x+16.155y$			0.895	0.707	21.789	2.170	< 0.001
GSL	$GSL = 15.779-0.0079x-1.2605y$			0.783	0.612	19.446	2.170	< 0.001

The C/N ratio also decreased with an increase in both precipitation and average daily temperature. This was consistented with the previously mentioned theory of stress proteins and an increase in the content of nitrogenous compounds. In the case of precipitation it was determined by decrease in the rate of physiological aging with the formation of an increased nitrogen content in late phenostages.

In the case of temperature, a stress response system was formed in the form of an increased content of stress proteins and, accordingly, a higher concentration of nitrogen in biomass. Against the background of the previously mentioned stable organic carbon content, this ultimately reduced the value of the C/N ratio. At the same time, the negative forming direction in the equation of the aridity index (I_{DM}) and the positive forming direction for the moisture coefficient (K_h) indicated a more important role of the precipitation to evapotranspiration ratio than precipitation to the sum of temperatures. In the first case, this contributed to the accumulation of both organic carbon and nitrogen compounds and was consistented with the estimates of Agren & Weih (2012). It was also conformed by the presented results of regression dependencies for the resultant component N_{upt}. For the indicator of soil coverage 'GC', the peculiarities of the formation of the indicator for oilseed radish were confirmed. It was found an increase in its value with an increase in precipitation and a decrease in evaporation in terms of the value of the moisture coefficient (K_h) and a decrease in the average daily air temperature. This was consistented with all the dependencies that determined the intensity of growth processes in the dynamics (Fig. 4) and with the conclusions of a number of studies (Ramirez-Garcia et al., 2012; Ugrenović et al., 2019; Kashyap et al., 2023).

The regression analysis proved a positive formative effect of the increase in average daily temperatures and a negative formative effect of precipitation on the accumulation of glucosinolates. The GSL content was consistented with a significantly higher concentration of its in the biomass of oilseed radish during the summer sowing period, especially under conditions of moisture deficit against the background of intensively increasing average daily temperatures. The GSL content was positively correlated with similar studies on other cruciferous crops (Milford & Evans, 1991; del Carmen Martínez-Ballesta et al., 2013, Bellec et al., 2023; Ben Ammar et al., 2023).

An important component in assessing the belonging of oilseed radish to the MSCC system is an attribute assessment of the component coefficients of the resulting equations of the corresponding conceptual direction of use. For scientific detailing and substantiation of the selected attributes, a systematization of a number of studies that directly or indirectly relate to the issues of MSCC formation was applied. The results of this generalization are presented in Table 7.

The formed array of initial data on the importance of the studied attributes in the formation of the direction of use of oilseed radish allowed to obtain its normalized matrix (Table 8).

The conditions of 2014 and 2023 were recognized as ensuring the maximum realization of the possibility of multicomponent use of aboveground biomass of oilseed radish in all defined areas. In contrast, the conditions of 2015 and 2017 had a significant lowest level of criterion realization. In the system of evaluation of individual attributes, its importance was confirmed on the basis of the systematization of the results of long-term studies. Aaccording to this studies, the indicator of the amount of formed aboveground biomass was dominant in the context of all studied areas of use of oilseed radish. The the fiber content or its dietary form was in the last ranking place.

The significance of the difference within the years of evaluation was minimal for the attributes 'GSL', 'CFb' and 'RQ', which was associated with the different directions of the identified trends of its formation for different uses in the MSCC system and was positively consistented with the data of Ramírez-García et al. (2015).

The results of the multicriteria analysis within different sowing dates established the final sums of normalized and weight-adjusted attributes (Table 9). Accordingly, it was determined that different sowing dates of oilseed radish have different years of optimality for a particular use. The maximum number of maximum values of the adjusted coefficients was observed for the conditions of 2019 for the spring sowing period and for the conditions of 2022 for the summer sowing period. On this basis the possibility of involving oilseed radish as an effective candidate for crops of the MSCC system was determined.

The sowing dates influenced the assessment of the efficiency of use, which is confirmed by the average normalized index for this attribute in the array of years of study. Shifting the sowing dates of oilseed radish from spring to summer increased the efficiency of its use in the such criterion area as 'Green manure', 'Fodder' and 'Catch crop' (increase in the rating position by 1–2 levels).

Table 7. Intensity of importance of the normalized attributes on fundamental scale in oilseed radish as the multi-service cover crop (MSCC) utility functions assigned by the decision makers based on analysis of publications for both sowing dates

Use	GC*	BM	C/N	N_{upt}	RQ	GSL	CFb	Attributes selected based on the analysis of publications
Cover crop	5	2	1	1	3	3	1	Snapp et al., 2005; Clark, 2008; Bodner et al., 2010; Tixier et al., 2010; Bangarwa et al., 2011; Zachariah, 2011; Justes et al., 2012; Gieske, 2013; Ramírez-García et al., 2015a; White et al., 2016; Wendling et al., 2016; Wollford & Jarvis, 2017; Warren, 2017; Couedel et al., 2018, 2019; Tribouillois et al., 2018; Bhogal et al., 2019; Toom et al., 2019; Ugrenović et al., 2019; Chapagain et al., 2020; Duff et al., 2020; Norberg & Aronsson, 2020; Hansen et al., 2021; Lövgren, 2022; Quintarelli et al., 2022; Ait Kaci Ahmed et al., 2022; Restovich et al., 2022
	**+	+	+	-	+	+	+	
Catch crop	2	2	1	2	2	3	1	Snapp et al., 2005; Molinuevo-Salces et al., 2014; Gieske, 2013; Alonso-Ayuso et al., 2014; Ramírez-García et al., 2015, 2015a; White et al., 2016; Wendling et al., 2016; Wollford & Jarvis, 2017; Warren, 2017; Couedel et al., 2018, 2019; Bhogal et al., 2019; Sieling et al., 2019; Toom et al., 2019; Chapagain et al., 2020; Duff et al., 2020; Hansen et al., 2021; Lövgren, 2022; Restovich et al., 2022
	+	+	-	-	+	+	+	
Green manure	3	5	2	3	5	7	3	Kirkegaard & Sarwar, 1998; Eberlein et al., 1998; Gimsing & Kirkegaard, 2006; Clark, 2008; Florentín, 2010; Bangarwa et al., 2011; Zachariah, 2011; Ramírez-García et al., 2015; Flores-Sánchez et al., 2016; Stubbs & Kennedy, 2017; Galaup, 2018; Hu et al., 2018; Heuermann et a., 2019; Li et al., 2019; Liu et al., 2020; Salume et al., 2020; Lövgren, 2022; Ait Kaci Ahmed et al., 2022; Lei et al., 2022; Jie, 2022; Jauhiainen, 2022; Wang et al., 2022; Israt & Parimal, 2023; Källén, 2023;
	+	+	-	-	+	+	-	
Fodder	3	5	3	3	1	7	5	Gustine & Jung, 1985; Capecka & Libik, 1998; Westwood & Mulcock, 2012; Ramírez-García et al., 2015, 2015a; Winkler, 2017; FOSS. 2018; Duff et al., 2020; Kılıç et al., 2021; Olofsson & Ernfors, 2022; Abdelrahman et al., 2022; Safaei et al., 2022; Jie, 2022; Ţiţei, 2022
	+	+	-	+	+	-	+	
Biogas	3	5	5	3	5	5	3	Chen et al., 2008; Cleemput, 2011; Herout et al., 2011; Murphy et al., 2011; Carvalho et al., 2011; Al Seadi et al., 2013; Molinuevo-Salces et al., 2013; Dandikas et al., 2014; Carvalho et al., 2014; Herrmann et al., 2014, 2016; Guarino et al., 2016; Einarsson & Persson, 2017; Maier et al., 2017; Martínez-Gutiérrez, 2018; Cerón-Vivas et al., 2019; Choi et al., 2020; Liu et al., 2020; Oliveira & Słomka, 2021; Launay et al., 2022; Jauhiainen, 2022; Fajobi et al., 2023; Lallement et al., 2023; Lymperatou et al., 2023; Manyi-Lohn & Lues, 2023; Shitophyta et al., 2023
	+	+	+	+	+	-	-	

Equations with attribute for uses (desirable trend of formation: growth '+', decline '-')

Cover crop	$5GC + 2BM + C/N - N_{upt} + 3RQ + 3GSL + CFb$
Catch crop	$2GC + 2BM - C/N - 2N_{upt} + 2RQ + 3GSL + CFb$
Green manure	$3GC + 5BM - 2C/N - 3N_{upt} + 5RQ + 7GSL - 3CFb$
Fodder	$3GC + 5BM - 3C/N + 3N_{upt} + RQ - 7GSL + 5DFb^{***}$
Biogas	$3GC + 5BM + 5C/N + 3N_{upt} + 5RQ - 5GSL - 4CFb$

*GC: ground cover (% at 60 days after sowing); BM: biomass reached at the end of the experiment (kg m^{-2}); CN: C/N ratio; N_{upt}: N uptake (g m^{-2}); RQ: residue quality (g kg$^{-1}_{DM}$); CFb: fiber content (g kg$^{-1}_{DM}$); DFb: dietary fibre content (g kg$^{-1}_{DM}$); GSL: glucosinolate productivity (mmol m^{-2}). **desirable trend of formation: growth '+', decline '-' ***DFb only for the 'fodder crop' direction.

