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# The formation of the microbial community in acidic sod-podzolic soil within the maize rhizosphere under the integrated application of fertilisers and soil amendments

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**Abstract.** This study investigated the effect of the combined application of soil amendments and fertilisers on the formation and functioning of the microbial community in the maize rhizosphere under sod-podzolic soil conditions. The aim was to determine how the integrated application of fertilisers and soil amendments affects the structural and functional characteristics of the microbiocenosis of sod-podzolic soil in the maize rhizosphere and to identify microbiological indicators for the ecological bioindication of the agrocenosis. Field studies were conducted in 2025 in a long-term experiment at the Institute of Agriculture of Western Polissia, NAAS of Ukraine. The experiment comprised eight treatments combining the residual effect of liming with dolomite flour or limestone and differentiated

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mineral fertilisation with two foliar applications of a micronutrient fertiliser. The abundance of ecological-trophic groups of microorganisms was determined by plating on selective agar media, microbial biomass by the rehydration method, and $CO_2$ emission by the adsorption method. Soil pH increased from 4.09 to 5.48-6.20, while hydrolytic acidity decreased 2.1- and 2.9-fold. The abundance of ammonifiers increased 2.9- and 3.8-fold and reached 27.61 million CFU/g soil. When dolomite flour was combined with fertilisers, the abundance of micromycetes decreased 2.1-fold to 28.80 thousand CFU/g soil. The greatest change was recorded for oligonitrophiles, whose abundance decreased 7.7-fold. Microbial biomass increased to 128.95 µg C/g soil, $CO_2$ emission fell to 14.2 mg/kg per day, and the metabolic quotient decreased from 183.8 to 111.1 mg $CO_2$ per 1 g of biomass carbon. The microbial community shifted from a fungal-oligotrophic to a bacterial-eutrophic type, with an oligotrophy coefficient of 0.08-0.15 and a mineralisation coefficient of 0.14-0.24. Hydrolytic acidity was the leading regulator of this transition ($r = 0.92$ and 0.96). The practical value of the work lies in substantiating the abundance of oligonitrophiles as a bioindicator of nitrogen saturation in maize agrocenoses and in demonstrating the advantage of a magnesium-containing amendment for controlling the fungal microbiota of acidic Polissia soils

**Keywords:** soil microbiome; taxonomic structure; bioindication; microbial biomass; oligonitrophiles

## INTRODUCTION

Soil is a living system, not merely a substrate for plant growth. Its functioning is determined by the activity of the microbial community, which ensures the cycling of carbon, nitrogen, phosphorus and sulphur, shapes soil structure, regulates the availability of nutrients and controls the population of plant pathogens. This is precisely why the study of microbiological indicators is of particular relevance: they enable the rapid assessment of soil condition, the detection of degradation processes at an early stage, and the justification of measures to restore soil health in the context of intensive agriculture and climate change.

J. Lehmann *et al*. (2020) define the concept of soil health as the soil's ability to function as a living ecosystem that supports plants, animals and humans. M. Hartmann & J. Six (2023) consider soil structure and the functions of the microbiome in agroecosystems as a single, interconnected system. N. Fierer *et al*. (2021) emphasise a substantial advantage of microbiological indicators over physical and chemical ones: they respond to changing conditions much more rapidly. Changes in soil organic carbon become detectable only after decades, whereas the abundance and activity of microorganisms can shift within a single growing season, which makes the microbiota a convenient tool for early diagnosis. O.S. Demyanyuk *et al*. (2020) substantiate this approach specifically for Ukrainian agroecosystems in the context of adapting agriculture to climate change. At the same time, A. Levishko *et al*. (2026) caution that microbiological indicators should be interpreted carefully because of the high functional redundancy of soil communities. The relevance of this topic stems from the ecological condition of the sod-podzolic soils of the Western Polissia region of Ukraine, where acidity acts as a powerful ecological filter and exerts selective pressure on microbial communities. At low pH values, acidophilic microfungi predominate, whilst the bacterial component is suppressed. Y. Duan *et al*. (2025) demonstrate that soil acidification destabilises terrestrial ecosystems by disrupting interactions within the microbiome. G. Agegnehu *et al*. (2021) further highlight mobile forms of aluminium and manganese as significant stress factors, the effects of which result in a reduction in functional diversity and a weakening of the soil's natural regulatory capacity. Q. Liu *et al*. (2025) found that it is precisely at pH values below 5.5 in soils that phytopathogenic fungi become dominant, whilst saprotrophs predominate under slightly acidic conditions.

