

Assessment of the direction of microbiological processes in Ukrainian chernozems in pea-barley intercropping agroecosystem under the influence of biostimulants

O. Tonkha¹, R. Tomashevskii¹, B. Mazurenko¹, O. Pikovska¹, O. Litvinova¹,
O. Kravchenko¹, T. Maievska², S. Azarkamand³, T. Melnychuk¹,
O. Havryliuk¹ and K. Shemetun¹

¹National University of Life and Environmental Sciences of Ukraine, Heroiv Oborony Str.13, UA–03041 Kyiv, Ukraine

²Ukraine’s Fishing Industry Cluster of Innovation, 18/B, Instutytska Street, UA–01021 Kyiv, Ukraine

³UNESCO Chair in Life Cycle and Climate Change ESCI-UPF, Pg. Pujades 1, ES08003 Barcelona, Spain

*Corresponding author: o.havryliuk@nubip.edu.ua

Received: March 11th, 2026; Accepted: August 6th, 2026; Published: October 6th, 2026

Abstract. Soil microorganisms are an important component of agroecosystems, and their structure, number and ratio allow us to characterize the direction of microbiological processes in the soil. The aim of this study was to determine impact of application of biostimulators on the activity of microbiological processes in typical chernozem soil in agroecosystem of pea-barley intercrops. The effect of different biostimulators in pea-barley intercropping on the number of different groups of microorganisms on the 7th, 60th and 90th day after emergence was established in field experiment on typical chernozem in Ukraine. Coefficients of mineralization-immobilization, oligotrophicity and pedotrophicity were calculated to determine the directionality of microbiological processes in the soil. The greatest impact on microbial biomass during the vegetation period was observed with the application of insect frass extract, particularly at 60 DAE, where the indicator reached 302 million CFU in the 0–20 cm soil layer. The use of vermicompost increased the number of ammonifying microorganisms to 14.3 million CFU in the 0–20 cm layer and 10.1 million CFU in the 20–40 cm layer. In contrast, the application of compost tea, humus extract, and fish hydrolysate almost halved the number of these microorganisms compared to the control on the 60th day. At 90 DAE, the highest number of ammonifying bacteria was recorded with compost tea are 7.8 CFU per 1.0 g of dry soil in the 0–20 cm layer and 4.8 CFU per 1.0 g of dry soil in the 20–40 cm layer. The highest number of amylolytic microorganisms was observed with the insect extract are 12.4 million CFU per 1.0 g of soil compared to 6.6 million CFU in the control. Regarding the content of phosphate-mobilizing microorganisms on the 60th day, only the insect frass variant showed an advantage over the control in the 0–20 cm layer (16.7 million CFU), while vermicompost showed the highest number in the 20–40 cm layer (10.4 million CFU); the other biopreparations showed

lower values. Thus, the use of biopreparations on pea-barley intercrops caused a significant impact on the microbiological activity of the soil and the content of labile organic substances.

Key words: microbiota, biological activity, soil, soil organic matter.

INTRODUCTION

The soil cover of Ukraine can maintain a high potential for the productivity of agricultural crops, especially concerning chernozem soils. However, increased anthropogenic pressure on them leads to a reduction in the population and depletion of the species diversity of microorganisms, as well as disruption of functional connections in the structure of microbial communities. This results in an increase in the quantity of humate-degrading microorganisms in the absence of organic additives and, consequently, a decrease in the level of effective and potential soil fertility.

Assessing the anthropogenic impact on ecosystems is possible based on many indicators, including the activity of microorganisms. According to the modern definition, soil is a biological and biochemical system, one of the main components of which is soil microbiota. Researchers pay attention to significant changes in microbiological activity depending on the cultivated crops and fertilizers. In the work of Malinovska & Litvinov (2013), it was established that the microbial communities of the root zone of the studied crops are more stable in crop rotation and are characterized by a much larger number of significant correlations than when grown in monocrops of soybeans and corn. Losses of soil organic matter were noted in monocrops, even in variants with manure application. Biological preparations provide an increase in the yield level of crops, in particular spinach (Dewang & Devi, 2020). Madende & Hayes (2020) predict that the use of plant growth and development biostimulants is increasing and will reach the level of 4.14 billion US dollars by 2025. Modern crop cultivation technologies widely use high rates of mineral fertilizers and pesticides, which negatively affect both soil microbiota and the state of the environment (Dudchenko et al., 2021; Khomenko et al., 2023).

According to EU regulations (EU 2019), biostimulants are defined as organic or inorganic products containing biologically active substances and/or microorganisms that, when applied to plants or the rhizosphere, stimulate plant growth and productivity by enhancing the efficiency of nutrient absorption and assimilation, tolerance to abiotic stresses, and/or product quality regardless of its nutrient content. Authors Maroulis et al. (2023) indicate that biostimulants can optimize fertilizer efficiency and reduce nutrient application rates.

Soil microorganisms are an integral part of biogeocenoses, participating in the global cycling of substances and energy in the biosphere. The fertility of the soil and the quality of plant production depend on their development. Biological processes continuously occur in the soil, leading to changes in the quantitative and qualitative composition of plant nutrients through the decomposition of plant litter and dead root systems (Hubachov, 2010; Malinovska & Litvinov, 2012; Demyanyuk et al., 2017). To study the rate of biological cycling in such a system, it is necessary to not only analyze the chemical composition of the soil but also to investigate the activity of microbiological processes, which determine the dynamics of organic and mineral substance transformations. (Bagyaraj & Ashwin, 2024).

Scientists studied the influence of various organic fertilizers and biological preparations on indicators of biological activity of soils (Pavlichenko et al., 2023; Dehodiuk et al., 2024; Bulygin et al., 2025). One of the effective biological preparations is vermicompost (Pathma & Sakthivel, 2012). The activity of soil alkaline phosphatase and β -glucosidase was significantly higher with the application of vermicompost. However, urease activity was not dependent on the applied organic fertilizer (Uz et al., 2016). It was found that vermicompost and mineral fertilizers significantly increased the yield of Indian mustard seeds, their oil content compared to the control (Kansotia et al., 2015).

Products derived from insects, such as insect frass, contain chitin and are rich in nitrogen, as well as other nutrients, which can improve soil quality and plant growth. Insect frass is colonized by bacteria that potentially protect or stimulate plant growth when added to the soil (Barragán-Fonseca et al., 2020). Besides influencing plant vegetative mass and yield, insect frass affects soil fertility by reducing leaching and infiltration of biogenic elements, as well as the spread of diseases and pathogens (Chavez & Uchanski, 2021).

The positive impact of compost tea on the yield of various crops has been noted in studies (Pant et al., 2012; Naidu et al., 2013; Kim et al., 2015). The authors found that treating with compost tea can be used as a technique to stimulate plant growth in organic farming systems. Compost teas should be used in organic farming systems. Treating with compost tea significantly increased the yield of lettuce and kohlrabi by 24% and 32%, respectively. As a result of compost tea, the physiological and nutritional status of plants improved, and the chlorophyll content increased throughout the plant's growth cycle. The results indicate the practical application of compost teas in organic farming systems (Pane et al., 2014).

The use of biostimulants derived from fish products can improve nutrient uptake, nutrient efficiency, plant yield, and product quality, offering a promising alternative to traditional chemical fertilizer use (Madende & Hayes, 2020).

Thus, based on the analysis of informational sources, the necessity of searching for new alternative ways to increase crop productivity, which will ensure sustainable agricultural development and the preservation of soil health and the environment, has been demonstrated. However, the results of studies on the effectiveness of various biopreparations on soil fertility indicators and crop yields are ambiguous. Research on soil microbiological indicators will allow a better understanding of the mechanisms of action of biopreparations and establish their impact on soil fertility.

The aim of the work was to establish the influence of biostimulants on the development of different groups of microorganisms in typical black soil in the joint sowing of peas and barley. In accordance with the goal, the following tasks were solved: to establish the dynamics of the total number of microorganisms during the growing season; the number of ammonifying, amylolytic, phosphate-mobilizing, oligotrophic, pedotrophic, humus-decomposing microorganisms and micromycetes; to analyze the direction of microbiological processes by the coefficients of mineralization-immobilization, oligotrophicity and pedotrophicity and to establish the correlation between the indicators of the microbiological state, the content of labile organic matter and mineral nitrogen in the soil.

MATERIALS AND METHODS

The research was conducted at the Separated Division of the National University of Life and Environmental Sciences of Ukraine 'Agronomic Research Station' in Vasylkivskyi district, Kyiv region, Pshenychne village (49°46' N, 30°44' E; 192 m above sea level) in 2023–2025. The object of the study is the ecological-trophic groups and the direction of microbiological processes in typical chernozem soil under the cultivation pea-barley intercropping.

Soil and weather conditions. The climate of the research zone is moderately continental. Overall, the weather conditions during the vegetation period of the binary barley and pea planting were typical for the region. Throughout the vegetation period, the average daily air temperature ranged from 16.5 to 24.1 °C, reaching its highest value in August. Overall, the weather conditions were satisfactory for the studied crops, with sufficient rainfall in April for the normal germination of the crops.

The soil of field trial is typical chernozem (CH, according to FAO-UNESCO soil classification), loamy-sandy, containing 34.5% physical clay, 22% silt, and 28% sand. The content of coarse dust is 46.3%, medium – 6.8%, fine – 3.4%. The humus content in the arable layer of soil is 3.6%, and in the subarable layer – 3.5%. The soil environment is alkaline (pH 8.2 ± 0.3), with a total absorbed cation content of 35.4 mg–eq/100 g of soil. The supply of easily hydrolyzable nitrogen according to Tyurin and Kononova is high in the humus horizon and increased in the upper transitional horizon. The presence of mobile forms of phosphorus and potassium according to Machigin is high in the arable layer and increased in the subarable soil layer.