Table 8. Average of normalized values for 7 attributes of oilseed radish evaluation as multi-service cover crop functions (MSCC), 2014–2023 (averaged for the complete data set, directions of use–sowing dates)

Year	GC*	BM	C/N	N_{upt}	RQ	GSL	CFb (DFb**)	Amount	Rating
2014	0.213^{a}	0.268^{b}	0.129^{c}	0.069^{b}	0.072^{b}	0.086^{b}	0.057^{c}	0.897	1
2015	0.128^{f}	0.196^{h}	0.118^{e}	0.064^{d}	0.075^{a}	0.089^{a}	0.061^{b}	0.730	9
2016	0.179^{c}	0.231^{e}	0.120^{e}	0.069^{b}	0.075^{a}	0.088^{a}	0.062^{a}	0.824	6
2017	0.151^{h}	0.208^{g}	0.123^{d}	0.070^{b}	0.076^{a}	0.089^{a}	0.064^{a}	0.782	8
2018	0.154^{g}	0.214^{f}	0.125^{d}	0.075^{a}	0.075^{a}	0.089^{a}	0.064^{a}	0.796	7
2019	0.168^{e}	0.278^{a}	0.136^{a}	0.067^{c}	0.073^{b}	0.088^{a}	0.057^{c}	0.868	3
2020	0.167^{e}	0.262^{c}	0.120^{e}	0.063^{d}	0.074^{a}	0.088^{a}	0.060^{b}	0.834	5
2021	0.159^{f}	0.263^{c}	0.117^{f}	0.069^{b}	0.076^{a}	0.089^{a}	0.060^{b}	0.834	5
2022	0.172^{d}	0.270^{b}	0.127^{c}	0.073^{a}	0.076^{a}	0.088^{a}	0.061^{b}	0.867	4
2023	0.185^{b}	0.262^{c}	0.132^{b}	0.071^{b}	0.076^{a}	0.088^{a}	0.060^{b}	0.873	2
Average	0.168	0.245^{d}	0.125^{d}	0.069^{b}	0.075^{a}	0.088^{a}	0.061^{b}	–	–
Rating	2	1	3	6	5	4	7	–	–

* GC: ground cover (% at 60 days after sowing); BM: biomass reached at the end of the experiment (kg m^{-2}); CN: C/N ratio; N_{upt}: N uptake (g m^{-2}); RQ: residue quality (g $kg^{-1}{}_{DM}$); CFb: fiber content (g $kg^{-1}{}_{DM}$); DFb: dietary fibre content (g $kg^{-1}{}_{DM}$); GSL: glucosinolate productivity (mmol m^{-2}). **DFb for the direction use only for 'fodder crop' direction.

Table 9. Sum of normalized values multiplied by the weighting coefficients for 7 attributes attained by each use oilseed radish as multi-service cover crop functions (MSCC), 2014–2023

Year of research	Direction of use in the concept of MSCC										Rating by MSCC
	Cover crop		Catch crop		Green manure		Fodder		Biogas		
	*SprS	SumS	SprS	SumS	SprS	SumS	SprS	SumS	SprS	SumS	
2014	0.82^{d}	0.86^{b}	0.95^{b}	0.85^{d}	0.88^{b}	0.91^{c}	0.96^{b}	0.91^{c}	0.95^{b}	0.88^{c}	1
2015	0.82^{d}	0.84^{c}	0.73^{g}	0.72^{f}	0.75^{f}	0.62^{h}	0.76^{g}	0.60^{g}	0.75^{g}	0.59^{g}	10
2016	0.83^{d}	0.82^{d}	0.76^{d}	0.83^{e}	0.80^{e}	0.89^{d}	0.79^{f}	0.89^{c}	0.78^{f}	0.87^{c}	7
2017	0.82^{d}	0.73^{g}	0.68^{h}	0.83^{e}	0.80^{e}	0.87^{e}	0.65^{i}	0.87^{d}	0.65^{i}	0.87^{c}	9
2018	0.83^{d}	0.79^{e}	0.63^{i}	0.87^{c}	0.80^{e}	0.89^{d}	0.70^{h}	0.88^{c}	0.69^{h}	0.93^{b}	8
2019	0.79^{e}	**0.89**^{a}	**0.98** ^{a}	0.82^{e}	**0.91**^{a}	0.76^{g}	**0.99** ^{a}	0.73^{f}	**0.99** ^{a}	0.72^{f}	4
2020	0.87^{b}	0.78^{f}	0.86^{c}	0.82^{e}	0.85^{c}	0.79^{f}	0.90^{c}	0.80^{e}	0.90^{c}	0.76^{e}	6
2021	**0.93**^{a}	0.84^{c}	0.74^{g}	0.86^{d}	0.82^{d}	0.87^{e}	0.80^{e}	0.87^{d}	0.80^{e}	0.85^{d}	5
2022	0.85^{c}	0.80^{e}	0.77^{f}	0.90^{b}	0.83^{d}	**0.99** ^{a}	0.82^{e}	**0.99** ^{a}	0.81^{e}	**0.98** ^{a}	3
2023	0.82^{d}	0.81^{d}	0.84^{c}	**0.93** ^{a}	0.85^{c}	0.93^{b}	0.88^{d}	0.94^{b}	0.87^{d}	0.94^{b}	2
Average	0.838^{a}		0.794^{d}		0.829^{b}		0.825^{b}		0.819^{c}		–
		0.816^{d}		0.843^{b}		0.852^{a}		0.849^{a}		0.839^{b}	–
Rating by use	1		5		2		3		4		–
		5		3		1		2		4	–
Consistensy index (CI)*	0.431		0.188		0.340		0.370		0.226		–
		0.244		0.357		0.415		0.407		0.305	

*SprS – Spring sowing; SumS – Summer sowing. In bold, the maximum values, and in italics, the minimum. Case letters indicate statistical differences ($p < 0.05$); *the indicator is a component of the scheme of Analytic Hierarchy Process (AHP) according to Saaty & Vargas (2012).

The positions in the criterion of 'Biogas' use remained unchanged. Its use in the direction of 'Cover crop' was significantly lower (decrease in the rating by 4 positions). Such changes, taking into account the saturating and intermediate nature of the summer sowing of oilseed radish, proved the technological potential of its use in a wide period of time in the MSCC system. It was also found that the rating by the direction of use depended on the conditions of the year. For example, for the conditions of 2018 and 2023, the direction 'Biogas' during the summer sowing period had the first rating among other directions of use with an average fourth position in the consolidated data set. Similar trends were found for other uses. This confirmed conclusions about the role of hydrothermal regimes of the growing season in shaping compliance with MSCC criteria.

CONCLUSIONS

According to the results of a multi-year study cycle, oilseed radish showed high productivity and adaptability. On soils of medium fertility potential with an unfertilized background, its average total bioproductive potential (leaf + root mass) in dry matter over 50–60 days of vegetation was 4.92 t ha^{-1} in spring and 4.06 t ha^{-1} in summer sowing. According to the results of a long-term integrated assessment of the biochemical portfolio of oilseed radish leaf mass, it was classified as a high-protein crop (crude protein content 15–23%$_{\mathrm{DM}}$) with a high fat content (3.2–5.8%$_{\mathrm{DM}}$) and an average content of cellulose-derived components (20–24%$_{\mathrm{DM}}$). This maked it possible to recommend it for cultivation in a wide range of intermediate sowing options and to form a fodder- green manure and green manure-bioenergy agrocenosis in areas of a wide climatic spectrum. According to the ash content and the content of basic macro and microelements, its use as a green manure was equivalent to an average of 20 t ha^{-1} of cattle manure. Its biofumigation potential in terms of glucosinolates content of 41.2–54.90 mol ha^{-1} will guarantee a high efficiency in different variants of soil biofumigation technologies.

Using the above data block with the application of Multi-criteria decision aiding (MCDA), the possibility of multi-purpose use of oilseed radish in the criterion system of multi-service cover crop (MSCC) was proved. The order of decreasing technological significance of oilseed radish for the conditions of unstable hydrothermal regime on soils with an average level of fertility (averaged for spring and summer sowing dates) was the following: 'Green manure' - 'Fodder' - 'Cover crop' - 'Biogas' - 'Catch crop'.

REFERENCES

Abdallah, I., Yehia, R. & Kandil, M.Ah. 2020. Biofumigation potential of Indian mustard (Brassica juncea) to manage Rhizoctonia solani. *Egyptian Journal of Biological Pest Control* **30**. 99 doi: 10.1186/s41938-020-00297-y

Abdel-Massih, R.M., Debs, E., Othman, L., Attieh, J. & Cabrerizo, F.M. 2023. Glucosinolates, a natural chemical arsenal: More to tell than the myrosinase story. *Frontiers in Microbiology* **14**, 1130208. doi: 10.3389/fmicb.2023.1130208

Abdelrahman, M., Wang, W., Lv, H., Di, Z., An, Z., Lijun, W., Shaukat, A., Bo, W., Guangsheng, Z., Liguo, Y. & Guohua, H. 2022. Evaluating the Effect of Forage Rape (*Brassica napus*) Ensiling Kinetics on Degradability and Milk Performance as Non-conventional Forage for Dairy Buffalo. *Frontiers in Veterinary Science* **9**, 926906. doi: 10.3389/fvets.2022.926906

Abe, A. 1984. Assessment of the Quality of Forage from Its Chemical Composition and Application to Feeding Program. *Tropical agriculture research series: proceedings of a symposium on tropical agriculture researches* **18**, 133–150.

Agathokleous, E., Belz, R.G., Kitao, M., Koike, T. & Calabrese, E.J. 2019. Does the root to shoot ratio show a hormetic response to stress? An ecological and environmental perspective. *Journal of Forestry Research* **30**, 1569–1580. doi: 10.1007/s11676-018-0863-7

Agren, G.I. & Weih, M. 2012. Plant stoichiometry at different scales: Element concen-tration patterns reflect environment more than genotype. *New Phytologist* **194**, 944–952.

Ahmad, P. 2017. Oilseed Crops. Yield and Adaptations under Environmental Stress. John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK, 310 pp.

Ahmad, P., Bhardwaj, R. & Tuteja, N. 2012. Plant signalling under abiotic stress environment. In: *Ahmad P, Prasad MNV (eds) Environmental adaptations and stress tolerance of plants in the era of climate change*. Springer, New York, pp. 297–323. doi: 10.1007/ 978-1-4614-0815-4

Ait Kaci Ahmed, N., Galaup, B., Desplanques, J., Dechamp-Guillaume, G. & Seassau, C. 2022. Ecosystem Services Provided by Cover Crops and Biofumigation in Sunflower Cultivation. *Agronomy* **12**, 120. doi: 10.3390/agronomy12010120

Akbarzadeh, A & Katsikas, S. 2021. Identifying and Analyzing Dependencies in and among Complex Cyber Physical Systems. *Sensors* **21**(5), 1685. doi: 10.3390/s21051685

Al Seadi, T., Rutz, D., Janssen, R. & Drosg, B. 2013. Biomass resources for biogas production. In: *The biogas handbook*: Science, production and applications, pp. 19–51.

Allam, M., Radicetti, E., Ben Hassine, M., Jamal, A., Abideen, Z. & Mancinelli, R. 2023. A Meta-Analysis Approach to Estimate the Effect of Cover Crops on the Grain Yield of Succeeding Cereal Crops within European Cropping Systems. *Agriculture* **13**(9), 1714. doi: 10.3390/agriculture13091714

Alonso-Ayuso, M., Gabriel, J.L. & Quemada, M. 2014. The kill date as a management tool for cover cropping success. *PLoS ONE* **9**, e109587.