Maize is a suitable model organism for studying such processes, as its root system forms a robust rhizosphere characterised by the intensive secretion of root exudates, which determine the composition of rhizosphere communities and nourish copiotrophic bacteria. S. Dlamini *et al*. (2023) found that the maize rhizosphere is capable of actively reshaping the diversity and structure of the microbiome to maintain plant health. The influence of environmental, edaphic and biotic factors depends on plant growth and development processes; however, hybrids and cultivation techniques play a dominant role. Unlike legumes, maize lacks its own symbiotic source of nitrogen and is therefore grown using high doses of mineral nitrogen. M. Tosi *et al.* (2021) found that prolonged nitrogen loading alters microbial communities more significantly than a single fertiliser application during the study year. T. Meng *et al.* (2024) found that as nitrogen rates increase, bacterial diversity initially rises and then declines. D. Bebber & V. Richards (2022) demonstrated that elevated nitrogen rates inhibit biological nitrogen fixation and disrupt the stability of microbial networks. Liming is an effective measure for the ecological restoration of acidic soils, as it reduces acid stress, alters the ratio of bacterial and fungal communities, and influences the course of biogeochemical processes. At the same time, its effectiveness may depend on the soil solution's pH, which largely determines the ability of microorganisms to utilise carbon. Y. Yu *et al.* (2024) note that the integration of soil improvement and mineral nutrition creates a multi-component system of interactions that requires targeted research. For the acidic soils of Polissia, quantitative characteristics of the microbiological response of the maize rhizosphere remain poorly studied. V. Polovyi *et al.* (2023) focused mainly on the carbon balance of the agrocenosis, whereas A. Levishko *et al.* (2026) analysed the microbiocenosis of leguminous crops. K. Shemetun *et al.* (2022) reported selected microbiological assessments of sod-podzolic soils under elements of farming biologisation. The methodological basis of the present study was the ecological-trophic group approach proposed by K.I. Andreyuk *et al.* (2001). As noted by A. Levishko *et al.* (2026), this approach makes it possible to describe the trophic structure of the community and the direction of organic matter transformation.

Thus, the aim of this study was to assess the impact of the integrated application of fertilisers and soil amendments on the structure and functional activity of the microbiocenosis of sod-podzolic soil in the maize rhizosphere, and to identify microbiological indicators for the ecological bioindication of this agrocenosis.

## MATERIALS AND METHODS

The study was conducted in a long-term field experiment at the Institute of Agriculture of Western Polissia of the National Academy of Agrarian Sciences of Ukraine (Rivne Region, Rivne District, Shubkiv village). The experiment was established in 2020 on a sod-podzolic loamy-sandy soil. The initial soil solution pH was 4.09, and hydrolytic acidity was 2.29 mmol per 100 g of soil. The preceding crop was sunflower. The experimental design comprised eight treatments with three replicates (24 experimental plots in total). The sown area of each plot was 99 m$^2$, with a harvested area of 50 m$^2$. The treatments were arranged systematically. The general study design is presented in Figure 1.

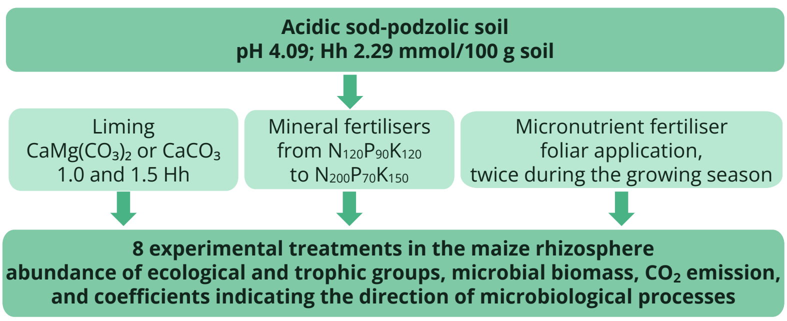


**Figure 1.** General scheme of the study

**Source:** developed by the authors

Liming was carried out in autumn 2020 prior to the first crop in the crop rotation by spreading soil amendments followed by incorporation into the soil. The after-effects of the soil amendments were assessed in 2025. The rates of soil amendments were calculated based on hydrolytic acidity (Ng): $CaMg(CO_3)_2$ at rates of 1.0 and 1.5 Nh, and $CaCO_3$ at a rate of 1.0 Ng. Mineral fertilisers were applied in spring 2025 during pre-sowing cultivation in accordance with the experimental design (Table 1). The microfertiliser was applied foliar (by spraying) twice during the growing season during the active growth phase of maize.