Scheme and characteristic of biostimulants. The basic object of observation was an agrocoenosis of pea-barley intercrops. The pea seeds of the cv. Orchestra and spring barley cv. Prospect were sown without fungicide treatment, and no protective agents or fertilizers were used. Pea were inoculated in rate 2 L t^{-1} of seeds with the strain *Rhizobium leguminosarum* bv. *pisum* (2×10^9 CFU mL^{-1}). Plant density in all variants was within 56 ± 1 plants m^{-2} for peas and 120 ± 5 plants m^{-2} for barley. The sowing method was in rows with an inter-row spacing of 12.5 cm, and the seeding depth was 6–8 cm for peas and 2–4 cm for barley. The peas and barley were placed in the same row.

Soil tillage included disking after harvesting the previous crop and plowing to a depth of 18–20 cm in the fall. Mineral fertilizers were not applied to the field plot. In spring, surface tillage was performed at the first opportunity to reduce evaporation. Solid biostimulants (biochar and vermicompost) were applied to designated plots according to the experimental design after marking the field.

Experimental plot parameters: Each experimental variant was placed in a paired plot measuring 1.5×10 m (the area of one variant in one replication is 30 m^2). The experiment was conducted with three replications.

The method of seed placement and the soil sampling approach were consistent across the entire experimental field. The detailed layout of plant placement in the row is shown in Fig. 1.

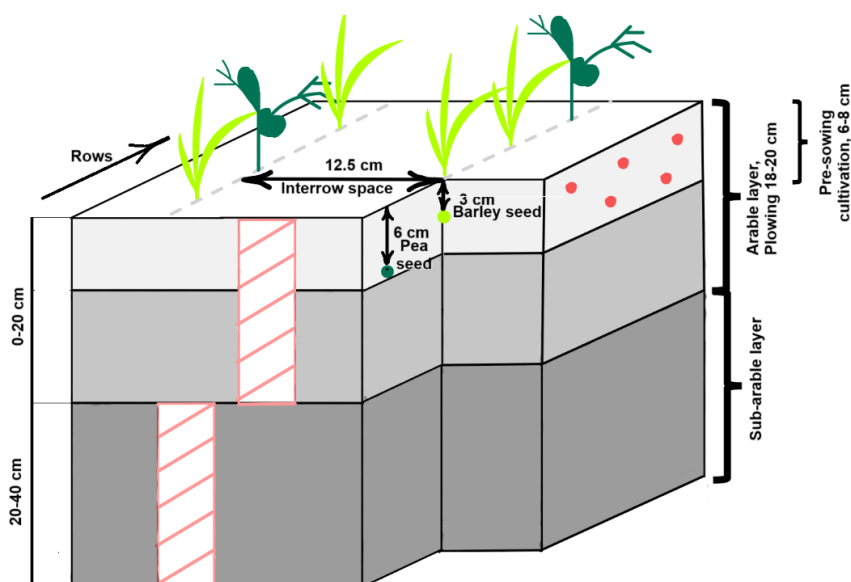


Figure 1. Seed and plant placement scheme in the field plot and soil sampling points (dark green – pea seed and plant; light green – barley seed and plant; red points – solid biostimulants).

Key dates for biostimulant application, emergence, and soil sampling are shown in the timeline in Fig. 2.

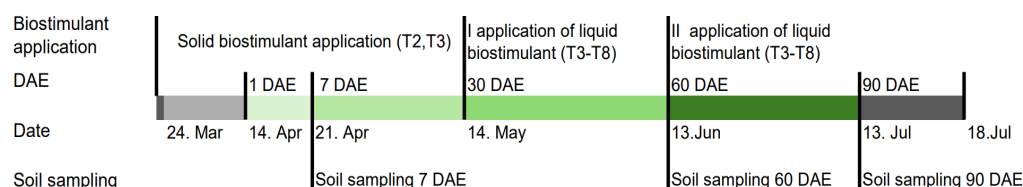


Figure 2. Timeline of field works (24th March is sowing, grey light is germination period).

The scheme of the study on investigating the effect of biostimulants application on soil microbiota in Table 1. The following types of biological preparations were used in the experiment:

The experiment utilized biochar, which is a product of fir wood shavings pyrolysis (500 °C exposure for 8 hours). The biochar contained over 70% carbon, with a particle size ranging from 0.1 to 2.0 mm.

Vermicompost was produced from the decomposition of organic raw materials (vegetable and field crop waste) and had a nitrogen, phosphorus, and potassium ratio of 2:1.5:1.5.

Insect Frass refers to a mixture of excreta obtained from cultivated insects, their parts, dead eggs, with the content of dead insects not exceeding 5% by volume and 3% by mass (according to EU regulations in 2021). The insect frass contained at least 30% chitin. The production process of the insect frass extract was identical to that of compost tea (described below).

Compost tea was obtained through 48-hour aerobic fermentation of compost (the raw material being well-decomposed cow manure compost). To prepare the extract, 10 kg of compost was mixed with 50 liters of water. After fermentation, the extract was filtered and diluted to a working solution (1:5 v/v) before being applied to the crops.

Humus extract (Humifriend) contains potassium humate 120 g L⁻¹, dilution for working solution 1:100 (v:v). (from a local manufacturer)

Fish hydrolysate – is a product of processing waste from trout production.

The variant number in the graphs corresponds to the sequential number of the biostimulant in Table 1.

Table 1. Scheme of biostimulant application

No	Treatment	Before sowing	30 day after emergence	60 day after emergence
T1	Control (w/o)	–	–	–
T2	Biochar	2.5 t ha ⁻¹	–	–
T3	Vermicompost	2.5 t ha ⁻¹	–	–
T4	Insect frass extract	–	50 L ha ⁻¹	50 L ha ⁻¹
T5	Compost tea	–	2.5 L ha ⁻¹	2.5 L ha ⁻¹
T6	Humus extract	–	2.5 L ha ⁻¹	2.5 L ha ⁻¹
T7	Fish hydrolysate	–	2.5 L ha ⁻¹	2.5 L ha ⁻¹
T8	Seaweed extract (Yara Vita Biotrac)	–	2.5 L ha ⁻¹	2.5 L ha ⁻¹

Experimental variants (T4–T8) were applied by foliar spraying the crops in the evening hours after collecting plant and soil samples (if sampling was included in the scheme). Planned doses of biostimulants were dissolved in water to create a working solution with an application rate of 300 L ha⁻¹.

Procedure of soil sampling and analysis. Soil samples were collected from the 0–20 cm and 20–40 cm layers and the rhizosphere of the plant root system according to ISO 10381 (DSTU ISO 10381–2:2004) on the 7th day after emergence (DAE), on the 60th and 90th DAE (after harvesting crops). To determine the number of soil microbiota, 10 g of soil was taken from each sample in flasks and, adding 90 mL of water, microorganisms were dispersed from soil particles using Zvyagintsev's method (Zvyagintsev, 1978).

The number of microorganisms of the main ecological–trophic and taxonomic groups was determined by the method of sowing soil suspension (after tenfold dilution) on standard nutrient media (Table 2).

After seeding the biological material onto nutrient media, they were incubated at a temperature of 28 °C for 5–14 days (depending on the growth rate of the respective groups of microorganisms).

Colonies that grew on the media were counted under the condition that one viable cell forms one colony. The number of microorganisms was expressed in colony-forming units (CFU) per 1 gram of absolutely dry soil, taking into account the moisture coefficient and dilution of the soil suspension. For this purpose, the moisture content of

the soil sample taken for the study was determined by the thermostat-weight method, and the obtained number of colonies was recalculated taking into account the moisture coefficient and dilution of the soil suspension.

Table 2. Target indicators of microbiota composition and corresponding cultivation media

Indicator	Type of media (features of preparation)
Total number of microorganisms	Peptone-glucose agar with soil extract (PGA)
Ammonifying microorganisms	Meat-peptone agar (MPA)
Spore-forming bacteria	MPA with husk after heating at 75 °C for 20 minutes
Oligotrophic microorganisms	Minimal agar (MA)
Streptomycetes and bacteria utilizing mineral nitrogen (amylolytic)	Starch-ammonium agar (SAA)
Pedotrophic microorganisms	Soil agar (SA)
Nitrogen-fixing bacteria	Nitrogen-free media Eshby and Winogradsky
Azotobacter	Fedorov's medium by the method of soil clump overgrowth
Micromycetes	Chapek's medium
Phosphomobilizing bacteria	Muromtsev's medium
Nitrifying bacteria	MA with ammonium–magnesium salt
Microorganisms synthesizing polysaccharides	Martin's medium
Microorganisms synthesizing melanins	Chapek's medium with pH = 5.0
Microorganisms decomposing humates	Medium with sodium humate
Number of cellulolytic microorganisms	Winogradsky's medium in Pushkin's modification

Analysis of the directionality of biological processes. The directionality of soil microbiological processes was determined using the following coefficients:

Mineralization-Immobilization Coefficient (C_{M-I}) is the ratio of the number of microorganisms immobilizing mineral forms of nitrogen to the population of organotrophs:

$$C_{M-I} = S_{SAA} / S_{MPA}, \quad (1)$$

where S_{SAA} and S_{MPA} represent the quantity of microorganisms that grew on starch-ammonium agar and meat-peptone agar, respectively.

Oligotrophy coefficient (K_{ol}) was calculated as the ratio of the population of microorganisms assimilating nutrients from very poor solutions to the total population of eutrophic microorganisms. nium agar and meat-peptone agar, respectively:

$$C_{ol} = S_{MA} / (S_{SAA} + S_{MPA}), \quad (2)$$

S_{MA} represents the quantity of microorganisms that grew on very poor solution (minimal agar).

Pedotrophy coefficient (C_{ped}) is the ratio of the quantity of microorganisms on soil agar (SA) to the quantity of microorganisms that grew on meat-peptone agar (S_{MPA}).

$$C_{ped} = S_{SA} / S_{MPA}, \quad (3)$$

The assessment of soil based on the degree of enrichment with microorganisms and enzymes was conducted using D. Zvyagintsev's scales (Zvyagintsev, 1978).