Amy, C., Avice, J-C., Laval, K., Trinsoutrot-Gattin, I. & Bressan, M. 2024. The Importance of Considering Levels of P and N Fertilization to Promote Beneficial Interaction between Rapeseed and Phosphate-Solubilizing Bacteria. *Agronomy* **14**(2), 334. doi:10.3390/agronomy14020334

Andini, S. 2020. *Antimicrobial isothiocyanates from Brassicaceae glucosinolates Analysis, reactivity, and quantitative structureactivity relationships*. PhD thesis. Wageningen University, Wageningen, The Netherlands, 208 pp.

Ansari, M.A., Choudhury, B.U., Layek, J., Das, A., Lal, R. & Mishra, V.K. 2022. Green manuring and crop residue management: Effect on soil organic carbon stock, aggregation, and system productivity in the foothills of Eastern Himalaya (India). *Soil Tillage Research* **218**, 105318. doi: 10.1016/j.still.2022.105318

Anzola-Rojas, M.D.P., Gonçalves da Fonseca, S., Canedo da Silva, C., Maia de Oliveira, V. & Zaiat, M. 2014. The use of the carbon/nitrogen ratio and specific organic loading rate as tools for improving biohydrogen production in fixed-bed reactors. *Biotechnology Reports* **4**(5), 46–54. doi: 10.1016/j.btre.2014.10.010

Arguello, L.G., Sensharma, D.K., Qiu, F., Nurtaeva, A. & Rassi, Z.E. 1999. High-Performance Liquid-Phase Separation of Glycosides Analytical and Micropreparative HPLC Combined with Spectroscopic and Enzymatic Methods for Generating a Glucosinolate Library. *Journal of AOAC INTERNATIONAL* **82**(5), 1115–1127. doi:10.1093/jaoac/82.5.1115

Asgari, A., Darzi-Naftchali, A., Nadi, M. & Saberali, S.F. 2021. Improvement in canola yield and growth indices and water-use efciency with subsurface drainage in a humid climate. *Paddy Water Environment* **19**(1), 23–33.

Ayres, L. & Clements, B. 2002. Forage brassicas – quality crops for livestock production. *Agfact P2* **1**, 1–3.

Azam, A., Khan, I., Mahmood, A. & Hameed, A. 2013. Yield, chemical composition and nutritional quality responses of carrot, radish and turnip to elevated atmospheric carbon dioxide. *Journal of the Science of Food and Agriculture* **93**, 3237–3244.

Bacher, H., Sharaby, Y., Walia, H. & Peleg, Z. 2021. Modifying root/shoot ratios improves root water influxes in wheat under drought stress. *bioRxiv*, 455065. doi: 10.1101/2021.08.04.455065

Bajgai, Y., Kristiansen, P., Hulugalle, N. & McHenry, M. 2014. Effect of residue management and conventional and organic soil management systems on crop yields and weed biomass. *Acta Horticulturae* **1018**, 227–234. doi: 10.17660/ActaHortic.2014.1018.23

Bakker, C., Hite, L., Wright, C., Smart, A., Dinh, T., Blair, A., Underwood, K. & Grubbs, J.K. 2021. Impact of feeding cover crop forage containing brassicas to steers during backgrounding on palatability attributes of beef strip steaks. *Foods* **10**, 1250.

Baltas, E. 2007. Spatial Distribution of Climatic Indices in Northern Greece. *Meteorological Applications* **14**, 69–78. doi: 10.1002/met.7

Bangarwa, S.K., Norsworthy, J.K., Mattice, J.D. & Gbur, E.E. 2011. Glucosinolate and Isothiocyanate Production from Brassicaceae Cover Crops in a Plasticulture Production System. *Weed Science* **59**(2), 247–254. doi:10.1614/WS-D-10-00137.1

Bell, L.W., Watt, L.J. & Stutz, R.S. 2020. Forage brassicas have potential for wider use in drier, mixed crop–livestock farming systems across Australia. *Crop Pasture Science* **71**, 924–943.

Bellec, L., Cortesero, A.M., Marnet, N., Faure, S. & Hervé, M.R. 2023. Age-specific allocation of glucosinolates within plant reproductive tissues. *Plant Science* **331**, 111690. doi: 10.1016/j.plantsci.2023.111690.

Bellostas, N., Sørensen, J.C. & Sørensen, H. 2004. Qualitative and quantitative evaluation of glucosinolates in cruciferous plants during their life cycles. *Agroindustria* **3**(3), 5611.

Ben Ammar, H., Arena, D., Treccarichi, S., Di Bella, M.C., Marghali, S., Ficcadenti, N., Lo Scalzo, R. & Branca, F. 2023. The Effect of Water Stress on the Glucosinolate Content and Profile: A Comparative Study on Roots and Leaves of *Brassica oleracea* L. Crops. *Agronomy* **13**, 579. doi: 10.3390/ agronomy13020579

Benjamin, J., Nielsen, D., Vigil, M., Mikha, M. & Calderon, F. 2014. Water Deficit Stress Effects on Corn (*Zea mays* L.) Root:Shoot Ratio. *Open Journal of Soil Science* **4**, 151–160. doi: 10.4236/ojss.2014.44018

Bhandari, S.R., Jo, J.S. & Lee, J.G. 2015. Comparison of Glucosinolate Profiles in Different Tissues of Nine Brassica Crops. *Molecules* **20**(9) 15827–15841. doi: 10.3390/molecules200915827

Bhogal, A., White, C. & Morris, N. 2019. *Project Report №. 620 Maxi Cover Crop: Maximising the benefits from cover crops through species selection and crop management*. AHDB Cereals & Oilseeds is a part of the Agriculture and Horticulture Development Board (AHDB). 111 pp.

Birch, A.N., Wynne Griffiths, D., Hopkins, R., Macfarlane smith, W.H. & McKinlay, R. 1992. Glucosinolate responses of swede, kale, forage and oilseed rape to root damage by turnip root fly (Delia floralis) larvae. *Journal of the Science of Food and Agriculture* **60**, 1–9.

Blažević, I., Montaut, S., Burčul, F., Olsen, C.E., Burow, M., Rollin, P. & Agerbirk, N. 2020. Glucosinolate structural diversity, identification, chemical synthesis and metabolism in plants. *Phytochemistry* **169**, 112100. doi: 10.1016/j.phytochem.2019.112100

Blume, R.Y., Lantukh, G.V., Levchuk, I.V., Lukashevych, K.M., Rakhmetov, D.B. & Blume, Y.B. 2020. Evaluation of potential biodiesel feedstocks: camelina, turnip rape, oilseed radish and Tyfon. *The Open Agriculture Journal* **14**, 299–320. doi: 10.2174/1874331502014010299

Bláha, L. 2021. Importance of Root-Shoot Ratio for Crops Production: A Review. *Current Topics in Agricultural Sciences* **1**, 37–49. doi: 10.9734/bpi/ctas/v1/12112D

Bodner, G., HImmelbauer, M., Loiskandl, W. & Kaul, H.-P. 2010. Improved evaluation of cover crop species by growth and root factors. *Agronomy for Sustainable Development* **30**, 455–464. doi: 10.1051/agro/2009029

Bohinc, T., Košir, I.J. & Trdan, S. 2013. Glucosinolates as arsenal for defending Brassicas against cabbage flea beetle (Phyllotreta spp.) attack. *Zemdirbyste-Agriculture* **100** (2), 199–204. doi: 10.13080/z-a.2013.100.026

Borgogno, F., D'Odorico, P., Laio, F. & Ridolfi, L. 2009. Mathematical models of vegetation pattern formation in ecohydrology. *Reviews of Geophysics* **47**, RG1005. doi: 10.1029/2007RG000256.

Boselli, R., Fiorini, A., Santelli, S., Ardenti, F., Capra, F., Maris, S.C. & Tabaglio, V. 2020. Cover crops during transition to no-till maintain yield and enhance soil fertility in intensive agro-ecosystems. *Field Crops Research* **255**, 107871. doi: 10.1016/j.fcr.2020.107871

Brown, C. 2021. Available Nutrients and Value for Manure from Various Livestock Types. *Factsheet № 21077*. AGDEX 538. Ministry of Agriculture, Food and Rural Affairs. Queen's Printer for Ontario. 10 pp.

Capecka, E. & Libik, A. 1998. Quality differences between radish (*Raphanus sativus* l.) cultivars determine the possibilities of their use. *Acta Horticultural* **459**, 89–96. doi: 10.17660/ActaHortic.1998.459.8

Carr, P.M., Cavigelli, M.A., Darby, H., Delate, K., Eberly, J.O., Fryer, H.K., Gramig, G.G., Heckman, J.R., Mallory, E.B., Reeve, J.R., Silva, E.M., Suchoff, D.H. & Woodley, A.L. 2020. Green and animal manure use in organic field crop systems. *Agronomy Journal* **112**, 648–674. doi: 10.1002/agj2.20082

Carvalho, L., Di Berardino, S. & Duarte, E. 2011. Biogas production from mediterranean crop silages. *Proceedings Sardinia 2011*. Thirteenth International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy; 3–7 October 2011. URL: https://repositorio.lneg.pt/bitstream/10400.9/1452/1/Artigo%20Sardenha%202011-crop-digestion.pdf (accessed on 06 February 2024)

Castillo-Umaña, M., Balocchi, O., Pulido, R., Sepúlveda-Varas, P., Pacheco, D., Muetzel, S., Berthiaume, R. & Keim, J.-P. 2020. Milk production responses and rumen fermentation of dairy cows supplemented with summer brassicas. *Animal* **14**, 1684–1692.

Cerón-Vivas, A., Cáceres, K.T., Rincón, A. & Cajigas, A.A. 2019. Influence of pH and the C/N ratio on the biogas production of wastewater. *Revista Facultad de Ingeniería Universidad de Antioquia* **92**, 88–95. doi: 10.17533/udea.redin.20190627

Chaddock, R.E. 1925. *Principles and Methods of Statistics* (1st Edition), Houghton Miffin Company. The Riverside Press, Cambridge, 471 pp.