**Table 1.** Field experiment design

| Treatment | Soil amendment | Mineral fertilisers | Micronutrient fertiliser |
|---|---|---|---|
| 1 | Not applied | Not applied | Not applied |
| 2 | $CaMg(CO_3)_2$, 1.0 Nh | Not applied | Not applied |
| 3 | $CaMg(CO_3)_2$, 1.0 Nh | $N_{120}P_{90}K_{120}$ | Twice during the growing season |
| 4 | $CaMg(CO_3)_2$, 1.0 Nh | $N_{165}P_{30}K_{50}$ | Twice during the growing season |
| 5 | $CaMg(CO_3)_2$, 1.0 Nh | $N_{200}P_{70}K_{150}$ | Twice during the growing season |
| 6 | $CaMg(CO_3)_2$, 1.0 Nh | $N_{165}$ | Twice during the growing season |
| 7 | $CaMg(CO_3)_2$, 1.5 Nh | $N_{120}P_{90}K_{120}$ | Twice during the growing season |
| 8 | $CaCO_3$, 1.0 Nh | $N_{120}P_{90}K_{120}$ | Twice during the growing season |

**Source:** compiled by the authors

Soil samples were collected in 2025 from the maize rhizosphere at the 7-9-leaf stage from the 0-20 cm soil layer in accordance with DSTU 4287:2004 (2004). From each experimental plot (replicate), a composite sample was prepared from five sampling points arranged diagonally across the plot. Thus, three independent composite samples were obtained for each experimental treatment, one from each replicate. The abundance of microorganisms was determined by the serial dilution plating method, using soil suspensions plated onto selective agar media in accordance with DSTU 7847:2015 (2015). Laboratory determinations of microbial abundance were performed in five replicates. Ammonifiers were enumerated on meat-peptone agar (MPA). Micromycetes were enumerated on Czapek agar (CZA). Bacteria capable of assimilating mineral forms of nitrogen and streptomycetes were enumerated on starch-ammonia agar (SAA). Oligotrophs were enumerated on nutrient-poor agar. Pedotrophs were enumerated on soil agar (SA). Oligonitrophilic diazotrophs were enumerated on Ashby's medium. The direction of microbiological processes was assessed using the oligotrophy, nitrogen mineralisation and immobilisation, and pedotrophy coefficients (Andreyuk *et al*., 2001). The mineralisation coefficient was calculated using the formula (1):

$$C_m = C_{SAA} / C_{MPA}, \quad (1)$$

where $C_m$ – the mineralisation coefficient, calculated as the ratio of the number of microorganisms that grew on starch-ammonia agar ($C_{SAA}$), to the number of microorganisms that grew on meat-peptone agar ($C_{MPA}$).

The oligotrophy coefficient was calculated using the formula (2):

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

where $C_{ol}$ – the oligotrophy coefficient, calculated as the ratio of the number of microorganisms that grew on nutrient-poor agar ($C_{NPA}$), to the sum of the numbers of microorganisms that grew on starch-ammonia agar ($C_{SAA}$) and meat-peptone agar ($C_{MPA}$).

The pedotrophy coefficient was calculated using the formula (3):

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

where $C_{ped}$ – the pedotrophy coefficient, calculated as the ratio of the number of microorganisms that grew on soil agar ($C_{SA}$), to the number of microorganisms that grew on meat-peptone agar ($C_{MPA}$).