The content of nitrate nitrogen ($N-NO_3^-$), ammonium nitrogen ($N-NH_4^+$) was determined according to DSTU 4729:2007, and the content of mineral nitrogen (N_{min}) was calculated as their sum.

Statistical analysis. All measurements for each variant were determined with three replications. Error bars in the figures represent the standard error (SE). Indexes indicate similar variants based on the Fisher's LSD₀₅ criterion. Mention statistical program used for analysis and the basis for significant differences between the means.

RESULTS AND DISCUSSION

Soil microorganisms are one of the crucial factors in agrobiocenoses. The growth and development of agricultural plants are closely linked not only to the elements of cultivation technology but primarily to interactions with the soil and its biota. The processes of soil fertility formation are the basis for the sustainable and safe development of the agricultural sector as a whole. Therefore, studying and identifying the features of microbial community functioning allow us to form an understanding of all components of the agrocenosis (Bagyaraj & Ashwin, 2024).

The results of accounting for agronomically beneficial groups of microorganisms showed that their numbers varied depending on the phase of development of agricultural crops and the biostimulants used. (Table 3).

Table 3. Dynamics of total number of microorganisms in pea-barley intercropping, million CFU per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	177.3 ^{cd}	164.6 ^{ab}	217.7 ^e	188.6 ^d	213.2 ^c	211.4 ^c	235.5	167.4 ^{abc}
20–40 cm	158.8 ^a	143.5	177.3 ^{cd}	156.6 ^a	156.6 ^a	156.6 ^a	174.5 ^{bc}	161.5 ^a
60 DAE								
0–20 cm	27.2 ^a	24.4 ^a	18.4 ^a	302.3	146 ^{cd}	213.5 ^c	213.5 ^c	154.3 ^d
20–40 cm	20.4 ^a	18.2 ^a	16.2 ^a	96.1 ^{bc}	94.6 ^{bc}	83.1 ^b	93.1 ^b	61.1 ^{ab}
90 DAE								
0–20 cm	174.2 ^{fg}	163.5 ^{ef}	198.2	217.4	151 ^{cde}	184.2 ^g	175.6 ^{fg}	148.6 ^{cd}
20–40 cm	120.6 ^b	118.2 ^b	153.2 ^{de}	156.1 ^{de}	104.5 ^a	103.1 ^a	138.2 ^c	139.2 ^c

Note: for Tables 3–8, the same letters indicate variants within the same similarity group (a – the lowest value, followed by increasing values).

The variants of introduction of biological products differed in the indicator of total number of soil microorganisms during the growing season. On the variants of Control, Biochar, Vermicompost, the indicators decreased at the 60 day after the emergence (60 DAE), and by 90 day after the emergence (90 DAE) the indicators were restored almost to the level at the 7 day after the emergence (7 DAE). On the option of the Insect frass extract, on the contrary at the 60 DAE, the figure was higher and amounted to 302 million CFU per g of dry soil in a layer of 0–20 cm. In our studies of total number of soil microorganisms for growing barley and peas in binary crops with compost tea in processing 5 was 213 and 157 million CFU per g of dry soil in layers 0–20 cm and 20–40 cm at the 7 DAE, respectively, only lagged behind the option with Fish hydrolysate. The population decreased to 146 and 95 million CFU per g of soil of dry soil at the 60 DAE in layers 0–20 and 20–40 cm and was also higher than in most other experimental options. Studies conducted in Canada on soybean–corn crop rotation showed that the application of compost tea did not affect either the structure or the

diversity of bacteria in the soil. Its significant impact on crop yield was also not established (Bali et al., 2021). Angulo et al. (2014) note that the reasons for the effectiveness of compost tea, whether growth regulators, minerals, microorganisms, or their combination, are ambiguous. They believe that plant growth stimulation may be associated not with microbial biomass, but rather with the release of extracellular microbial signals, nutrients, and nutrient availability. Thus, we have a positive effect of the Insect frass extract, Humus extract and Fish hydrolysate on the total number of soil microorganisms. At the same time, data on the content of Compost of tea are controversial.

The course of processes in the soil is primarily characterized by the activity and quantity of ammonifiers utilizing soil organic matter. For example, the largest number of colonies of ammonifies microorganisms was obtained when using Vermompost: 7.7 CFU per g of soil at 7 DAE, 14.3 - at 60 DAE at a layer 0–20 cm and 6.9 and 10.1- in a layer of 20–40 cm respectively. The intensity of the ammonia development was provided by the high content of the biohumus of easily hydrolyzed organic matter (Table 4).

Table 4. Dynamics of the population of ammonifying microorganisms in pea-barley intercropping, million CFU per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	3.8 ^{cd}	3.2 ^{abcd}	7.7 ^g	3.3 ^{bcd}	4.2 ^{de}	5.2 ^{ef}	5.4 ^f	3.6 ^{cd}
20–40 cm	4.2 ^{de}	3.4 ^{bcd}	6.9 ^d	2.2 ^a	2.2 ^a	2.2 ^a	2.8 ^{abc}	2.4 ^{ab}
60 DAE								
0–20 cm	12.5 ^g	11.1 ^f	14.3	11.3 ^{fg}	5.9 ^{bc}	6.3 ^{cd}	6.9 ^{cde}	6.6 ^{cd}
20–40 cm	7.3 ^{de}	8.1 ^e	10.1 ^f	8.1 ^e	2.1	4.6 ^{ab}	4.8 ^{ab}	3.8 ^a
90 DAE								
0–20 cm	5.1 ^e	3.3 ^{abc}	3.7 ^{bcd}	3.9 ^{bcd}	7.8	4.3 ^{cde}	3.5 ^{bc}	5.2 ^e
20–40 cm	5.4 ^e	2.3 ^a	3.5 ^{bc}	2.8 ^{ab}	4.8 ^{de}	3.7 ^{bcd}	3.2 ^{abc}	3.7 ^{bcd}

The population of ammonifying microorganisms in pea-barley intercropping at 7 DAE using biochar and insect frass in the study (3.2 and 3.3 million CFU per g of soil) was lower compared to the control. This, in our opinion, is associated with the combined nutritional system, as the easily hydrolyzable organic matter was largely utilized by pea plants for growth and development. Maximum population of soil ammonifying microorganisms (6.8–14.3 million CFU per 1.0 g of dry soil) was observed at the 60 DAE, indicating the most physiologically active phase in terms of crop growth. At the 90th DAE the highest number of ammonifying bacteria were on the Compost tea 7.8 CFU per 1.0 g of dry soil 0–20 and 4.8 CFU per 1.0 g of dry soil in 20–40 cm of soil layer. Other biopreparates had no significant impact on the number of ammonifies at the 90th DAE. It is also worth emphasizing that the observed regularities of microorganism population increase during this period of time are determined by optimal hydrothermal conditions, especially the availability of moisture in the soil. During the budding phase, water uptake and absorption of nutrients from the soil by pea plants are maximized compared to the pod formation phase. On the 90th DAE, a decrease in the number of ammonifying microorganisms to the level of 2.3–5.4 million CFU per 1.0 g of dry soil was noted.

According to the research results, it was found that the density of microbial cells per unit volume of soil in the pea-barley intercropping was higher compared to the studied ecotrophic groups and consistently maintained throughout the vegetation period.

Unlike ammonifying organisms that utilize organic nitrogen, amylolytic organisms assimilate mineral nitrogen. Their dynamics in typical chernozem soil varied throughout the vegetation period (Table 5).

Table 5. Dynamics of the population of amylolytic microorganisms in pea-barley intercropping, million CFU per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	2.0 ^{ab}	2.5 ^c	2.7 ^{bc}	1.3 ^a	1.3 ^a	1.5 ^a	1.5 ^a	1.6 ^a
20–40 cm	2.8 ^c	2.5 ^{bc}	2.9 ^c	1.6 ^a	1.6 ^a	1.6 ^a	1.7 ^a	1.7 ^a
60 DAE								
0–20 cm	6.6 ^{gf}	8.8 ^j	9.3 ^j	12.4	5.9 ^{fg}	5.3 ^{ef}	7.4 ^{hi}	4.6 ^{de}
20–40 cm	3.4 ^{ab}	4.3 ^{cd}	7.8 ⁱ	7.5 ⁱ	3.6 ^{abc}	3.6 ^{abc}	3.9 ^{bcd}	3.0 ^a
90 DAE								
0–20 cm	3.1 ^{de}	2.7 ^{cd}	2.5 ^{bcd}	2.7 ^{cd}	3.6 ^c	2.5 ^{bcd}	2.6 ^{bcd}	3.2 ^{de}
20–40 cm	2.7 ^{cd}	1.3 ^a	1.8 ^{ab}	1.5 ^a	1.8 ^{ab}	1.6 ^a	2.0 ^{abc}	2.8 ^{cde}

The highest population of amylolytic microorganisms was observed on the 60th DAE in the intercropping, reaching 6.6–12.4 million CFU per 1.0 g of soil in the 0–20 cm layer of typical chernozem soil and 3.4–7.8 million CFU per 1.0 g of soil in the 20–40 cm layer. Fluctuations in the microbial population depended on both weather conditions and the application of bio-preparations. According to the experiments, the highest number of amylolytic microorganisms is established on the Insect frass extract – 12.4 million CFU per 1.0 g of soil. The variants of tea Compost and Humus extract caused the decrease in this group of microorganisms comparable to control on the 60th DAE. On the 7th DAE and 90th DAE, the variants were little different in the number of amylolytic microorganisms.

A similar trend in dynamics to ammonifying microorganisms was also noted for phosphate-mobilizing microorganisms (Table 6).