Chapagain, T., Lee, E.A. & Raizada, M.N. 2020. The Potential of Multi-Species Mixtures to Diversify Cover Crop Benefits. *Sustainability* **12**(5), 2058. doi: 10.3390/su12052058

Chen, S., Zhang, X., Shao, L., Sun, H., Niu, J. & Liu, X. 2020. Effects of straw and manure management on soil and crop performance in North China plain. *Catena* **187**, 104359. doi: 10.1016/j.catena.2019.104359

Chen, Y., Cheng, J. J. & Creamer, K. 2008. Inhibition of anaerobic digestion process: A review. *Bioresource Technology* **99**, 4044–4064. doi: 10.1016/j.biortech.2007.01.057

Choi, Y., Ryu, J. & Lee, S.R. 2020. Influence of carbon type and carbon to nitrogen ratio on the biochemical methane potential, pH, and ammonia nitrogen in anaerobic digestion. *Journal of Animal Science and Technology* **62**(1), 74–83. doi: 10.5187/jast.2020.62.1.74

Chowdhury, P. 2022. Glucosinolates and Its Role in Mitigating Abiotic and Biotic Stress in Brassicaceae. In: Plant Stress Physiology - Perspectives in Agriculture. *IntechOpen*, 14 pp. doi: 10.5772/intechopen.102367

Ciska, E., Honke, J. & Kozłowska, H. 2008. Effect of light conditions on the contents of glucosinolates in germinating seeds of white mustard, red radish, white radish, and rapeseed. *Journal of Agricultural and Food Chemistry* **56**(19), 9087–9093. doi: 10.1021/jf801206g.

Clark, A. 2008. *Managing cover crops profitably*. DIANE Publishing (3rd ed.), 248 pp.

Cleemput, S. 2011. *Breeding for a reduced glucosinolate content in the green mass of rapeseed to improve its suitability for biogas production*. PhD Thesis. Georg-August-Universität Göttingen, 104 pp. doi: 10.53846/goediss-1837

Composts & Fertilisers. 2023. NPK Nutritional Values of Animal Manures & Compost Etc. Available online: https://www.allotment-garden.org/composts-fertilisers/npk-nutritional-values-animal-manures-compost/#google_vignette (accessed on 06 February 2024).

Couedel, A. 2018. Analysis of performances of crucifers-legumes cover crop mixtures to provide multiple-ecosystem services. *Agricultural sciences*. Institut National Polytechnique de Toulouse -INPT, 197 pp.

Couëdel, A., Kirkegaard, J., Alletto, L. & Justes, É. 2019. Cruciferlegume cover crop mixtures for biocontrol: Toward a new multiservice paradigm. *Advances in Agronomy* **157**, 55–139. doi: 10.1016/bs.agron.2019.05.003

Dandikas, V., Heuwinkel, H., Lichti, F., Drewes, J.E. & Koch, K. 2014. Correlation between biogas yield and chemical composition of energy crops. *Bioresource Technology* **174**, 316–320. doi: 10.1016/j.biortech.2014.10.019

De Kok, L.J., Tausz, M., Hawkesford, M.J., Hoefgen, R., McManus, M.T., Norton, R.M., Rennenberg, H., Saito, K., Schnug, E. & Tabe, L. 2012. *Sulfur Metabolism in Plants: Mechanisms and Applications to Food Security and Responses to Climate Change*; Springer: Dordrecht, The Netherlands, 284 pp.

de Ruiter, J., Wilson, D., Maley, S., Fletcher, A., Fraser, T., Scott, W., Berryman, S., Dumbleton, A. & Nichol, W. 2009. *Management practices for forage brassicas*. Forage rassica development group, 7 pp.

del Carmen Martínez-Ballesta, M., Moreno, D.A. & Carvajal, M. 2013. The Physiological Importance of Glucosinolates on Plant Response to Abiotic Stress in Brassica. *International Journal of Molecular Sciences* **14**, 11607–11625 doi:10.3390/ijms140611607

Dorissant, L., Brym, Z.T. & Swartz, S. 2022. Residue decomposition dynamics in mixed ratios of two warm-season cover crops. *Agrosystems, Geosciences & Environment* **5**, e20311. https://doi.org/10.1002/agg2.20311

Dorsainvil, F., Durr, C.C., Justes, E.E. & Carrera, A. 2005. Characterisation and modelling of white mustard (Sinapis alba L.) emergence under several sowing conditions. *European Journal of Agronomy* **23** (2) 146–158. doi: 10.1016/j.eja.2004.11.002⟩

Drost, S.M., Rutgers, M., Wouterse, M., de Boer, W. & Bodelier, P.L.E. 2019. Decomposition of mixtures of cover crop residues increases microbial functional diversity. *Geoderma* **114060**. doi: 10.1016/j.geoderma.2019.114060

Duff, J., van Sprang, C., O'Halloran, J. & Hall, Z. 2020. *Guide to Brassica Biofumigant Cover Crops Managing soilborne diseases in vegetable production systems*. Horticulture Innovation through VG16068 Optimising cover cropping for the Australian vegetable industry. State of Queensland. Department of Agriculture and Fisheries 40 pp.

Dzvene, A.R., Tesfuhuney, W.A., Walker, S. & Ceronio, G. 2023. Management of Cover Crop Intercropping for Live Mulch on Plant Productivity and Growth Resources: A Review. *Air, Soil and Water Research* **16**. doi:10.1177/11786221231180079

Dębowski, M., Kazimierowicz, J., Zieliński, M. & Bartkowska, I. 2022. Co-Fermentation of Microalgae Biomass and Miscanthus × giganteus Silage-Assessment of the Substrate, Biogas Production and Digestate Characteristics. *Applied Sciences* **12**(14), 7291. doi: 10.3390/app12147291

Eberlein, C.V., Morra, M.J., Guttieri, M.J., Brown, P.D. & Brown, J. 1998. Glucosinolate Production by Five Field-Grown Brassica napus Cultivars Used as Green Manures. *Weed Technology* **12**(4), 712–718. doi:10.1017/S0890037X00044596

Edwards, S. & Ploeg, A. 2014. Evaluation of 31 potential biofumigant brassicaceous plants as hosts for three meloiodogyne species. *Journal of Nematology* **46**(3), 287–295.

Einarsson, R & Persson, U.M. 2017. Analyzing key constraints to biogas production from crop residues and manure in the EU–A spatially explicit model. *PLoS ONE* **12**(1), e0171001. doi: 10.1371/journal.pone.0171001

El Amine, M., Pailhès, J. & Perry, N. 2016. Selection and use of a multi-criteria decision aiding method in the context of conceptual design with imprecise information: Application to a solar collector development. Concurrent Engineering: *Research and Applications* **24**(1), 35–47. doi: 10.1177/1063293X15613838

Fajobi, M.O., Lasode, O.A., Adeleke, A.A., Ikubanni, P.P. & Balogun, A.O. 2023. Prediction of Biogas Yield from Codigestion of Lignocellulosic Biomass Using Adaptive Neuro-Fuzzy Inference System (ANFIS) Model. *Journal of Engineering* **Article ID 9335814**. doi: 10.1155/2023/9335814

Florentín, M.A., Peñalva, M., Calegari, A., Translated, R.D. & Mcdonald, M.J. 2010. *Green Manure/Cover Crops and Crop Rotation in Conservation Agriculture on Small Farms*. Integrated Crop Management: Rome, Italy, **12**, 97 pp.

Flores-Sánchez, D., Pastor, A., Rossing, W.A.H., Kropff, M.J. & Lantinga, E.A. 2016. Decomposition, N contribution and soil organic matter balances of crop residues and vermicompost in maize-based cropping systems in southwest Mexico. *Journal of Soil Science and Plant Nutrition* **16**(3), 801–817.

FOSS. 2018. Fibre analysis of animal feed Crude fibre, neutral detergent fibre and acid detergent fibre – the standards and the automation options. eBook. Available online: https://www.fossanalytics.com/-/media/files/documents/papers/laboratories-segment/ebook-fibre-analysis-of-animal-feed-gb.ashx (accessed on 06 February 2024).

Franzen, D.W. 2023. Fertilizing Canola and Mustard. SF1122. URL: https://www.ndsu.edu/agriculture/extension/publications/fertilizing-canola-and-mustard (date of access April 25, 2024).

Galaup, B. 2018. Assessment of the potential of biotic regulation by Brassica cover-crops used as biofumigants. Case of Verticillium dahliae affecting Sunflower crop in southwestern France. Mster Thesis. Norwegian University of Life Science. 42 pp.

Gamba, M., Asllanaj, E., Raguindin, P.F., Glisic, M., Franco, O.H., Minder, B., Bussler, W.W., Metzger, B., Kern, H.J. & Muka, T. 2021. Nutritional and phytochemical characterization of radish (*Raphanus sativus*): A systematic review. *Trends in Food Science & Technology* **113**, 205–218.

Gan, Y.T., Campbell, C.A., Janzen, H.H., Lemke, R., Liu, L.P., Basnyat, P. & McDonald, C.L. 2009. Root mass for oilseed and pulse crops: Growth and distribution in the soil profile. *Canadian Journal of Plant Science* **89**, 883–893.

Gastal, F. & Lemaire, G. 2002. N uptake and distribution in crops: an agronomical and ecophysiological perspective. *Journal of Experimental Botany* **53** (370), 789–799. doi: 10.1093/jexbot/53.370.789

Gieske, M.F. 2013. *Radish and other brassica cover crop effects on nitrogen availability and weed management*. PhD Thesis. University of Minnesota Digital Conservancy, 122 pp.

Gimsing, A.L. & Kirkegaard, J.A. 2006. Glucosinolate and isothiocyanate concentration in soil following incorporation of Brassica biofumigants. *Soil Biology and Biochemistry* **38**, 2255–2264.

Green Manure Global Market Report 2024. By Type (Leguminous, Non Leguminous), By Source (Dhaincha, Sesbania, Sunhemp, Other Sources), By Application (Grains And Cereals, Pulses And Oilseeds, Fruits And Vegetables, Other Applications) - Market Size, Trends, And Global Forecast 2024–2033. URL: https://www.thebusinessresearchcompany.com/report/green-manure-global-market-report (date of access April 25, 2024).

Grzebisz, W., Diatta, J., Barłóg, P., Biber, M., Potarzycki, J., Łukowiak, R., Przygocka-Cyna, K. & Szczepaniak, W. 2022. Soil Fertility Clock – Crop rotation as a paradigm in nitrogen fertilizer productivity control. *Plants* **11**, 2841.

Grzebisz, W., Zielewicz, W. & Przygocka-Cyna, K. 2023. Deficiencies of Secondary Nutrients in Crop Plants – A Real Challenge to Improve Nitrogen Management. *Agronomy* **13**(1), 66. doi:10.3390/agronomy13010066

Guarino, G., Carotenuto, C., Di Cristofaro, F., Papa, S., Morrone, B. & Minale, M. 2016. Does the C/N ration really affect the biomethane yield? a three years investigation of buffalo manure digestion. *Chemical Engineering Transactions* **49**, 463–468. doi: 10.3303/CET1649078

Guinet, M., Voisin, A-S. & Nicolardot, B. 2023. Potential C and N Mineralisation of Shoot and Root Residues from Ten Grain Legume Species As Related to their Biochemical Characteristics. *World Journal of Agriculture and Soil Science* **8**(4), WJASS.MS.ID.000691.