Microbial biomass was determined using the rehydration method in accordance with DSTU ISO 14240-1:2003. $CO_2$ emission rates were determined using Shtatnov's adsorption method in accordance with DSTU ISO 16072:2005 (2005). Soil solution reaction and hydrolytic acidity were determined in accordance with DSTU ISO 10390:2022 (2022) and DSTU 7537:2014 (2014), respectively. In addition, two derived ecological indices were calculated. The specific metabolic rate ($qCO_2$) was calculated as the ratio of $CO_2$ emissions to microbial biomass carbon. This indicator characterises the energy efficiency of the community and its level of stress (Clayton *et al*., 2021). The efficiency of carbon utilisation by microorganisms is considered a key factor in the accumulation of organic carbon in the soil (Tao *et al*., 2023). The bacterial-fungal ratio was calculated as the ratio of the abundance of ammonifiers to that of microfungi (Wang *et al*., 2019).

Statistical analysis was applied at all stages of processing the experimental data. Microbiological studies were conducted in quintuplicate; the abundance of microorganisms belonging to the main ecological-trophic groups was reported as the arithmetic mean with standard error. Based on the mean abundance values of the groups, coefficients indicating the direction of microbiological processes – mineralisation – immobilisation, oligotrophy and pedotrophy – were calculated, as well as indicators of total microbial biomass and $CO_2$ emission intensity. Mathematical and statistical processing of the experimental data was carried out using Microsoft Excel 2019 and Minitab 19. Statistical analysis was performed using one-way analysis of variance (One-way ANOVA). The significance of differences between the mean values of the experimental treatments was assessed using Fisher's exact test at a statistical significance level of $p \leqslant 0.05$. Field studies were conducted in accordance with the principles of biodiversity conservation as set out in the Convention on Biological Diversity (1992), as well as bioethical principles and environmental safety standards. Sampling was carried out with minimal impact on the plants and their habitats.

## RESULTS AND DISCUSSION

Experimental studies were carried out in the Western Polissia region on sod-podzolic loamy-sandy soil, which is characterised by a natural tendency towards acidification and requires systematic optimisation of its physico-chemical properties. The assessment was carried out as part of a long-term field experiment, studying the long-term after-effects of chemical soil amendments applied in 2020. Particular attention was paid to a comprehensive analysis of the impact of variable maize mineral nutrition systems on the acid-base balance of the soil solution. Given the key role of the microbiome in ensuring the availability of nutrients, the structural and functional reorganisation of the rhizosphere microbial community, the potential for metabolic activity of the local microbiota, and the overall direction and dynamics of biochemical and microbiological processes were studied in detail. The after-effects of soil conditioners, in combination with mineral fertilisation, altered the ecological conditions of the microbiota (Table 2).

**Table 2.** Acid-base status and nutrient availability in the soil of the maize rhizosphere

| Treatment | Soil pH | Hydrolytic acidity, mmol/100 g soil | Easily hydrolysable N, mg/kg | Available $P_2O_5$, mg/kg | Available $K_2O$, mg/kg |
|---|---|---|---|---|---|
| 1 | 4.09 | 2.29 | 47.8 | 193.5 | 63.9 |
| 2 | 5.60 | 0.79 | 57.6 | 257.0 | 94.2 |
| 3 | 5.71 | 0.79 | 65.8 | 284.1 | 125.4 |
| 4 | 5.91 | 0.90 | 63.5 | 117.5 | 108.1 |
| 5 | 5.48 | 1.11 | 72.9 | 290.4 | 143.2 |
| 6 | 5.53 | 0.96 | 59.5 | 216.6 | 106.3 |
| 7 | 6.20 | 0.84 | 67.4 | 311.1 | 139.5 |
| 8 | 6.18 | 0.83 | 66.8 | 261.6 | 130.2 |

**Source:** compiled by the authors

The soil solution pH increased from 4.09 in the control to a range of 5.48-6.20. Hydrolytic acidity decreased 2.1- and 2.9-fold. Acid stress was alleviated most effectively in treatments 7 and 8. The soil's supply of nutrients also increased. The exception was treatment 4, where the content of available phosphorus was the lowest in the experiment. The abundance of the main ecological and trophic groups is presented in Table 3. Changes relative to the control are shown in Figure 2.