Table 6. Dynamics of the phosphate-mobilizing microorganisms in pea-barley intercropping, million CFU per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	2.1 ^h	2.0 ^{gh}	1.9 ^{gh}	1.1 ^{bc}	1.0 ^{ab}	0.8 ^a	1.0 ^{ab}	1.6 ^{ef}
20–40 cm	1.8 ^{fg}	1.5 ^{de}	1.3 ^{cd}	1.3 ^{cd}	1.3 ^{cd}	1.3 ^{cd}	1.3 ^{cd}	1.5 ^{de}
60 DAE								
0–20 cm	12.9 ^e	7.7 ^b	12.4 ^e	16.7	10.1 ^{cd}	7.6 ^b	7.6 ^b	6.9 ^{ab}
20–40 cm	9.5 ^{cd}	4.3	10.4 ^d	9.3 ^c	9.1 ^c	6.3 ^a	7.3 ^{ab}	6.3 ^a
90 DAE								
0–20 cm	8.4	5.5 ^{cd}	5.7 ^{cde}	7.3 ^g	6.7 ^{efg}	6.1 ^{cdef}	5.5 ^{cd}	7.0 ^{fg}
20–40 cm	6.5 ^{defg}	4.3 ^{ab}	3.4 ^a	6.3 ^{defg}	4.1 ^{ab}	4.3 ^{ab}	4.3 ^{ab}	5.1 ^{bc}

Their population on the 7th DAE ranged from 0.8–2.1 million CFU per 1.0 g of soil in the 0–20 cm layer to 1.3–1.8 million CFU per 1.0 g of soil in the 20–40 cm layer, but the highest values were recorded, reaching 7.6–16.7 million CFU per 1.0 g of soil in the 0–20 cm layer and 4.3–10.4 million CFU per 1.0 g of soil in the 20–40 cm layer on 60th DAE. On the 90th DAE, the phosphate-mobilizing microorganisms showed population levels of 5.5–8.4 million CFU per 1.0 g of soil in the 0–20 cm layer and 3.4–6.5 million CFU per 1.0 g of soil in the 20–40 cm layer.

The application of biopreparations significantly impacts the indicators of soil biological activity and alters soil fertility as a whole (Caballero et al., 2022; García-Martínez et al., 2010; Rodríguez-Morgado et al., 2015). Biostimulants promote plant development, increase microbial activity, and enhance the quantity of specific microorganism groups in the rhizosphere, which in some cases can have a similar effect to seed inoculation with beneficial strains (Mazurenko et al., 2020). Modification of trophic chains and the synthesis of biologically active substances in the rhizosphere mutually benefit plant growth and soil fertility (Honchar et al., 2020). Monitoring the microbiological condition of soil is becoming increasingly relevant in modern conditions due to the growing anthropogenic influence on soil, including intensive agricultural practices (Tonkha et al., 2019; Dudchenko et al., 2021).

The partial replacement of mineral phosphorus with organic fertilizers can alter the soil biota composition, including those involved in the transformation of phosphorus compounds in the soil, thereby effectively managing crop productivity (Bi et al., 2020). It is worth noting that the abundance of microbial populations in the soil is determined not only by seasonal fluctuations in edaphic factors (nutrient content, soil temperature, availability of moisture, etc.) but also by the composition of cultivated agricultural crops (Litvinova et al., 2019b). The addition of insect frass stimulates soil microbial activity, especially when mixed with mineral fertilizer, indicating a synergistic effect between the two fertilizers (Houben et al., 2020).

In other article both types of insect frass and application rates stimulated microbial growth and nitrogen mineralization. For instance, a 3% application rate suppressed seed germination, possibly due to salinity or the toxicity of ammonia (Watson et al., 2021). Avian guano and insect frass were more effective in restoring soil biological fertility, as demonstrated by the increase in active carbon content in the soil and the activity of enzymes involved in nutrient cycling (Cardarelli et al., 2023).

The differences between treatments were less pronounced at the beginning of the vegetation period and on the 90th DAE. The application of Vermicompost had a significant impact on soil biota.

Among the biological products for 90th DAE the highest values for the introduction of Insect Fras (16.7 million CFU per 1.0 g of soil) and Vermikopost (12.4 million CFU per 1.0 g of soil) in the layer of 0–20 cm and 9.3 and 10.4 million CFU per 1.0 g of soil layer of 20–40 cm. Slightly lower values were observed in treatment 5 with compost tea, measuring 10.1 and 9.1 million CFU per 1.0 g of soil. With the application of biochar, the abundance of phosphate-mobilizing microorganisms was lower compared to the control by 67.5% in the 0–20 cm layer and by 121% in the 20–40 cm layer. Therefore, it is recommended to pay special attention to phosphorus nutrition and the content of available phosphates in the soil when using this fertilizer. The results of studies on the effectiveness of biochar are somewhat contradictory. Song et al. (2014)

found that garlic productivity increased with the application of biochar, while Gaskin et al. (2010) did not find a positive impact of biochar on crop yield. It has been established that the indices of bacterial and fungal diversity in the soil were generally higher with biochar treatment (Yang et al., 2021).

The carbon content of soil microbial biomass, respiration, alkaline phosphatase activity, urease activity, and invertase activity were higher with the addition of vermicompost made from grass residues compared to the control. Compared to chemical fertilizers, treatments with vermicompost showed increased soil urease and alkaline phosphatase activity, as well as soil respiration intensity. Moreover, the effectiveness increased with higher doses of vermicompost (Lv et al., 2020).

In the works of I. M. Malinovska (2016), it is stated that the active application of fertilizers leads to an increase in the population of ammonifying, amylolytic, and pedotrophic bacteria. Research by Malinovska et al. (2014) has shown that the application of organic fertilizers along with simultaneous use of mineral fertilizers and liming promotes an increase in the population of microorganisms of the following ecological-trophic groups: ammonifiers - by 11.8%, immobilizers of mineral nitrogen - by 114.6%, oligonitrophiles - by 210.6%, cellulose-degrading - by 10.8%, polysaccharide-synthesizing - by 52.8%, autochthonous - by 52.0%, acid-forming - by 51.7%.

The abundance of oligotrophs is determined by the biological characteristics of this group of microorganisms. It is known that they thrive in nutrient-poor soils. This is due to their trophic specificity and lack of competition, as well as their ability to exist in conditions of limited energy and nutrient sources. Therefore, oligotrophic microorganisms act as indicators of a shortage of readily available nutrients, as they satisfy their trophic needs with minimal amounts of nutrients. Thus, the abundance of oligotrophic microorganisms was highest when Vermicompost was applied. The observed patterns indicate a reduction in readily available nutrient reserves and an enhancement of humification processes (see Table 7).

Table 7. Abundance of oligotrophic microorganisms in pea-barley intercropping, million CFU per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	1.7 ^{de}	1.4 ^{bcd}	8.2	1.4 ^{bcd}	1.7 ^{de}	1.2 ^{ab}	1.6 ^{cde}	1.6 ^{cde}
20–40 cm	1.3 ^{abc}	1.2 ^{ab}	4.7	1.4 ^{bcd}	1.3 ^{abc}	1.0 ^a	1.3 ^{abc}	1.8 ^c
60 DAE								
0–20 cm	4.9 ^j	3.5 ^{efg}	7.3	6.7	2.5 ^{cd}	3.8 ^{gh}	4.7 ^{ij}	5.1 ^j
20–40 cm	3.0 ^{de}	2.2 ^{bc}	5.1 ^j	4.2 ^{hi}	1.3 ^a	1.8 ^{ab}	3.2 ^{ef}	3.7 ^{figh}
90 DAE								
0–20 cm	4.7 ^d	3.2 ^{bc}	3.2 ^{bc}	5.2 ^d	5.6 ^d	5.0 ^d	5.0 ^d	4.7 ^d
20–40 cm	2.9 ^{abc}	2.0 ^a	2.4 ^{ab}	3.5 ^c	3.3 ^{bc}	3.5 ^c	3.4 ^c	3.5 ^c

According to Iutynska (2008), pedotrophic microorganisms are involved in the decomposition of peripheral chains of humic molecules, while humus-degrading microorganisms are responsible for deep degradation. The dynamics of microorganisms are crucial for understanding the diversity and functioning of ecosystems. Based on the obtained results, deterministic processes (homogeneous selection) dominated in the

microbial group at two soil depths during prolonged vegetation succession. It is known that the most favorable conditions for the proliferation and functioning of pedotrophic microorganisms occur in the presence of sufficient organic fertilizers.

It is worth noting that the number of pedotrophic microorganisms on the 7 DAE was minimal in all variants of biostimulant application, except for the variant with the use of vermicompost. During the budding phase (60 DAE), the number of pedotrophic organisms increased, but their quantity significantly decreased, amounting to 2.7–6.1 million CFU per 1.0 g of soil in the 0–20 cm soil layer at 90 DAE (Table 8).

Table 8. Number of pedotrophic microorganisms in pea-barley intercropping, million CFU per 1 g of soil (a – 7 DAE, b – 60 DAE, c – 90 DAE)

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	5.6 ^g	5.4 ^{fg}	16.3 ^h	2.9 ^{abcd}	1.7 ^a	1.7 ^a	4.7 ^{efg}	3.9 ^{cdef}
20–40 cm	3.4 ^{bcde}	3.8 ^{cdef}	17.4 ^h	1.8 ^{ab}	1.8 ^{ab}	2.4 ^{abc}	4.4 ^{defg}	2.8 ^{abcd}
60 DAE								
0–20 cm	9.1 ^g	6.3 ^{ef}	9.1 ^g	8.8 ^g	8.7 ^g	6.9 ^f	5.5 ^{de}	7.2 ^f
20–40 cm	5.7 ^{de}	4.2 ^{bc}	7.3 ^f	4.8 ^{cd}	5.3 ^{de}	3.4 ^{ab}	2.9 ^a	5.8 ^{de}
90 DAE								
0–20 cm	4.8 ^g	2.7 ^{cd}	2.4 ^{bc}	3.9 ^f	6.1 ^h	3.3 ^{def}	3.3 ^{def}	5.5 ^{gh}
20–40 cm	3.6 ^{ef}	1.7 ^{ab}	1.6 ^{ab}	2.6 ^{cd}	4.8 ^g	1.5 ^a	2.8 ^{cde}	3.4 ^{def}

Such patterns in the development of microbiota at the beginning of the vegetative period of the studied crops are associated with changes in soil moisture reserves, the deficiency of which limited their development. The research showed that by the end of the vegetation period of the crops, the decrease in the number of pedotrophic microorganisms was caused by depletion of organic matter content, which serves as a substrate for nutrition and energy.