Gustine, D.L. & Jung, G.A. 1985. Influence of some management paramters on glucosinolate levels in Brassica forage. *Agronomy Journal* **77**, 593–597. doi: 10.2134/agronj1985.00021962007700040020x

Hadas, A., Kautsky, L., Goek, M. & Kara, E.E. 2004. Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. *Soil Biology and Biochemistry* **36**(2), 255–266. doi: 10.1016/j.soilbio.2003.09.012

Hansen, V., Eriksen, J. & Jensen, L.S. 2021. Towards integrated cover crop management: N, P and S release from aboveground and belowground residues. *Agriculture, Ecosystems & Environment* **313**. doi: 10.1016/j.agee.2021.107392

Hansen, V., Müller-Stöver, D. & Magid, J. 2022. Green manure crops for low fertility soils URL: https://orgprints.org/id/eprint/37832/1/poster_Veronika%20Hansen.pdf (date of access April 25, 2024).

Herout, M., Malaťák, J., Kučera, L. & Dlabaja, T. 2011. Biogas composition depending on the type of plant biomass used. *Research in Agricultural Engineering* **57**, 137–143.

Herrmann, C., Idler, C. & Heiermann, M. 2016. Biogas crops grown in energy crop rotations: Linking chemical composition and methane production characteristics. *Bioresource Technology* **206**, 23–35. doi: 10.1016/j.biortech.2016.01.058

Herrmann, C., Prochnow, A., Heiermann, M. & Idler, C. 2014. Biomass from landscape management of grassland used for biogas production: effects of harvest date and silage additives on feedstock quality and methane yield. *Grass Forage Science* **69**, 549–566. doi: 10.1111/gfs.12086

Heuermann, D., Gentsch, N., Boy, J., Schweneker, D., Feuerstein, U., Groß, J., Bauer, B., Guggenberger, G. & von Wirén, N. 2019. Interspecific competition among catch crops modifies vertical root biomass distribution and nitrate scavenging in soils. *Scientific Reports* **9**(1), 11531. doi: 10.1038/s41598-019-48060-0

Honcharuk, I., Tokarchuk, D., Gontaruk, Y. & Hreshchuk, H. 2023. Bioenergy recycling of household solid waste as a direction for ensuring sustainable development of rural areas. *Polityka Energetyczna – Energy Policy Journal* **26**(1), 23–42. doi: 10.33223/epj/161467

Honcharuk, I.V. & Yemchyk, T.V. 2024. Waste-free biofuel production technologies as a way to the European Green Deal. *Polityka Energetyczna – Energy Policy Journal* **27**(1), 81–94. doi: 10.33223/epj/175284

Hu, T., Olesen, J.E., Christensen, B.T. & Sørensen, P. 2018. Release of carbon and nitrogen from fodder radish (Raphanus sativus) shoots and roots incubated in soils with different management history. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science* **68**(8), 749–756. doi: 10.1080/09064710.2018.1480730

Israt, I.J. & Parimal, B.K. 2023. Residual Effect of Green Manure on Soil Properties in Green Manure-Transplant Aman-Mustard Cropping Pattern. *Indian Journal of Agricultural Research* **57**(1), 67–72. doi: 10.18805/IJARe.AF-696

IUSS Working Group WRB. 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. *World Reference Base for Soil Resources* 2014, Update 2015, 106 pp.

Iwar, K., Desta, K.T., Ochar, K. & Kim, S-H. 2024. Unveiling Glucosinolate Diversity in Brassica Germplasm and In Silico Analysis for Determining Optimal Antioxidant Potential. *Antioxidants* **13**(3), 376. doi: 10.3390/antiox13030376

Jacob, G.A., Prabhakaran, S.P.S., Swaminathan, G. & Joseyphus, R.J. 2022. Thermal kinetic analysis of mustard biomass with equiatomic iron-nickel catalyst and its predictive modeling. *Chemosphere* **286**(Pt 3), 131901. doi: 10.1016/j.chemosphere.2021.131901

Jahanzad, E., Barker, A.V., Hashemi, M., Eaton, T. & Sadeghpour, A. 2016. Nitrogen release dynamics and decomposition of buried and surface cover crop residues. *Agronomy Journal* **108**, 1735–1741. doi: 10.2134/agronj2016.01.0001

Jauhiainen, M. 2022. *Grass Silage as a Feedstock for a Biogas Plant – A feasibility study and development of a cost calculation tool*. PhD Thesis. Savonia University of Applied Sciences, 69 pp.

Jie, O.Y. 2022. *Comparison of nutritional composition, antiinflammatory and antioxidative activities between the raw and boiled Raphanus sativus subsp. longipinnatus roots. PhD thesis*. Universiti Tunku Abdul Rahman. 74 pp.

Jing, Q., Shang, J., Qian, B., Hoogenboom, G., Hufman, T., Liu, J., Ma, B.L., Geng, X., Jiao, X., Kovacs, J. & Walters, D. 2016. Evaluation of the CSM-CROPGRO-Canola Model for Simulating Canola Growth and Yield at West Nipissing in Eastern Canada. *Agronomy Journal* **108**(2), 1–10.

Justes, E. & Richard, G. 2017. Contexte, Concepts et Definition des cultures intermediaires multiservices. *Innovations Agronomiques* **62**, 17–32.

Justes, E.E., Rechauchère, O. & Chemineau, P. 2012. The use of cover crops to reduce nitrate leaching: Effect on the water and nitrogen balance and other ecosystem services. *INRA*. 8 pp.

Kaletnik, G., Honcharuk, I. & Okhota, Yu. 2020 The Waste Free Production Development for the Energy Autonomy Formation of Ukrainian Agricultural Enterprises. *Journal of Environmental Management and Tourism* **3**(43), 513–522. doi:10.14505/jemt.v11.3(43).02

Kaletnik, H., Pryshliak, V. & Pryshliak, N. 2019. Public Policy and Biofuels: Energy, Environment and Food Trilemma. *Journal of Environmental Management and Tourism* (Volume **X**, Summer), **3**(35), 479–487. doi: 10.14505/jemt.v10.3(35).01

Kashyap, A., Kumari, S., Garg, P., Kushwaha, R., Tripathi, S., Sharma, J., Gupta, N.C., Kumar, R.R., Yadav, R. & Vishwakarma, H. 2023. Indexing Resilience to Heat and Drought Stress in the Wild Relatives of Rapeseed-Mustard. *Life* **13**(3), 738. doi: 10.3390/life13030738

Keim, J., Daza, J., Beltrán, I., Balocchi, O., Pulido, R., Sepúlveda-Varas, P., Pacheco, D. & Berthiaume, R. 2020. Milk production responses, rumen fermentation, and blood metabolites of dairy cows fed increasing concentrations of forage rape (Brassica napus ssp. Biennis). *Journal of Dairy Science* **103**, 9054–9066.

Kemper, R., Bublitz, T.A., Müller, P., Kautz, T., Döring, T.F. & Athmann, M. 2020. Vertical root distribution of different cover crops determined with the profile wall method. *Agriculture* **10**, 503. doi: 10.3390/agriculture10110503

Kemper, R., Döring, T.F., Legner, N., Meinen C. & Athmann, M. 2023. Oilseed radish, winter rye and crimson clover: root and shoot performance in cover crop mixtures. *Plant Soil*. URL: https://link.springer.com/article/10.1007/s11104-023-06240-y#citeas (Access April 25, 2024) doi: 10.1007/s11104-023-06240-y

Kirkegaard, J.A. & Sarwar, M. 1998. Biofumigation potential of brassicas: I. Variation in glucosinolate profiles of diverse field-grown brassicas. *Plant and Soil* **201**(1), 71–89.

Kou, X, Han, W. & Kang, J. 2022. Responses of root system architecture to water stress at multiple levels: A meta-analysis of trials under controlled conditions. *Frontiers Plant Science* **13**, 1085409. doi: 10.3389/fpls.2022.1085409

Kriaučiūnienė, Z., Velička, R. & Raudonius, S. 2012. The infuence of crop residues type on their decomposition rate in the soil: a litterbag study. *Zemdirbyste* **99**, 227–236.

Kul, R., Ekinci, M., Turan, M., Ors, S. & Yildirim, E. 2021. How Abiotic Stress Conditions Affects Plant Roots. *IntechOpen*. URL: https://www.researchgate.net/publication/348208107_How_Abiotic_Stress_Conditions_Affects_Plant_Roots (Access April 20, 2024) doi: 10.5772/intechopen.95286

Källén, A.S. 2023. *Underlying mechanisms behind nitrous oxide emissions in oilseed radish, Raphanus sativus var. oleiformis, and Phacelia tanacetifolia*. Independent Project in Biology, A2E. Swedish University of Agricultural Sciences, SLU, 49 pp.

Kılıç, Ü., Erişek, A., Garipoğlu, A., Ayan, İ. & Önder, H. 2021. The effects of different forage types on feed values and digestibilities in some brassica fodder crops. *Turkish Journal of Agricultural and Natural Sciences* **8**(1), 94–102. doi: 10.30910/turkjans.747031

Lallement, A., Peyrelasse, C., Lagnet, C., Barakat, A., Schraauwers, B., Maunas, S. & Monlau, F. 2023. A Detailed Database of the Chemical Properties and Methane Potential of Biomasses Covering a Large Range of Common Agricultural Biogas Plant Feedstocks. *Waste* **1**(1), 195–227. doi: 10.3390/waste1010014

Latief, A., Raihana, K.H., Sabah, P. & Syed, S.M. 2017. *Experimental Agrometeorology: A Practical Manual*. Cham: Springer International Publishing, 159 pp.

Launay, C., Houot, S., Frédéric, S., Girault, R., Levavasseur, F., Marsac, S. & Constantin, J. 2022. Incorporating energy cover crops for biogas production into agricultural systems: benefits and environmental impacts. A review. *Agronomy for Sustainable Development* **42**, 57. doi: 10.1007/s13593-022-00790-8

Lee, C.-R., Kim, S.H., Oh, Y., Kim, Y.J. & Lee, S.-M. 2023. Effect of Green Manure on Water-Stable Soil Aggregates and Carbon Storage in Paddy Soil. *Korean Journal of Soil Science and Fertilizer* **56**(2), 191–198. doi:10.7745/KJSSF.2023.56.2.191

Lei, B., Wang, J. & Yao, H. 2022. Ecological and environmental benefits of planting green manure in paddy fields. *Agriculture* **12**(2), 223. doi: 10.3390/agriculture12020223

Letey, J., Jarrell, W.M. & Valoras, N. 1982. Nitrogen and water uptake patterns and growth of plants at various minimum solution nitrate concentrations. *Journal of Plant Nutrition* **5**(2), 73–89. doi: 10.1080/01904168209362939

Li, S., Yu, W., Liu, X. & Wang, M. 2020. Analysis of root system architecture affected by swarming behavior. *Journal of Horticultural Research* **28**(1), 1–12. doi: 10.2478/johr-2020-0006

Li, W.G.M., Yang, X.X., Huang, C.G., Xue, N.W., Xia, Q., Liu, X.L., Zhang, X.Q., Yang, S., Yang, Z.P. & Gao, Z.Q. 2019. Effects of rapeseed green manure on soil fertility and bacterial community in dryland wheat field. *Agricultural Sciences in China* **52**, 2664–2677.