**Table 3.** Abundance of the main ecological and trophic groups of microorganisms in the maize rhizosphere

| No. | Ammonifiers, million CFU/g | Micromycetes, thousand CFU/g | Mineral-nitrogen bacteria, million CFU/g | Streptomycetes, million CFU/g | Oligotrophs, million CFU/g | Pedotrophs, million CFU/g | Oligonitrophiles, million CFU/g |
|---|---|---|---|---|---|---|---|
| 1 | 7.20 ± 0.16 | 61.20 ± 4.68 | 4.93 ± 0.21 | 4.18 ± 0.26 | 4.03 ± 0.08 | 4.75 ± 0.63 | 3.60 ± 0.33 |
| 2 | 24.12 ± 0.72 | 43.20 ± 5.21 | 5.69 ± 0.17 | 4.82 ± 0.21 | 3.49 ± 0.11 | 3.49 ± 0.18 | 3.31 ± 0.19 |
| 3 | 27.61 ± 0.87 | 43.60 ± 8.15 | 4.25 ± 0.12 | 3.45 ± 0.18 | 2.76 ± 0.15 | 3.09 ± 0.12 | 2.54 ± 0.27 |
| 4 | 20.52 ± 0.29 | 50.40 ± 4.46 | 4.25 ± 0.23 | 3.74 ± 0.32 | 3.60 ± 0.17 | 4.21 ± 0.52 | 3.20 ± 0.12 |
| 5 | 24.71 ± 0.99 | 39.97 ± 3.75 | 5.78 ± 0.54 | 4.58 ± 0.38 | 2.47 ± 0.25 | 3.12 ± 0.87 | 1.45 ± 0.16 |
| 6 | 24.34 ± 0.49 | 47.23 ± 6.48 | 3.74 ± 0.23 | 3.20 ± 0.17 | 2.62 ± 0.32 | 1.27 ± 0.36 | 1.02 ± 0.08 |
| 7 | 27.00 ± 0.65 | 28.80 ± 4.54 | 3.78 ± 0.15 | 2.92 ± 0.11 | 3.85 ± 0.22 | 3.82 ± 0.62 | 1.04 ± 0.16 |
| 8 | 24.71 ± 0.62 | 87.20 ± 3.61 | 5.27 ± 0.64 | 4.61 ± 0.31 | 3.60 ± 0.18 | 3.49 ± 0.31 | 0.47 ± 0.07 |

**Source:** compiled by the authors

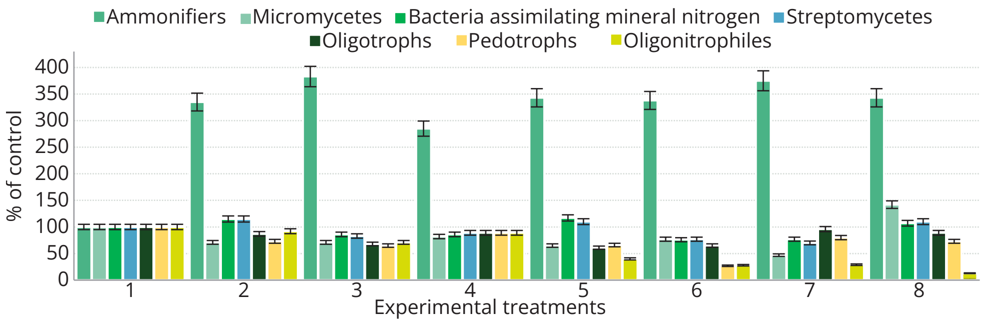


**Figure 2.** Abundance of key ecological and trophic groups of microorganisms in the maize rhizosphere, % of control

**Source:** compiled by the authors

In the control treatment, micromycetes and pedotrophs predominated. The abundance of ammonifiers was low, at 7.20 million CFU/g soil. This ratio corresponds to a fungal-oligotrophic type of organic matter decomposition, which is characteristic of uncultivated acidic soils. Ammonifiers showed the most pronounced response to agromelioration. The residual effect of dolomite flour increased their abundance 3.3-fold. The application of the full mineral fertiliser combination increased their abundance 3.8-fold, to 27.61 million CFU/g soil. This group showed the strongest relationship with soil solution pH. The correlation coefficient was +0.87, while the correlation with hydrolytic acidity reached -0.94. Thus, acidity, rather than the fertiliser rate, was the limiting factor for the ammonifying microbiota.