The highest number of pedotrophic microorganisms, which decompose the peripheral system of humic substances and serve as an available resource for plant nutrition, in the 0–20 cm and 20–40 cm soil layers was obtained with the use of vermicompost (16.3 and 17.4 million CFU per 1.0 g of soil, respectively), which is 16.7 million and 14.0 million CFU per 1.0 g of soil higher compared to the control. Since significant increases in humus-degrading microorganisms were not observed during this period, we can conclude that plants are supplied with "ready-made organic substances" that are available to them and contribute to crop productivity.

Analysis of the dynamics of the number of humus-degrading microorganisms in the soil in pea-barley intercropping showed that the lowest indicators of the number of humus-degrading microorganisms, which participate in the degradation of the nuclear part of humic substances, were obtained on the 7th DAE at the beginning of the vegetation of the studied plants (Table 9).

The number of humus-degrading microorganisms showed the highest values (1.9–8.7 times higher) on 60 DAE compared to the observation at 7 DAE, but subsequently, a decrease in the number of humus-degrading microorganisms was noted by 1.2–1.8 times on the 90th DAE (after harvesting), except for the variants with Biochar and Insect Frass.

Table 9. Dynamics of the number of humus-degrading microorganisms in pea-barley intercropping, million CFU per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	2.6 ^f	2.6 ^f	2.4 ^{def}	1.4	3.2	2.3 ^{cdef}	2.1 ^{abcd}	2.2 ^{bde}
20–40 cm	2.2 ^{bcd}	2.2 ^{bcd}	2.2 ^{bcd}	2.2 ^{bcd}	2.5 ^{ef}	1.8 ^a	1.9 ^{ab}	2.0 ^{abc}
60 DAE								
0–20 cm	10.3 ^d	5.1 ^c	9.6 ^{fg}	9.4 ^f	7 ^e	6.2 ^d	7.1 ^e	6.8 ^{de}
20–40 cm	7.4 ^c	3.6 ^a	6.2 ^d	5.2 ^c	4.5 ^{bc}	4.3 ^{ab}	4.0 ^{ab}	5.1 ^c
90 DAE								
0–20 cm	6.0 ^{gh}	5.7 ^{fg}	5.6 ^{efg}	7.1 ⁱ	7.6 ⁱ	4.8 ^{def}	4.8 ^{def}	6.9 ^{hi}
20–40 cm	4.6 ^{cde}	3.6 ^{abc}	3.1 ^a	4.6 ^{cde}	4.8 ^{def}	3.1 ^a	3.4 ^{ab}	4.2 ^{bcd}

In contrast, the dynamics of the number of micromycetes involved in the synthesis of humic substances showed the opposite trend. Their highest numbers were observed at the beginning of crop vegetation, with sufficient rainfall and moderate solar insolation. An exception was the variant with Insect Frass, where a significant increase in microorganisms was observed in June after the application of the preparations (see Table 10).

Table 10. Dynamics of micromycete population in pea-barley intercropping, thousands per 1.0 g of soil on the 7th, 60th, and 90th day

Soil layer	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	41.9 ^{gh}	54.0 ⁱ	54.7 ⁱ	34.9 ^{defg}	29.4 ^{cd}	27.0 ^{bc}	38.5 ^{efgh}	38.9 ^{fgh}
20–40 cm	33.5 ^{cdef}	44.5 ^h	45.2 ^h	28.4 ^{bcd}	21.1 ^{ab}	19.3 ^a	34.3 ^{cdef}	31.4 ^{cde}
60 DAE								
0–20 cm	36.3 ^{bcd}	31.3 ^{ab}	47.9 ^{ef}	84.8	56.0 ^f	42.8 ^{cde}	47.8 ^{ef}	45.8 ^{def}
20–40 cm	29.1 ^{ab}	24.4 ^a	38.2 ^{bcd}	48.4 ^{ef}	34.1 ^{abc}	34.3 ^{abc}	42.3 ^{cde}	35.6 ^{bcd}
90 DAE								
0–20 cm	16.3 ^{bc}	16.3 ^{bc}	27.7 ^e	77.0	46.0 ^f	53.5 ^g	26.0 ^{de}	27.8 ^e
20–40 cm	10.3 ^{ab}	9.6 ^a	19.2 ^c	52.6 ^g	21.1 ^{cd}	49.3 ^{fg}	21.4 ^{cde}	20.1 ^{cd}

Analysis of the experimental data on the determination of the total number of micromycetes showed that the soil under investigation generally contains a significant quantity of them, ranging from 19.3 to 54.7 thousand CFU per gram of soil. The number of micromycetes was highest on the 7th DAE in plots with vermicompost and biochar, exceeding the control variant by 28.5% to 29.4%. These trends can be explained by the presence of plant residues with a high cellulose content in the soil, which stimulates the activation of fungal microflora development.

Throughout the vegetation period, the number of micromycetes gradually decreased, reaching a minimum at maturity (90 DAE) in all variants except for the application of humus extract. When humus extract was applied, the number of micromycetes at 90 days exceeded the values at 60 days by 15% to 44%. The application of Insect frass significantly increased (by 1.6 to 2.7 times) the number of micromycetes compared to other variants, which could be important for increasing the humus content.

Researchers are attempting to characterize nitrogen immobilization using various methods. According to Y.M. Mishustin, the ratio between the number of microorganisms utilizing mineral forms of nitrogen and those decomposing organic forms of nitrogen is called the mineralization-immobilization coefficient, which can indirectly indicate the intensification of organic matter mineralization. The higher the value of this indicator, the more intensive the transformation of organic matter. The highest mineralization-immobilization coefficient was observed on the 7th DAE in plots with Biochar, and on the 60th DAE when using insect frass extract and compost tea (Table 11). Thus, the best conditions for preserving organic matter in an important period for plants are provided by the use of insect frass ($C_{M-I} = 1.1$) and compost tea ($C_{M-I} = 1.0$).

Table 11. Directionality of microbiological processes in typical chernozem under different variants of biostimulants in the 0–20 cm layer

Sampling day	Microbial indices	Variants (Treatment)							
		T1	T2	T3	T4	T5	T6	T7	T8
7 DAE	C_{M-i}	0.53	0.79	0.35	0.40	0.31	0.28	0.56	0.70
	C_{ol}	0.45	0.44	1.07	0.43	0.41	0.23	0.43	0.24
	C_{ped}	1.48	1.69	2.12	0.88	0.43	0.32	0.89	0.59
60 DAE	C_{M-i}	0.53	0.80	0.65	1.10	1.00	0.85	1.08	0.70
	C_{ol}	0.40	0.32	0.51	0.60	0.43	0.61	0.69	0.77
	C_{ped}	0.73	0.57	0.64	0.78	1.48	1.10	0.80	1.09
90 DAE	C_{M-i}	0.61	0.82	0.68	0.70	0.47	0.64	0.75	0.62
	C_{ol}	0.93	0.97	0.65	1.34	1.17	1.43	1.60	0.90
	C_{ped}	0.95	0.82	0.87	1.00	0.77	1.06	1.10	1.06

The coefficient of pedotrophy indicates the degree of organic matter utilization. The variant with vermicompost had the highest coefficient of pedotrophy on 7 DAE ($C_{ped} = 2.12$). During the vegetation period of the pea-barley intercrop (at 60 DAE), the pedotrophy coefficient decreased across all variants, with the highest value observed in the compost tea treatment ($C_{ped} = 1.48$). The control variant and insect frass promoted the development of autochthonous microbiota and increased mineralization processes from the overall pool, as observed at 90th DAE. Therefore, biostimulants influence the abundance of key physiological groups of microorganisms involved in carbon, nitrogen, phosphorus cycles, and overall microbial biomass.

Research by Symochko & Roshko (2007), Malinovska (2016), Patyka et al. (2018) has demonstrated that plants actively influence the microbiota of agroecosystems primarily through root exudates, and leguminous crops additionally through symbiosis. Plant root exudates serve as an energy source for microorganisms, promoting their development and accumulation in the rhizosphere and rhizoplane. The majority of rhizosphere bacteria are heterotrophs, relying on readily available organic compounds such as carbohydrates and amino acids. Hrynyk et al. (2011) in their research have shown that the availability of organic matter in soil has a stronger influence on microbial development than soil type.

The composition of soil microbiota depends on the content of organic matter and the type and rates of fertilizers applied, as microorganisms capable of effectively utilizing specific nutrients are localized accordingly (Balaev et al., 2019; Shi et al., 2023).

Studies conducted by Aislabie et al. (2013) suggest that labile organic matter in the soil is readily utilized by microbial communities in the process of mineralization and typically indicate changes in early soil carbon stocks. These results indicate that long-term vegetation succession increases the complexity and stability of microbial networks and that microbial communities are mainly associated with labile organic carbon (OC) (Litvinova et al., 2019a; Balaev et al., 2019). Research by Jiao et al. (2022) has demonstrated that labile organic carbon, being an energy source for microorganisms, influences the taxonomic structure of microbial communities based on its content.

The mobile forms of humus play an important role in soil formation and fertility, as they actively participate in many soil processes. As a result of complex biochemical transformations in the soil complex, thermodynamically most stable structures with a common principle of construction accumulate. The heterogeneity of the entire system of humic substances is a characteristic feature, resulting in variations in physicochemical properties (Kanivets, 2001; Swaminathan et al., 2021). Firstly, they serve as the starting material for the formation of all groups of stable humic substances, activate the mobilization of nutrients, and enhance their migratory ability. Therefore, it was important to establish the impact of the investigated biostimulants on the water-soluble organic matter of chernozem soils. Table 12 shows the content of mobile (labile) organic matter depending on the application of different types of biostimulants.