Li, Z.Y. & Zhou, D. 2002. Optimization of C/N ratio preparation of protein-rich and multi-enzymes feed thallus through synergic fermentation of mixed distillers' grains. *Journal of Environmental Sciences (China)* **14**(1), 141–144.

Liu, X.H., Zhou, X., Deng, L.C., Fan, L.Y., Qu, L. & Li, M. 2020. Decomposition characteristics of rapeseed green manure and effect of nutrient release on soil fertility. *Hunan Agricultural Science* **416**, 39–44.

Lopez, G., Ahmadi, S.H., Amelung, W., Athmann, M., Ewert, F., Gaiser, T, Gocke, M.I., Kautz, T., Postma, J., Rachmilevitch, S., Schaaf, G., Schnepf, A., Stoschus, A., Watt, M., Yu, P. & Seidel, S.J. 2023. Nutrient deficiency effects on root architecture and root-to-shoot ratio in arable crops. *Frontiers Plant Science* **13**, 1067498. doi: 10.3389/fpls.2022.1067498

Lucadamo, E.E., Holmes, A.A., Wortman, S.E. & Yannarell, A.C. 2022. Post-termination Effects of Cover Crop Monocultures and Mixtures on Soil Inorganic Nitrogen and Microbial Communities on Two Organic Farms in Illinois. *Frontiers Soil Science* **2**, 824087. doi: 10.3389/fsoil.2022.824087

Lymperatou, A., Engelsen, T.K., Skiadas, I.V. & Gavala, H.N. 2023. Prediction of methane yield and pretreatment efficiency of lignocellulosic biomass based on composition. *Waste Management* **155**, 302–310. doi: 10.1016/j.wasman.2022.10.040

Lövgren, E. 2022. *Complete removal of biomass from oilseed radish as a cover crop decreased nitrous oxide emissions*. Master's degree project. Swedish University of Agricultural Sciences, 46 pp.

Maier, S., Szerencsits, M. & Shahzad, K. 2017. Ecological evaluation of biogas from catch crops with Sustainable Process Index (SPI). *Energy, Sustainability and Society* **7**, 4. doi: 10.1186/s13705-017-0106-3

Manyi-Loh, C.E. & Lues, R. 2023. Anaerobic Digestion of Lignocellulosic Biomass: Substrate Characteristics (Challenge) and Innovation. *Fermentation* **9**(8), 755. doi: 10.3390/fermentation9080755

Martínez-Gutiérrez, E. 2018. Biogas production from different lignocellulosic biomass sources: advances and perspectives. *Biotechnology* **8**(5), 233. doi: 10.1007/s13205-018-1257-4

Mbambalala, L., Rani, Z.T., Mpanza, T.D.E., Mthana, M.S., Ncisana, L. & Mkhize, N.R. 2023. Fodder Radish as a Potential Alternative Feed Source for Livestock in South Africa. *Agriculture* **13**(8), 1625. doi: 10.3390/agriculture13081625

McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G. & Yepez, E.A. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist* **178**, 719–739. doi: 10.1111/j.1469-8137.2008.02436.x

Milford, G.F.J. & Evans, E.J. 1991. Factors Causing Variation in Glucosinolates in Oilseed Rape. *Outlook on Agriculture* **20**(1), 31–37. doi: 10.1177/003072709102000107

Mocniak, L.E., Elkin, K.R., Dillard, S.L., Bryant, R.B. & Soder, K.J. 2023. Building comprehensive glucosinolate profiles for brassica varieties. *Talanta* **251**, 123814. doi: 10.1016/j.talanta.2022.123814

Molinuevo-Salces, B., Larsen, S. U., Ahring, B. K. & Uellendahl, H. 2013. Biogas from Italian ryegrass and oil seed radish: Effect of nitrogen application on biomass yield and methane production. Poster presented at 21st European Biomass Conference and Exhibition, Copenhagen, Denmark. URL: https://core.ac.uk/download/pdf/60543231.pdf (date of application 22.08.2023).

Molinuevo-Salces, B., Larsen, S.U., Ahring, B.K. & Uellendahl, H. 2014. Biogas production from catch crops: a sustainable agricultural strategy to increase biomass yield by coharvest of catch crops and straw. In *22nd European Biomass Conference and Exhibition* (EU BC&E 2014 - Hamburg, Germany. 5 pp.

Moral, F.J., Rebollo, F.J., Paniagua, L.L., García-Martín, A. & Honorio, F. 2016. Spatial Distribution and Comparison of Aridity Indices in Extremadura, Southwestern Spain. *Theoretical and Applied Climatology* **126**, 801–814. doi: 10.1007/s00704-015-1615-7

Murphy, J., Braun, R., Weiland, P. & Wellinger, A. 2011. Biogas from Crop Digestion. Task 37 - Energy from Biogas. *IEA Bioenergy*, 24 pp.

Navarro, D.M.D.L., Abelilla, J.J. & Stein, H.H. 2019. Structures and characteristics of carbohydrates in diets fed to pigs: a review. *Journal of Animal Science and Biotechnology* **10**, 39. doi: 10.1186/s40104-019-0345-6

Ngatia, L.W., Reddy, K.R., Nair, P.R., Pringle, R.M., Palmer, T.M. & Turner, B.L. 2014. Seasonal patterns in decomposition and nutrient release from East African savanna grasses grown under contrasting nutrient conditions. *Agriculture, Ecosystems & Environment* **188**, 12–19.

Nielsen, S.S. 2010. *Complexometric Determination of Calcium*. In: Nielsen, S.S. (eds) Food Analysis Laboratory Manual. Food Science Texts Series. Springer, Boston, MA., 61–67. doi: 10.1007/978-1-4419-1463-7_8

Nithisha, A., Bokado, K. & Charitha, K.S. 2022. Mulches: Their impact on the crop production. *The Pharma Innovation Journal* **11**(7), 3597–3603.

Nobile, C., Houben, D., Michel, E., Firmin, S., Lambers, H., Kandeler, E. & Faucon, M.-P. 2019. Phosphorus-acquisition strategies of canola, wheat and barley in soil amended with sewage sludges. *Science Reports* **9**, 14878. doi: 10.1038/s41598-019-51204-x

Norberg, L. & Aronsson, H. 2020. Effects of cover crops sown in autumn on N and P leaching. *Soil Use and Management* **36**(2), 200–211. doi: https://doi.org/10.1111/sum.12565

Oliveira, W.K. & Słomka, A. 2021. Assessment of the Biogas Yield of White Mustard (Sinapis alba) Cultivated as Intercrops. *Journal of Ecological Engineering* **22**(7), 67–72. doi: 10.12911/22998993/138815

Olofsson, F. & Ernfors, M., 2022. Frost killed cover crops induced high emissions of nitrous oxide. *Science Total Environment* **837**, 155634. doi: 10.1016/j. scitotenv.2022.155634.

Omokanye, A., Hernandez, G., Lardner, H.A., Al-Maqtari, B., Gill, K.S. & Lee, A. 2021. Alternative forage feeds for beef cattle in Northwestern Alberta, Canada: Forage yield and nutritive value of forage brassicas and forbs. *Journal of Applied Animal Research* **49**, 203–210.

Pan, D., Tang, J., Zhang, L., He, M. & Kung, C. 2021. The impact of farm scale and technology characteristics on the adoption of sustainable manure management technologies: Evidence from hog production in China. *Journal of Cleaner Production* **280**, 1243–1250. doi: 10.1016/j.jclepro.2020.124340

Pekarek, R.A., Hoyt, G., Monks, D. & Jennings, K. 2013. Biomass Production of Biofumigant Cover Crops – 'Caliente' Mustard and Oilseed Radish. *NC State Extension Publications*. AG-782. URL: https://content.ces.ncsu.edu/biomass-production-of-biofumigant-cover-crops-caliente-mustard-and-oilseed-radish (date of access April 21, 2024).

Perniola, O.S., Chorzempa, S.E., Staltari, S. & Molina, M. del C. 2019. Biofumigación con Brassica juncea: efecto sobre la flora arvense. *Revista De La Facultad De Agronomía* **118**(1), 25–35. doi: 10.24215/16699513e003

Poorter, H., Niklas, K.J., Reich, P.B., Oleksyn, J., Poot, P. & Mommer, L. 2012. Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. *New Phytologist* **193**, 30–50. doi: 10.1111/j.1469-8137.2011.03952.x

Prieto, M., López, C.J. & Simal-Gandara, J. 2019. Glucosinolates: Molecular structure, breakdown, genetic, bioavailability, properties and healthy and adverse effects. *Advances in Food and Nutrition Research* **90**, 305–350.

Quemada, M. & Cabrera, M.L. 1995. Carbon and nitrogen m ineralized from leaves and stem s of 4 cover crops. *Soil Science Society of America Journal* **59**, 471–477.

Quintarelli, V., Radicetti, E., Allevato, E., Stazi, S.R., Haider, G., Abideen, Z., Bibi, S., Jamal, A. & Mancinelli, R. 2022. Cover Crops for Sustainable Cropping Systems: A Review. *Agriculture* **12**, 2076. doi: 10.3390/agriculture12122076

Rajković, D., Marjanović Jeromela, A., Pezo, L., Lončar, B., Zanetti, F., Monti, A. & Kondić Špika, A. 2022. Yield and Quality Prediction of Winter Rapeseed–Artificial Neural Network and Random Forest Models. *Agronomy* **12**(1), 58. doi: 10.3390/agronomy12010058

Ramirez-Garcia, J., Almendros, P. & Quemada, M. 2012. Ground cover and leaf area index relationship in a grass, legume and crucifer crop. *Plant, Soil and Environment* **58**, 385–390.