The abundance of micromycetes decreased in all treatments with dolomite flour. The minimum was recorded in treatment 7, where it was 28.80 thousand CFU/g soil, 2.1-fold lower than in the control. In contrast, in treatment 8 with the calcium-based soil amendment, fungal abundance increased to 87.20 thousand CFU/g soil. The soil solution pH in these two treatments was practically identical, at 6.20 and 6.18, respectively. Thus, the threefold difference in fungal abundance cannot be explained by pH. The most likely reason is the absence of magnesium in the composition of calcite. An imbalance in the calcium-to-magnesium ratio in the soil exchange complex reduces the competitive position of the bacterial component. The greatest change in abundance was observed for oligonitrophiles.

This group is adapted to a deficiency of available nitrogen. Its abundance decreased progressively from 3.60 million CFU/g soil in the control to 0.47 million CFU/g soil in treatment 8, i.e. 7.7-fold. In treatments 5-7, it ranged from 1.02 to 1.45 million CFU/g soil. This result directly reflects the alleviation of nitrogen deficiency under high nitrogen rates. In the presence of available mineral nitrogen, oligonitrophiles lose their competitive advantage. Within the same long-term experiment, the soybean rhizosphere was previously examined. At nitrogen rates of 45-65 kg/ha, the abundance of oligonitrophiles did not decrease but increased. Under maize, at rates of 120-200 kg/ha, this group almost disappeared. The comparison was made on the same soil, in the same crop rotation and by the same method. This provides a basis for proposing oligonitrophile abundance as a bioindicator of nitrogen saturation in the agrocenosis.

The abundance of pedotrophs decreased moderately in most treatments. A sharp decline to 1.27 million CFU/g soil, i.e. 3.7-fold, was recorded only in treatment 6. This treatment involved the application of nitrogen alone. The value obtained illustrates the suppression of soil-specific microbial forms under unbalanced nutrition. Complete mineral nutrition maintained pedotroph abundance at 3.09-3.82 million CFU/g soil. The abundance of mineral-nitrogen bacteria and streptomycetes changed only slightly. No significant relationship between these groups and soil solution pH was detected. The absolute values of the correlation coefficients did not exceed 0.22. The results of the assessment of the functional activity of the microbial community are presented in Table 4 and Figure 3.

**Table 4.** Microbial biomass, $CO_2$ emissions and derived ecological indices

| Treatment | Biomass, μg C/g soil | $CO_2$ emissions, mg/kg per day | Specific metabolic rate, mg $CO_2$ per 1 g C of biomass | Bacteria-to-fungi ratio |
|---|---|---|---|---|
| 1 | 99.55±6.5 | 18.3±1.2 | 183.8 | 118 |
| 2 | 114.78±8.4 | 20.0±1.3 | 174.2 | 558 |
| 3 | 102.81±10.2 | 17.6±1.5 | 171.2 | 633 |
| 4 | 97.19±9.6 | 15.4±1.7 | 158.5 | 407 |
| 5 | 103.99±7.5 | 17.1±2.1 | 164.4 | 618 |
| 6 | 128.95±9.3 | 16.6±3.1 | 128.7 | 515 |
| 7 | 127.77±8.4 | 14.2±1.8 | 111.1 | 938 |
| 8 | 117.08±10.5 | 15.6±2.4 | 133.2 | 283 |

**Source:** compiled by the authors

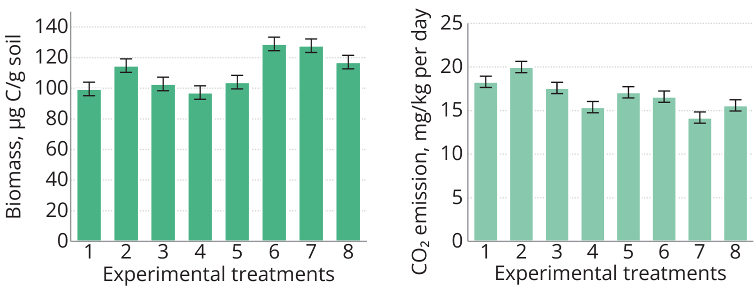


**Figure 3.** Microbial biomass (a) and $CO_2$ emission rate (b) in the maize rhizosphere
**Note:** the dotted line indicates the control level
**Source:** compiled by the authors