Table 12. Labile organic matter (C) with the application of different biostimulants, % by DSTU 4732:2007 method

Sampling day	Variants (Treatment)							
	T1	T2	T3	T4	T5	T6	T7	T8
7 DAE								
0–20 cm	0.040 ^a	0.106 ^a	0.179 ^a	0.038 ^d	0.037 ^c	0.037 ^{bc}	0.041 ^{cd}	0.038 ^c
20–40 cm	0.034 ^{ab}	0.063 ^d	0.106 ^c	0.036 ^d	0.036 ^c	0.031 ^{cd}	0.036 ^d	0.042 ^{de}
60 DAE								
0–20 cm	0.030 ^{bc}	0.096 ^b	0.117 ^b	0.098 ^a	0.125 ^a	0.046 ^a	0.118 ^a	0.098 ^a
20–40 cm	0.027 ^{bc}	0.083 ^c	0.073 ^d	0.060 ^c	0.104 ^b	0.028 ^d	0.120 ^a	0.086 ^b
90 DAE								
0–20 cm	0.026 ^c	0.051 ^c	0.054 ^c	0.070 ^b	0.086 ^c	0.046 ^a	0.052 ^b	0.046 ^{cd}
20–40 cm	0.024 ^c	0.046 ^c	0.051 ^c	0.055 ^c	0.075 ^d	0.039 ^{ab}	0.048 ^{bc}	0.051 ^c

Note: the same letters indicate variants within the same similarity group (a – the lowest value, followed by increasing values) separately within each sampling set (7, 60, 90 DAE).

The highest amount of labile organic matter accumulates in the 0–20 cm soil layer. It was established that on the 7th day after emergence, the highest content of labile organic substances was on the plots with Fish hydrolysate and Humus extract and was 0.194 and 0.180% in the 0–20 cm layer and 0.118 and 0.099% in the 20–40 cm layer. On the 60th day after emergence, the highest values of the content of labile organic substances were on the plots with of Insect Frast and Humus Extract in 0–20 cm - 0.443 and 0.422%. On the 90th day after emergence, the indicators were 0.142–0.703% in the 0–20 cm layer and 0.186–0.403% in the 20–40 cm layer according to different variants of the experiment. It should be noted that the highest content of labile organic substances was for the application of Compost tea in the 0–20 cm layer - 0.703%, the lowest – for the application of Fish hydrolysate and Yara Vita: 0.144 and 0.142% in the 20–40 cm layer.

Table 13. Dynamics of nitrate form nitrogen (N-NO₃⁻), ammonium form nitrogen (N-NH₄⁺), mineral nitrogen (N_{min}) in typical chernozem under different variants of biostimulants in the 0–20 cm layer, mg × kg⁻¹ of soil

Variants (Treatment)	N-NO ₃ ⁻			N-NH ₄ ⁺			N _{min}		
	7	60	90	7	60	90	7	60	90
T1	4.7	8.4	11.5	15.6	13.7	10.9	20.3	22.1	22.4
T2	7.8	8.8	8.1	17.4	16.8	12.2	25.2	25.6	20.3
T3	11.5	9.7	7.8	24.7	19.8	14.6	36.2	29.5	22.4
T4	6.3	7.6	6.3	16.3	12.8	8.3	22.6	20.4	14.6
T5	4.6	5.9	6.5	15.7	15.1	14.4	20.3	21.0	20.9
T6	4.8	6.3	9.7	15.1	14.8	14.8	19.9	21.1	24.5
T7	4.8	7.1	8.6	16.0	15.7	14.8	20.8	22.8	23.4
T8	8.6	7.7	8.1	17.8	16.7	15.1	26.4	24.4	25.9

The content of nitrate form nitrogen was 4.6–11.5 on the 7th DAE, 5.9–9.7 on the 60th DAE and 6.3–11.5 mg × kg⁻¹ on the 90th DAE in the typical chernozem layer; the content of ammonium form nitrogen was higher and was 15.1–24.7, 12.8–19.8 and 8.3–15.1 mg × kg⁻¹ on the 7th, 60th, and 90th DAE. At the beginning of the growing season on the 7th and 60th DAE, the highest content of N-NO₃⁻ and N-NH₄⁺ was on the plots with Vermicompost, the lowest content of nitrate form nitrogen at these times of soil sampling were on the plots with Compost tea and Humus extract. On the 90th DAE, the highest content of nitrate form nitrogen was found in the Control, while ammonium form nitrogen was found in the plots with Seaweed extract, and the lowest nitrate form nitrogen content was on the plots with Insect frass and Humus extract, the ammonium form nitrogen content was also found on the plots Insect frass, which may indicate some fixation of mineral nitrogen with the use of this biological preparation. In general, characterizing the mineral nitrogen content, which was calculated as the sum of nitrate and ammonium nitrogen, it was found that on the 7th DAE, the plots did not differ significantly, except for the Vermicompost variant, where the indicator was 36.2 mg × kg⁻¹ of soil in the 0–20 cm layer of typical chernozem, and the lowest content was in the Control and plots with Compost tea (20.3 mg × kg⁻¹). On the 60th DAE, the highest mineral nitrogen (29.5 mg × kg⁻¹) was also found on the plots with Vermicompost, the lowest – on the plots with Insect frass (20.4 mg × kg⁻¹). On the 90th DAE, it should be noted that the mineral nitrogen content was significantly lower on the plots with Insect frass – 14.6 mg × kg⁻¹, and the highest on the plots with the Seaweed extract. Thus, biological products affect the indicators of the nitrogen regime of chernozem typical for intercropping and have their features during the growing season.

The results of the correlation analysis (Fig. 3) indicate significant relationships between the parameters of soil's properties, indicators of microbial activity (particularly humus-degraders and total microbial biomass), and crop productivity. The analysis focused on two key time points that exhibited the highest microbial activity- 60 and 90 days after emergence (DAE).

The strongest positive correlations were observed between the abundance of humus-degrading microbes in the upper soil layer and microbial biomass at different growth stages: HM_60_0 ↔ Biomass_60_0 ($r = 0.89$) and HM_90_0 ↔ Biomass_90_0 ($r = 0.86$). This highlights the pivotal role of these functional microbial groups in sustaining the rhizosphere's trophic potential, especially during early ontogenetic

phases. A high level of microbial biomass in the upper horizon is also associated with optimal soil physical characteristics e.g., PM_90_0 ↔ Biomass_90_0 ($r = 0.97$) confirming the synergistic effect of soil structure on bioactivity and productivity.

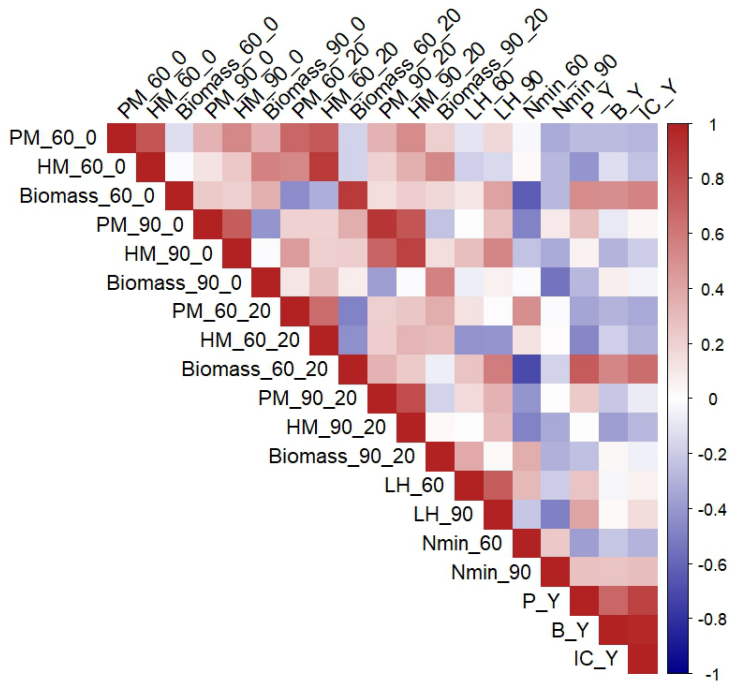


Figure 3. Correlation matrix of the interactions among key soil microbiological process indicators under pea-barley intercropping and their relationship with grain yield.

Note: PM – Pedotrophic microorganisms; HM – Microorganisms decomposing humates; Biomass – microbiota biomass; _60_ and _90_ – day of sampling, 0 – soil layer 0–20 cm; 20 – soil layer 20–40 cm, LH – labil organic matter, Nmin – mineral nitrogen, P_Y – pea yield, B_Y – barley yield, IC_Y – intercropping yield.

The microbial activity indicators, like humus-degraders (HM), pedotrophs (PM), and total microbial biomass (Biomass) showed strong within-layer, within-period correlations ($r = 0.75$ – 0.88), indicating trophic and functional integration of the biocenosis in the root zone. In contrast, the same indicators measured in the upper and subsurface horizons displayed weaker correlations ($r = 0.34$ – 0.53), pointing to a vertical stratification of microbial niches.

Across crop growth stages (60 and 90 DAE), stable relationships persisted within individual groups: notably HM_60_0 ↔ HM_90_0 ($r = 0.70$) and PM_60_0 ↔ PM_90_0 ($r = 0.77$), underscoring the consistency of the microbial profile in the surface layer. At the same time, a noticeable negative correlation between Biomass_60_0 and PM_60_20 ($r \approx -0.45$) suggests the presence of stressful or competitive conditions in the subsurface layer for microbiota dependent on root exudates.

The strongest positive associations between microbial indicators and yield were recorded at 90 DAE in the 0–20 cm layer: HM ↔ intercrop yield ($r \approx 0.34$), PM ↔ intercrop yield ($r \approx 0.29$), and Biomass ↔ intercrop yield ($r \approx 0.28$). These results are

consistent with Monsalud et al. (2021), who conclude that soil microbial diversity increases with increased crop productivity and higher nitrogen cycling rates. Microbial biomass at day 60 – Biomass_60_0 ($r = 0.55$) and Biomass_60_20 ($r = 0.65$) – also correlated with yield, although these links weakened at later stages, suggesting the influence of other abiotic and biotic factors.