Ramírez-García, J., Carrillo, J.M., Ruiz, M., Alonso-Ayuso, M. & Quemada, M. 2015. Multicriteria Decision Analysis Applied to Cover Crop Species and Cultivars Selection. *Field Crops Research* **175**, 106–115.

Ramírez-García, J., Gabriel, J.L., Alonso-Ayuso, M. & Quemada, M. 2015a. Quantitative characterization of five cover crop species. *The Journal of Agricultural Science* **153**, 1174–1185. doi:10.1017/S0021859614000811

Rao, R.V. 2007. *Decision Making in the Manufacturing Environment, Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods*. Springer: Berlin/Heidelberg, Germany, 294 pp.

Redha, A.A., Torquati, L., Langston, F., Nash, G.R., Gidley, M.J. & Cozzolino, D. 2023. Determination of glucosinolates and isothiocyanates in glucosinolate-rich vegetables and oilseeds using infrared spectroscopy: A systematic review. *Critical Reviews in Food Science and Nutrition* **10**, 1–17. doi: 10.1080/10408398.2023.2198015

Restovich, S.B., Andriulo, A.E. & Portela, S.I. 2022. Cover crop mixtures increase ecosystem multifunctionality in summer crop rotations with low N fertilization. *Agronomy for Sustainable Development* **42**, 19. doi: 10.1007/s13593-021-00750-8

Ricardo, L.L., Bernardi, D.I., Mantovanelli, G.C., Moreno, B.P., Mito, M.S., Silva, A.A., Oliveira, R.S., Iwamoto, E.L., Sarragiotto, M.H. & Baldoqui, D.C. 2018. Phytochemical investigation and phytotoxic activity of aerial parts of oilseed radish (*Raphanus sativus* var. *oleifer* Stokes). *Biochemical Systematics and Ecology* **78**, 52–58. doi: 10.1016/j.bse.2018.03.009

Rinasoa, S., Nishigaki, T., Rabeharisoa, L., Tsujimoto, Y. & Rakotoson, T. 2022. Organic materials with high P and low C:P ratio improve P availability for lowland rice in highly weathered soils: Pot and incubation experiments. *Journal of Plant Nutrition and Soil Science* **185**, 475–485. doi: 10.1002/jpln.202100266

Rowland, A.P. & Roberts, J.D. 1994. Lignin and cellulose fractionation in decomposition studies using acid-detergent fibre methods. *Communications in Soil Science and Plant Analysis* **25**(3–4), 269–277. doi: 10.1080/00103629409369035

Saaty, T.L. & Vargas, L.G. 2012. *Models, Methods, Concepts & Applications of the Analytic Hierarchy Process*. Second Edition. Springer New York Heidelberg Dordrecht London, 345 pp.

Safaei, A.R., Rouzbehan, Y. & Aghaalikhani, M. 2022. Canola as a potential forage. *Translational Animal Science* **6**(3), txac100. doi: 10.1093/tas/txac100.

Salisbury, P.A., Potter, T.D., Gurung, A.M., Mailer, R.J. & Williams, W.M. 2018. Potential impact of weedy Brassicaceae species on oil and meal quality of oilseed rape (canola) in Australia. *Weed Research* **58**(3), 200–209. doi: 10.1111/wre.12296.

Salume, J.A., Oliveira, R.A., Sete, P.B., Comin, J.J., Ciotta, M.N., Lourenzi, C.R., Soares, C.R.F.S., Loss, A., Carranca, C., Giacomini, S.J., Boitt, G. & Brunetto, G. 2020. Decomposition and nutrient release from cover crop residues under a pear orchard. *Revista Brasileira de Ciências Agrárias* **43**, 72–81.

Sanchez, P.A., Cuoto, W. & Boul, S.W. 1982. The fertility capability soil classification system; interpretation application and modification. *Geoderma* **27**, 238–309.

Sang, J.P., Minchinton, I.R., Johnstone, P.K. & Truscott, R.J.W. 1984. Glucosinolate profiles in the seed, root and leaf tissue of cabbage, mustard, rapeseed, radish and swede. *Canadian Journal of Plant Science* **64**(1), 77–93. doi: 10.4141/cjps84-011

Sarıkamıs, G., Aydınlı, G. & Mennan, S. 2017. Glucosinolates in some brassica species as sources of bioactive compounds against root knot nematodes. *International Journal of Advanced Research* **5**, 271–278. doi: 10.21474/IJAR01/5530

Scavo, A., Fontanazza, S., Restuccia, A., Pesce, G.R., Abbate, C. & Mauromicaleet, G. 2022. The role of cover crops in improving soil fertility and plant nutritional status in temperate climates. A review. *Agronomy for Sustainable Development* **42**(5), 93. doi: 10.1007/s13593-022-00825-0ff.ffhal-04201630

Sharma, P. & Dubey, R.S. 2019. Protein Synthesis by Plants Under Stressful Conditions. In: *Handbook of Plant and Crop Stress, Fourth Edition*. CRC Press, 45 pp.

Sharma, S., Kaur, S., Parkash Choudhary, O., Singh, M., Al-Huqail, A.A., Ali, H.M., Kumar, R. & Siddiqui, M.H. 2022. Tillage, green manure and residue retention improves aggregate-associated phosphorus fractions under rice–wheat cropping. *Scientific Reports* **12**, 7167. doi: 10.1038/s41598-022-11106-x

Shitophyta, L.M., Putri, S.R., Salsabiella, Z.A., Budiarti, G.I., Rauf, F. & Khan, A. 2023. Theoretical Biochemical Methane Potential Generated by the Anaerobic Digestion of Mustard Green Residues in Different Dilution Volumes. *Polish Journal of Environmental Studies* **32**(5), 4799–4804. doi: 10.15244/pjoes/162690

Sieling, K. 2019. Improved N transfer by growing catch crops – a challenge. *Journal für Kulturpflanzen* **71**(6), 145–160. doi: 10.5073/JfK.2019.06.01

Silva, G.O.A., Southam, G. & Gagen, E.J. 2023 Accelerating soil aggregate formation: a review on microbial processes as the critical step in a post-mining rehabilitation context. *Soil Research* **61**(3), 209–223. doi: 10.1071/SR22092

Simeão, R.M., Silva, D.D., Santos, F.C., Vilela, L., Silveira, M.C.T., Resende, A.C. & Albuquerque, P.E.P. 2023. Adaptation and indication of forage crops for agricultural production in sandy soils in western Bahia State, Brazil. *Acta Scientiarum. Agronomy* **45**, e56144. doi: 10.4025/actasciagron.v45i1.56144

Singh, D., Devi, K.B., Ashoka, P., Bahadur, R., Kumar, N., Devi, O.R. & Shahni, Y.S. 2023. Green Manure: Aspects and its Role in Sustainable Agriculture. *International Journal of Environment and Climate Change* **13**(11), 39–45. doi: 10.9734/ijecc/2023/v13i113142

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J. & O'neil, K. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. *Agronomy Journal* **97**(1), 322–332. doi: 10.2134/ agronj2005.0322a

Snecdecor, G.W. & Cochran, W.G. 1991. *Statistical Methods, 8th Edition*. Wiley-Blackwell, 524 pp.

Sousa, D.C., Medeiros, J.C., Lacerda, J.J.J., Rosa, J.D., Boechat, C.L., Sousa, M.N. G., Mafra, A.L. 2019. Dry mass accumulation, nutrients and decomposition of cover plants. *Journal of Agricultural Science* **11**(5), 152–160. doi: https://doi.org/10.5539/jas.v11n5p152

Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T. & Sumner, M.E. 1996. *Methods of Soil Analysis*, Part 3: Chemical Methods. Soil Science Society of America, Inc., American Society, 1424 pp.

Stubbs, T. & Kennedy, A.C. 2017. Prediction of Canola Residue Characteristics Using Near-Infrared Spectroscopy. *International Journal of Agronomy*, 4813147, 1–9. doi: 10.1155/2017/4813147

Swarcewicz, M., Adaszynska, M. & Wrzesinska, E. 2013. Chemical Composition of Macerated Plant Parts of White Mustard Sinapis alba. *Chemistry of Natural Compounds* **49**, 557–558. doi: 10.1007/s10600-013-0671-4

Szczepanek, M & Siwik-Ziomek, A.P 2019. K Accumulation by Rapeseed as Affected by Biostimulant under Different NPK and S Fertilization Doses. *Agronomy* **9**(9), 477. doi: 10.3390/agronomy9090477

Sánchez, R.D.G., Sánchez, D.J.I., Ochoa, M.E., González Cifuentes, A.I., Reyes González, A. & Hernández, R.K. 2023. Yield and nutritional value of forage brassicas compared to traditional forages. *Revista Mexicana de Ciencias Pecuarias* **14**, 237–247.

Śmiechowska, A., Bartoszek, A. & Namieśnik, J. 2010. Determination of glucosinolates and their decomposition products-indoles and isothiocyanates in cruciferous vegetables. *Critical Reviews in Analytical Chemistry* **40**, 202–216. doi: 10.1080/ 10408347.2010.490489

Test Guidelines for the conduct of tests for distinctness. uniformity and stability of Fodder Radish (*Raphanus sativus* L. var. *oleiformis* Pers.). 2017. Geneva, 23 pp.