Microbial biomass in the control treatment was 99.55 μg C/g soil. Integrated agromelioration increased it to an average of 112.97 μg C/g soil. The maximum values were recorded in treatments 6 and 7, at 128.95 and 127.77 μg C/g soil, respectively. The increase in biomass in treatment 6 had a different underlying cause: it was driven by the supply of readily available nitrogen without phosphorus or potassium. Under these conditions, heterotrophic bacteria accelerate the decomposition of available organic matter to balance the carbon-to-nitrogen ratio. Indirect confirmation of this is provided by the minimum abundance of pedotrophs observed specifically in this treatment. In contrast, the increase in biomass in treatment 7 was supported by balanced nutrition and was therefore more environmentally sustainable. The $CO_2$ emission rate in the control treatment was 18.3 mg/kg per day. The maximum was recorded in treatment 2, where it reached 20.0 mg/kg. In treatments receiving complete mineral nutrition, emissions decreased to a range of 14.2-17.6 mg/kg per day. In treatment 7, the reduction relative to the control was 22%.

The combination of increased biomass and reduced respiration is a key ecological finding of the study. The specific metabolic quotient decreased from 183.8 in the control to 111.1 mg $CO_2$ per 1 g biomass carbon in treatment 7, representing a 1.65-fold decrease. According to the study by R. Dang *et al*. (2024), such a reduction in this indicator may indicate reduced stress on the microbial community and increased carbon-use efficiency. The practical consequence is a reduction in unproductive carbon losses from the agrocenosis. The bacterial-fungal ratio increased from 118 to 938, confirming a shift in the type of organic matter decomposition. The values of the coefficients indicating the direction of microbiological processes are presented in Table 5 and Figure 4.

**Table 5.** Direction of microbiological processes in the maize rhizosphere

| Treatment | Oligotrophy coefficient | Nitrogen mineralisation and immobilisation coefficient | Pedotrophy coefficient | Type of process direction |
|---|---|---|---|---|
| 1 | 0.35 | 0.69 | 0.66 | coprotrophic-mineralising |
| 2 | 0.12 | 0.24 | 0.14 | transitional |
| 3 | 0.09 | 0.15 | 0.11 | eutrophic-immobilising |
| 4 | 0.15 | 0.21 | 0.21 | transitional-immobilising |
| 5 | 0.08 | 0.23 | 0.13 | eutrophic-immobilising |
| 6 | 0.09 | 0.15 | 0.05 | eutrophic-immobilising |
| 7 | 0.13 | 0.14 | 0.14 | eutrophic-immobilising |
| 8 | 0.12 | 0.21 | 0.14 | eutrophic-immobilising |

**Source:** compiled by the authors

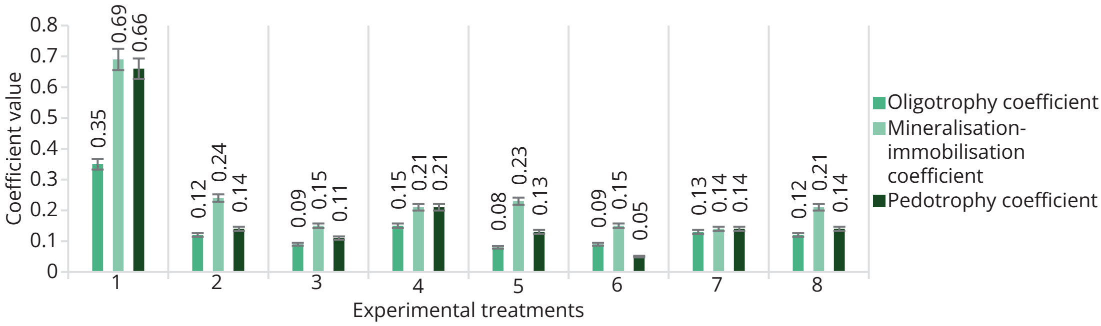


**Figure 4.** Directionality coefficients of microbiological processes in the maize rhizosphere
**Source:** compiled by the authors