By contrast, in the subsurface layer (20–40 cm), negative correlations were observed, indicating environmentally limiting conditions. Specifically, HM_60_20 and HM_90_20 exhibited inverse relationships with labile humus in the upper layer at 60 and 90 days, respectively ($r = -0.42$ and -0.37), pointing to premature mineralization of organic carbon. Likewise, PM_60_20 $\leftrightarrow$ intercrop yield ($r = -0.33$) implies an unfavorable effect of this layer's physical properties on agronomic performance. Most notably, the HM_60_20 $\leftrightarrow$ barley yield correlation ($r = -0.47$) underscores that active mineralization in the subsurface layer does not translate to higher yields because resource availability to the root system is limited.

The rhizosphere's microbiological indicators in the upper horizon (0–20 cm,) especially at 90 DAE, possess the greatest prognostic value for yield. Cusset et al. (2024) also conclude that soil microbial activity indicators are the most informative in assessing the impact of crop rotation and organic practices. In many cases, biological activity in the subsurface layer serves as an indicator of stress or degradation processes. The obtained data are consistent with the conclusions of Singh & Wang (2024) on the interaction between soil microorganisms, soil physicochemical properties and crop productivity. These findings justify a zonal-stratified approach to monitoring soil microbial status in agro-ecological studies.

Overall, the matrix underscores that the spatio-temporal distribution of microbial activity, particularly its intensification near roots during grain filling. This phenomenon explains yield gains in pea-barley intercrops more effectively than microbiota indicators from the 20–40 cm soil layer.

CONCLUSIONS

A comprehensive study of microbial communities in intercrops of peas and barley in typical chernozem soil with the use of biostimulants showed that the population of the main groups of microorganisms was the lowest at 7th DAE, and the highest at the 60th DAE. The highest content of most groups of microorganisms, with the exception of humate-decomposers, was most affected by the application of Frast insects in the amount of 50 L ha⁻¹ on the 30th and 60th days of vegetation and Vermicompost in the amount of 2.5 t ha⁻¹ before sowing. The highest number of pedotrophic microorganisms, which decompose the peripheral system of humic substances and provide plant nutrition, was when using Vermicompost with indicators from 16.3 to 17.4 million CFU in the dry mass of the soil. The lowest indicators of humate-destroying microorganisms, which participate in the degradation of the nuclear part of humic substances, were observed in the control and after applying 2.5 t ha⁻¹ of Biochar. The pedotrophic coefficient, which indicates the degree of use of organic matter, was the highest on the Vermicompost option ($C_{\text{ped}} = 2.12$) on the 7th day after emergence, and on the 60th DAE the highest values were observed when using Compost tea ($C_{\text{ped}} = 1.48$). The best conditions for the preservation of soil organic matter were formed when Insect Frast and Compost tea were

applied on the 30th and 60th days of the growing season, since the immobilization–mineralization coefficient was more than 1 on these variants of the experiment. The content of labile humic substances was also the highest when Compost tea was applied, Vermicompost and Insect Fras. Thus, the use of biopreparations on joint crops of peas and barley caused a significant impact on the microbiological activity of the soil and the content of labile organic substances.

ACKNOWLEDGEMENTS. This study was conducted as part of the ECOTWINS (Research Capacity Building and Upskilling and Upgrading the Research Team in NUBiP (Ukraine) on Agroecological Intensification for Crop Production) project. ECOTWINS has received funding from the Horizon Europe Framework Programme (HORIZON) under the grant agreement №101079308.

Special thanks to the FOREL team for providing fish hydrolysate ®Peptostart, produced by the Research and Production Centre "Forel," UA, for conducting the research.

REFERENCES

- Aislabie, J.A., Deslippe, J. & Dymond, J. 2013. Soil microbes and their contribution to soil services. In: Dymond J.R. (Ed.), *Ecosystem services in New Zealand – conditions and trends*. Manaaki Whenua Press, New Zealand, 143–161.
- Angulo, J., Ortega, R., Martínez, M.M., Molina, M. & Torres A. 2014. Evaluation of solid and liquid soil organic amendments for agronomic use in Chile. *Acta Horticulturae* **1018**, 109–114. <https://doi.org/10.17660/ActaHortic.2014.1018.8>
- Bagyaraj, D.J. & Ashwin, R. 2024. Soil microbiota and their role in sustainable agriculture: A review. *Journal of Soil Biology and Ecology* **44**(2), 92–100 (in Ukrainian).
- Balaev, A., Pikovska, O. & Tonkha, O.L. 2019. Humus content and labile organic matter under different uses of typical chernozem. *Naukovyi visnyk NUBiP Ukrainy* **286**, 173–179 (in Ukrainian).
- Bali, R., Pineault, J., Chagnon, P.L. & Hijri, M. 2021. Fresh compost tea application does not change rhizosphere soil bacterial community structure and has no effects on soybean growth or yield. *Plants* **10**(8), 1638. <https://doi.org/10.3390/plants10081638>
- Barragán-Fonseca, K.Y., Nurfikari, A., Van de Zande, E.M., Wantulla, M., Van Loon, J.J.A., De Boer, W. & Dicke, M. 2022. Insect frass and exuviae to promote plant growth and health. *Trends in Plant Science* **27**(7), 646–654. <https://doi.org/10.1016/j.tplants.2022.01.007>
- Bi, Q.F., Li, K.J., Zheng, B.X., Liu, X.P., Li, H.Z., Jin, B.J. & Zhu, Y.G. 2020. Partial replacement of inorganic phosphorus by organic manure reshapes phosphate–mobilizing bacterial community and promotes P bioavailability in paddy soil. *Science of the Total Environment* **703**, 134977. <https://doi.org/10.1016/j.scitotenv.2019.134977>
- Bulygin, S., Kucher, L., Panchuk, T., Kava, L., Moroz, S., Havryliuk, O., Yevchenko, O., Honchar, M., Retman, M. & Melnychuk, F. 2025. The effectiveness of agrotechnical anti-erosion measures on sloping soils in the conditions of the forest-steppe of Ukraine. *Journal of Ecological Engineering* **26**(8), 174–186. <https://doi.org/10.12911/22998993/203963>
- Caballero, P., Macías-Benítez, S., Moya, A., Rodríguez-Morgado, B., Martín, L., Tejada, M. & Parrado, J. 2022. Biochemical and microbiological soil effects of a biostimulant based on *Bacillus licheniformis*-fermented sludge. *Agronomy* **12**(8), 1743. <https://doi.org/10.3390/agronomy12081743>
- Cardarelli, M., El Chami, A., Iovieno, P., Rouphael, Y., Bonini, P. & Colla, G. 2023. Organic fertilizer sources distinctly modulate productivity, quality, mineral composition and soil enzyme activity of greenhouse lettuce grown in degraded soil. *Agronomy* **13**(1), 194. <https://doi.org/10.3390/agronomy13010194>

- Chavez, M. & Uchanski, M. 2021. Insect leftover substrate as plant fertiliser. *Journal of Insects as Food and Feed* 7(5), 683–694. <https://doi.org/10.3920/JIFF2020.0063>
- Dehodiuk, S., Davydiuk, H., Klymenko, I., Butenko, A., Litvinova, O., Tonkha, O., Havryliuk, O. & Litvinov, D. 2024. Agroecological monitoring of water ecosystems and soils in the basin of a small river under the influence of anthropogenic factors. *Agriculture and Forestry* 70(4), 109–135. <https://doi.org/10.17707/AgricultForest.70.4.09>
- Demyanyuk, O.S., Symochko, L.Yu. & Tertychna, O.V. 2017. Modern methodological approaches to assessing the ecological state of soil based on microbiocenosis activity. *Issues of Bioindication and Ecology* 22(1), 55–68 (in Ukrainian).
- Dewang, S.P. & Devi, C.U. 2021. Influence of soil application of fish–protein hydrolysate on growth and yield of spinach (*Spinacia oleracea* L.). *Asian Journal of Dairy and Food Research* 40(1), 69–75. <https://doi.org/10.18805/ajdfr.DR-1544>
- DSTU 4732:2007. 2008. Soil quality. Methods for determining available (labile) organic matter. Kyiv: Derzhspozhivstandard of Ukraine (in Ukrainian).
- DSTU ISO 10381–2:2004 (ISO 10381–2:2002, IDT). Soil quality. Sampling. Part 2: Guidance on sampling techniques (in Ukrainian).
- Dudchenko, V.V., Markovska, O.Ye. & Sidiyakina, O.V. 2021. Effectiveness of a biodestructor in decomposing post–harvest rice residues in soybean cultivation technology. *Cereal Crops* 5(2), 374–382. <https://doi.org/10.31867/2523-4544/0198>
- Cusset, E., Bennegadi-Laurent, N., Recous, S., Bernard, P.Y., Perrin, A.S., Tscheiller, R., Trinsoutrot-Gattin, I. & Riah-Anglet, W. 2024. Which soil microbial indicators should be included in routine laboratory tests to support the transition to sustainable management of arable farming systems? A meta-analysis. *Ecological Indicators* 167, 112706. <https://doi.org/10.1016/j.ecolind.2024.112706>
- FAO. 1997. *FAO–UNESCO Soil Map of the World: Revised legend with corrections and updates*.
- García–Martínez, A.M., Díaz, A., Tejada, M., Bautista, J., Rodríguez, B., Santa María, C. & Parrado, J. 2010. Enzymatic production of an organic soil biostimulant from wheat-condensed distiller solubles: effects on soil biochemistry and biodiversity. *Process Biochemistry* 45(7), 1127–1133. <https://doi.org/10.1016/j.procbio.2010.04.005>
- Gaskin, J.W., Speir, R.A., Harris, K., Das, K.C., Lee, R.D., Morris, L.A. & Fisher, D.S. 2010. Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status and yield. *Agronomy Journal* 102(2), 623–633. <https://doi.org/10.2134/agronj2009.0083>
- Honchar, L., Mazurenko, B., Sonko, R., Kyrpa–Nesmiian, T., Kovalenko, R. & Kalenska, S. 2020. Biochemical responses of buckwheat cultivars to seed treatment with *Azospirillum brasilense*. *Agronomy Research* 18(S3), 1680–1688. <https://doi.org/10.15159/AR.20.080>
- Houben, D., Daoulas, G., Faucon, M.P. & Dulaurent, A.M. 2020. Potential use of mealworm frass as fertilizer: impact on crop growth and soil properties. *Scientific Reports* 10, 4659. <https://doi.org/10.1038/s41598-020-61765-x>
- Hrynyk, I.V., Patyka, V.P. & Shykula, Yu.M. 2011. Microbiological basis of improving yield and quality of crops. *Bulletin of Poltava State Agrarian Academy* 4, 7–10 (in Ukrainian).
- Hubachov, O.I. 2010. Use of plants for soil biotesting to determine environmental safety of industrial areas. *Scientific Bulletin of KUEIT. New Technologies* 29(3), 164–171 (in Ukrainian).
- Iutynska, H.O. 2008. Regulation of soil microbial community functions under biologization of agriculture. *Microbiological Journal* 1, 7–18 (in Ukrainian).
- Jiao, S., Chen, W. & Wei, G. 2022. Core microbiota drive functional stability of soil microbiome in reforestation ecosystems. *Global Change Biology* 28(3), 1038–1047. <https://doi.org/10.1111/gcb.16024>
- Kanivets, V.I. 2001. *Soil life*. Kyiv: Ahrarna nauka, 132 pp. (in Ukrainian).