Thiébeau, P., Jensen, L.S., Ferchaud, F. & Recous, S. 2021. Dataset of biomass and chemical quality of crop residues from European areas. *Data in Brief* **37**, 1–8. doi: 10.1016/j.dib.2021.107227ff

Thorup-Kristensen, K. & Kirkegaard, J. 2016. Root system-based limits to agricultural productivity and efficiency: the farming systems context. *Annals Bottany* **118**(4), 573–592. doi: 10.1093/aob/mcw122

Tian, Y. & Deng, F. 2020. Phytochemistry and biological activity of mustard (Brassica juncea): a review. *CyTA – Journal of Food* **18**(1), 704–718. doi: 10.1080/19476337.2020.1833988

Tixier, P, Lavigneb, C., Álvareza, S., Gauquierb, A., Blancharda, M.G., Ripochea, A. & Acharda, R. 2010. Model evaluation of cover crops, application to eleven species for banana cropping systems. *European Journal of Agronomy* **34**(2), 53–61. doi: 10.1016/j.eja.2010.10.004

Tjørve, K.M.C. & Tjørve, E. 2017. The use of Gompertz models in growth analyses, and new Gompertz-model approach: An addition to the Unified-Richards family. *PLoS One* **12**(6), e0178691. doi: 10.1371/journal.pone.0178691

Tokarchuk, D., Pryshliak, N., Yaremchuk, N. & Berezyuk, S. 2023. Sorting, Logistics and Secondary Use of Solid Household Waste in Ukraine on the Way to European Integration. *Ecological Engineering and Environmental Technology* **24**(1), 207–220. doi: 10.12912/27197050/154995

Toleikiene, M., Arlauskiene, A., Fliesbach, A., Iqbal, R., Sarunaite, L. & Kadziuliene, Z. 2020. he decomposition of standardised organic materials in loam and clay loam arable soils during a non-vegetation period. *Soil and Water Research* **15**(3), 181–190. doi: 10.17221/31/2019-swr

Toom, M., Talgre, L., Pechter, P., Narits, L., Tamm, S. & Lauringson, E. 2019. The effect of sowing date on cover crop biomass and nitrogen accumulation. *Agronomy Research* **17**(4), 1779–1787. doi: https://doi.org/10.15159/AR.19.164

Tsytsiura, Y. 2022. The influence of agroecological and agrotechnological factors on the generative development of oilseed radish (*Raphanus sativus* var. *oleifera* Metzg.). *Agronomy Research* **20**(4), 842–880. doi: 10.15159/ar.22.035

Tsytsiura, Y. 2023a. Estimation of biomethane yield from silage fermented biomass of oilseed radish (*Raphanus sativus* L. var. *oleiformis* Pers.) for different sowing and harvesting dates. *Agronomy Research* **21**(2), 940–978. 10.15159/AR.23.101

Tsytsiura, Y 2024. Ecological Approach to the Identication of the Degree of Phytophage Damage Based on Chlorophyll Fluorescence Induction in Oilseed Radish (*Raphanus sativus* L. var. *oleiformis* Pers.). *Journal of Ecological Engineering* **25**(2), 227–243. doi: 10.12911/22998993/176983

Tsytsiura, Y. 2020a. Formation and determination of the individual area of oilseed radish leaves in agrophytocenosises of different technological construction. *Agronomy Research* **18**(3), 2217–2244. doi: 10.15159/AR.20.219

Tsytsiura, Y. 2023b. Evaluation of oilseed radish (*Raphanus sativus* l. var. *oleiformis* Pers.) oil as a potential component of biofuels. *Engenharia Agrícola, Jaboticabal* **43**(Special issue), e20220137. doi: 10.1590/1809-4430-Eng.Agric.v43nepe20220137/2023.

Tsytsiura, Y. 2023c. Assessment of the relation between the adaptive potential of oilseed radish varieties (*Raphanus sativus* L. var. *oleiformis* Pers.) and chlorophyll fluorescence induction parameters. *Agronomy Research* **20**(1), 193–221. doi: 10.15159/AR.23.001

Tsytsiura, Y.H. 2019. Evaluation of the efficiency of oilseed radish agrophytocoenosis construction by the factor of reproductive effort. *Bulgarian Journal of Agricultural Science* **25**(6), 1161–1174.

Tsytsiura, Y.H. 2020. Modular-vitality and ideotypical approach in evaluating the efficiency of construction of oilseed radish agrophytocenosises (*Raphanus sativus* var. *oleifera* Pers.). *Agraarteadus* **31**(2), 219–243. doi: 10.15159/jas.20.27

Tsytsiura, Y.H. 2021. Matrix quality variability of oilseed radish (Raphanus sativus l. var. oleiformis Pers.) and features of its formation in technologically different construction of its agrophytocenosis. *Agronomy Research* **19**(1), 300–326 doi: 10.15159/ar.21.003

Ugrenović, V., Filipović, V., Jevremović, S., Marjanović, J.A., Popović, V., Buntić, A. & Delić, D. 2019. Effect of Brassicaceae as cover crops. *Selekcija i semenarstvo* **25**(2), 1–8. doi: 10.5937/SelSem1902001U (in Serbian).

Undersander, D., Mertens, D.R. & Thiex, N. 1993. *Forage analyses*. Procedures. National Forage Testing Association, 139 pp.

Van Soest, P.J., Robertson, J.B. & Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* **74**, 3583–3597. doi: 10.3168/jds.S0022-0302(91)78551-2

Velasco, P., Soengas, P., Vilar, M., Cartea, M.E. & del Rio, M. 2008. Comparison of glucosinolate profiles in leaf and seed tissues of different Brassica napus crops. *Journal of the American Society for Horticultural Science* **133**(4), 551–558. doi: 10.21273/JASHS.133.4.551

Venslauskas, K., Navickas, K., Rubežius, M., Žalys, B. & Gegeckas, A. 2024. Processing of Agricultural Residues with a High Concentration of Structural Carbohydrates into Biogas Using Selective Biological Products. *Sustainability* **16**(4), 1553. doi: 10.3390/su16041553

Villalobos, L. & Brummer, J. 2013. Evaluation of Brassicas for fall forage. In *Proceedings of theWestern States Alfalfa and Forage Symp*, Reno, NV, USA, 17–31.

Wadman, W.P. & de Haan, S. 1997. Decomposition of organic matter from 36 soils in a long-term pot experiment. *Plant and Soil* **189**(2), 289–301.

Wahlström, E.M., Hansen, E.M., Mandel, A., Garbout, A., Kristensen, H.L. & Munkholm, L.J. 2015. Root development of fodder radish and winter wheat before winter in relation to uptake of nitrogen. *European Journal of Agronomy* **71**, 1–9. doi:10.1016/J.EJA.2015.07.002

Wallace, A. & Mueller, R.T. 1980. Calcium uptake and distribution in plants. *Journal of Plant Nutrition* **2**, 247–256.

Wang, X., Ma, H., Guan, C. & Guan, M. 2022. Decomposition of Rapeseed Green Manure and Its Effect on Soil under Two Residue Return Levels. *Sustainability* **14**, 11102. doi: 10.3390/su141711102

Wang, X., Yang, G., Feng, Y., Ren, G. & Han, X. 2012. Optimizing feeding composition and carbon-nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. *Bioresource Technology* **120**, 78–83. doi: 10.1016/j.biortech.2012.06.058

Warren, J., Meeks, K. & Edwards, J.. 2017. Benefits of using cover crops in Oklahoma no-till. *Bull. PSS-2161*. Oklahoma Cooperative Extension Service. Oklahoma State University. Stillwater, OK, 41 pp.

Weih, M., Hamner, K. & Pourazari, F. 2018. Analyzing plant nutrient uptake and utilization efficiencies: Comparison between crops and approaches. *Plant Soil* **430**, 7–21.

Wendling, M., Büchi, L., Amossé, C., Sinaj, S., Walter, A. & Charles, R. 2016. Influence of root and leaf traits on the uptake of nutrients in cover crops. *Plant and Soil* **409**(1–2), 419–434.

Werker, A.R. & Jaggard, K.W. 1997. Modelling asymmetrical growth curves that rise and then fall: applications to foliage dynamics of sugar beet (*Beta vulgaris* L.). *Annals of Botany* **79**, 657–665.

Westwood, C.T. & Mulcock, H. 2012. Nutritional evaluation of five species of forage brassica. *Journal of New Zealand Grasslands* **74**, 31–38.

White, C.A., Holmes, H.F., Morris, N.L. & Stobart, R.M. 2016. *A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species*. Research Review №. 90. AHDB Cereals & Oilseeds, 90 pp.

Williams, J.D., McCool, D.K., Reardon, C.L., Douglas, C.L., Albrecht, S.L. & Rickman, R.W. 2013. Root:shoot ratios and belowground biomass distribution for Pacific Northwest dryland crops. *Journal of Soil and Water Conservation* **68**(5), 349–360. doi: 10.2489/jswc.68.5.349

Winkler, O.R.T. 2017. *Agronomic studies of forage brassicas as full-season and cover crops for grazing in North Dakota*. PhD Thesis. North Dakota State University, 219 pp.

Wollford, A.R. & Jarvis, P.E. 2017. *Cover, catch and companion crops. Benefits, challenges and economics for UK growers*. Game & Wildlife Trust The Allerton Project, 28 pp.

Wong, J. 2018. *Handbook of statistical analysis and data mining applications*. Cambridge, Academic Press. 589 pp.

Wu, X., Huang, H., Childs, H., Wu, Y., Yu, L. & Pehrsson, P.R. 2021. Glucosinolates in Brassica Vegetables: Characterization and Factors That Influence Distribution, Content, and Intake. *Annual Review of Food Science and Technology* **12**(1), 485–511. doi: 10.1146/annurev-food-070620-025744

Yahbi, M., Keli, A., El Alami, N., Nabloussi, A., Maataoui, A. & Daoui, K. 2024. Chemical composition and quality of rapeseed meal as affected by genotype and nitrogen fertilization. *OCL* **31**, 5. doi: 10.1051/ocl/2024004

Yan, C., Huang, Y., Zhang, S., Cui, L., Jiao, Z., Peng, Z., Luo, X., Liu, Y. & Qiu, Z. 2023. Dynamic profiling of intact glucosinolates in radish by combining UHPLC-HRMS/MS and UHPLC-QqQ-MS/MS. *Frontiers Plant Science* **14**, 1216682. doi: 10.3389/fpls.2023.1216682

Yasumoto, S., Matsuzaki, M., Hirokane, H. & Okada, K. 2010. Glucosinolate Content in Rapeseed in Relation to Suppression of Subsequent Crop. *Plant Production Science* **13**(2), 150–155. doi: 10.1626/pps.13.150

Yi, G., Lim, S., Chae, W.B., Park, J.E., Park, H.R., Lee, E.J. & Huh, J.H. 2016. Root Glucosinolate Profiles for Screening of Radish (*Raphanus sativus* L.) Genetic Resources. *Journal of Agricultural and Food Chemistry* **64**(1), 61–70. doi: 10.1021/acs.jafc.5b04575

Yousefi, M., Dray, A. & Ghazoul, J. 2024. Assessing the effectiveness of cover crops on ecosystem services: a review of the benefits, challenges, and trade-offs. *International Journal of Agricultural Sustainability* **22**(1), 2335106 doi: 10.1080/14735903.2024.2335106

Zachariah, H. 2011. *Potential of three brassica cover crops for biofumigation in the field and the relationship between soil myrosinase and biofumigation efficacy*. PhD Thesis. Clemson University. TigerPrints. 1248, 136 pp.

Zhou, P., Graether, S.P., Hu, L. & Zhang, W. 2023. Editorial: The role of stress proteins in plants under abiotic stress. *Frontiers in Plant Science* **4**(14), 1193542. doi: 10.3389/fpls.2023.1193542

Ţiţei, V. 2022. The quality of fresh and ensiled biomass from white mustard, Sinapis alba, and its potential uses. *Scientific Papers. Series A. Agronomy* **1**(65), 559–566.