- Kansotia, B.C., Sharma, Y. & Meena, R.S. 2016. Effect of vermicompost and inorganic fertilizers on soil properties and yield of Indian mustard. *Journal of Oilseed Brassica* **1**(1), 198–201.
- Khomenko, T., Tonkha, O. & Pikovska, O. 2023. Humus and nitrogen content of sod–podzolic soil under the influence of biopreparations for potato cultivation. *Plant and Soil Science* **14**(1), 82–95. <https://doi.org/10.31548/plant1.2023.82>
- Kim, M.J., Shim, C.K., Kim, Y.K., Hong, S.J., Park, J.H., Han, E.J. & Kim, S.C. 2015. Effect of aerated compost tea on growth promotion in organic cultivation. *Plant Pathology Journal* **31**(3), 259. <https://doi.org/10.5423/PPJ.OA.02.2015.0024>
- Litvinova, O., Litvinov, D., Romanova, S. & Kovalyova, S. 2019. Soil biological activity under anthropogenic impact in farmed ecosystems. *International Journal of Ecosystems and Ecology Science* **9**(3), 529–536. <https://doi.org/10.31407/ijees9316>
- Litvinova, O.A., Litvinov, D.V. & Bodnar, Yu.D. 2019. Labile organic matter in typical chernozem depending on winter wheat cultivation technology. *Plant and Soil Science* **10**(1), 48–53.
- Lv, M., Li, J., Zhang, W., Zhou, B., Dai, J. & Zhang, C. 2020. Microbial activity in soils amended with vermicompost. *Soil Ecology Letters* **2**, 209–219. <https://doi.org/10.1007/s42832-020-0034-6>
- Madende, M. & Hayes, M. 2020. Fish by–products as biostimulants: current state and legislation. *Molecules* **25**(5), 1122. <https://doi.org/10.3390/molecules25051122>
- Malinovska, I.M. 2012. Direction of microbiological processes in dark–gray podzolic soil under soybean cultivation technologies. *Problems of Environmental Biotechnology* **14**, 77–90 (in Ukrainian).
- Malinovska, I.M. 2016. Influence of crop type on abundance and physiological activity of rhizosphere microorganisms. *Silskogospodarska mikrobiologiya* **24**, 22–28 (in Ukrainian).
- Malinovska, I.M. & Litvinov, D.V. 2012. Microbiological processes in the root zone of pea and winter wheat under monoculture and crop rotation. *Silskogospodarska mikrobiologiya* **14**, 77–90 (in Ukrainian).
- Malinovska, I.M. & Litvinov, D.V. 2013. Influence of monoculture cultivation on microbiological processes in the root zone of maize and soybean. *Soil Science* **14**(1–2), 49–60 (in Ukrainian).
- Malinovska, I.M., Tkachenko, M.A., Sachok, V.H. & Skumina, M.O. 2014. Influence of agronomic measures on microbial communities of gray forest soil. *Problems of Environmental Biotechnology* **1**, 22–28 (in Ukrainian).
- Maroulis, M., Matsia, S., Lazopoulos, G., Pârvulescu, O.C., Ion, V.A., Bujor, O.C. & Salifoglou, A. 2023. Chemical and biological profiling of fish and seaweed residues for plant fertilization. *Agronomy* **13**(9), 2258. <https://doi.org/10.3390/agronomy13092258>
- Monsalud, R.G., Arguelles, E.D., Brown, M.B., Pedro, M.S., Nepomuceno, R.A., Villadiego, S.A.D. & Monsalud, F.C. 2021. Relationship between microbial soil quality indicators and soil productivity under cassava-based farming systems in various sites in the Philippines. *Journal Article*. 5245. <https://www.ukdr.uplb.edu.ph/journal-articles/5245>
- Mazurenko, B., Novytska, N. & Honchar, L. 2020. Response of triticale to microbial preparations under different nitrogen nutrition. *Journal of Central European Agriculture* **21**(4), 763–774.
- Naidu, Y., Meon, S. & Siddiqui, Y. 2013. Foliar application of microbial–enriched compost tea enhances growth, yield and quality of muskmelon. *Scientia Horticulturae* **159**, 33–40. <https://doi.org/10.1016/j.scienta.2013.04.024>
- Pane, C., Palese, A.M., Celano, G. & Zaccardelli, M. 2014. Compost tea effects on productivity of lettuce and kohlrabi under organic management. *Italian Journal of Agronomy* **9**(3), 153–156.

- Pant, A.P., Radovich, T.J.K., Hue, N.V. & Paull, R.E. 2012. Biochemical properties of compost tea associated with compost quality and plant growth. *Scientia Horticulturae* **148**, 138–146. <https://doi.org/10.1016/j.scienta.2012.09.019>
- Pathma, J. & Sakthivel, N. 2012. Microbial diversity of vermicompost bacteria with agricultural potential. *SpringerPlus* **1**, 1–19.
- Patyka, M.V., Tonkha, O.L., Patyka, T.I., Kiroiants, M.O. & Veretyuk, S.V. 2018. Assessment of the prokaryotic metagenome of chernozem under agricultural use. *Microbiological Journal* **80**(6), 109–122 (in Ukrainian).
- Pavlichenko, A., Dmytrenko, O., Litvinova, O., Kovalova, S., Litvinov, D. & Havryliuk, O. 2023. Changes in gray forest soil organic matter pools under anthropogenic load in agroecosystems. *Agronomy research* **21**(3), 1266–1277. <https://doi.org/10.15159/AR.23.095>
- Regulation (EU) 2019/1009. 2019. Laying down rules on the making available on the market of EU fertilising products. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R1009>
- Rodríguez-Morgado, B., Gómez, I., Parrado, J., García-Martínez, A.M., Aragón, C. & Tejada, M. 2015. Edaphic biostimulants obtained from sewage sludge: effects on soil biological properties. *Environmental Technology* **36**(17), 2217–2226. <https://doi.org/10.1080/09593330.2015.1024760>
- Shi, J., Yang, L., Liao, Y., Li, J., Jiao, S., Shangguan, Z. & Deng, L. 2023. Labile organic carbon fractions mediate microbial community assembly during vegetation succession. *iMeta* **2**(4), e142.
- Singh, B. & Wang, J. 2024. Incorporating microbial metrics improves soil health and yield predictions. *Available at SSRN, 4911705*. <http://dx.doi.org/10.2139/ssrn.4911705>
- Song, X.D., Xue, X.Y., Chen, D.Z., He, P.J. & Dai, X.H. 2014. Application of sewage sludge biochar: effects on yield and heavy metal accumulation. *Chemosphere* **109**, 213–220. <https://doi.org/10.1016/j.chemosphere.2014.01.070>
- Swaminathan, C., Nivethadevi, P. & Pandian, K. 2021. Soil organic matter decomposition: roles and mechanisms. In: Porte S.S. (Ed.), *Latest Trends in Soil Sciences*, Vol. 1. Integrated Publishers, New Delhi, 61–91.
- Symochko, L. & Roshko, V. 2007. Influence of electromagnetic field on microbial soil cenosis. In: *Proceedings of the International Scientific Conference “Modern Problems of Microbiology and Biotechnology”*, 28–31 (in Ukrainian).
- Tonkha, O., Pikovska, O., Balaev, A., Kovalyshyna, G., Zavgorodniy, V. & Kovalenko, V. 2019. Monitoring of microbiological condition of virgin chernozem under different management. In: *Monitoring 2019*. European Association of Geoscientists & Engineers. <https://doi.org/10.3997/2214-4609.201903256>
- Uz, I., Sönmez, S., Tavali, I.E., Çitak, S., Uras, D.S. & Çitak, S.O. 2016. Vermicompost effects on chemical and biological properties of alkaline soil. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **44**, 280–290.
- Watson, C., Preißing, T. & Wichern, F. 2021. Plant nitrogen uptake from insect frass affected by nitrification rate. *Frontiers in Sustainable Food Systems* **5**, 721840. <https://doi.org/10.3389/fsufs.2021.721840>
- Yang, W., Li, C., Wang, S., Zhou, B., Mao, Y., Rensing, C. & Xing, S. 2021. Influence of biochar-based fertilizer on tea yield and soil microbial community. *Applied Soil Ecology* **166**, 104005. <https://doi.org/10.1016/j.apsoil.2021.104005>
- Zvyagintsev, D.G. 1978. Biological activity of soils and scales for assessing its indicators. *Soil Science* **6**, 48–54 (in Ukrainian).