The control treatment was clearly differentiated from the other experimental treatments, with an oligotrophy coefficient of 0.35, a mineralisation and immobilisation coefficient of 0.69, and a pedotrophy coefficient of 0.66. This combination corresponds to a coprotrophic-mineralising regime. Under these conditions, the microbial community intensively decomposes its own reserves of soil organic matter. For the agrocenosis, this means a gradual depletion of the humus pool. Integrated agromelioration radically altered this pattern. In the fertilised treatments, the oligotrophy coefficient decreased to a range of 0.08-0.15. The mineralisation and immobilisation coefficient ranged from 0.14 to 0.24. This corresponds to a eutrophic-immobilising type. The microbial community is supplied with readily available substances and actively immobilises nitrogen in its biomass. This regime promotes the accumulation of organic matter and reduces nitrogen losses. Both coefficients showed a very strong relationship specifically with hydrolytic acidity. The correlation coefficients were +0.92 and +0.96, respectively (Fig. 5). This provides grounds for considering hydrolytic acidity to be the principal regulator of the direction of microbiological processes in sod-podzolic soils.

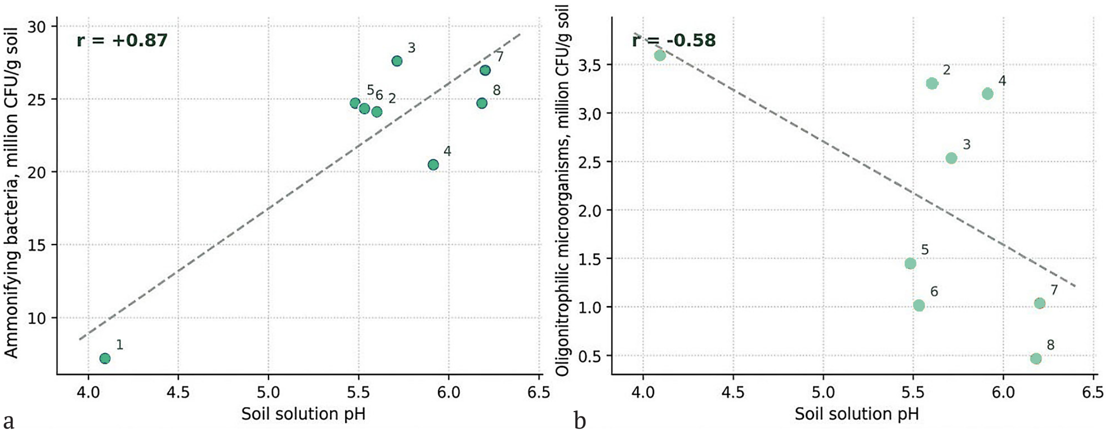


**Figure 5.** Relationship between the abundance of ammonifiers (a) and oligonitrophiles (b) and the reaction of the soil solution

**Note:** the numbers indicate the option numbers

**Source:** compiled by the authors

The data obtained describe a sequential ecological transition of the microbiocenosis. This transition occurs from a fungal-oligotrophic system, characterised by intensive mineralisation of its own organic matter reserves, to a bacterial-eutrophic system with an immobilisation orientation (Fig. 6).

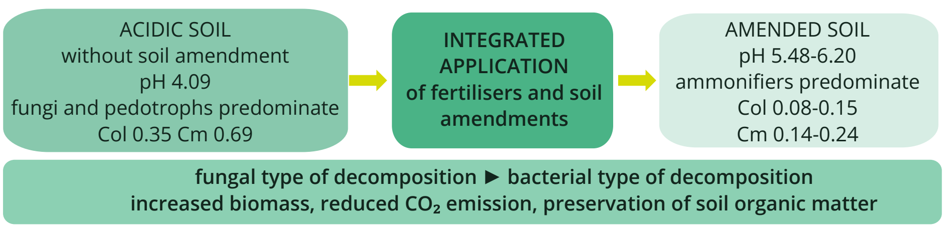


**Figure 6.** Diagram illustrating the ecological transformation of the maize rhizosphere microbiocenosis following the integrated application of fertilisers and soil amendments

**Source:** compiled by the authors

This pattern of changes is consistent with current understanding of the role of soil acidity. Y. Duan *et al.* (2025) demonstrated that soil acidification destabilises terrestrial ecosystems by disrupting interactions within the microbiome. Meanwhile, research by P. Wenyika *et al*. (2025) summarised the impact of liming on soil biota and confirmed that soil improvement can significantly alter the structure of microbial communities. The most striking finding of the study was the behaviour of oligonitrophiles. A 7.7-fold reduction in their abundance represents the greatest change among all the groups studied. Within the same long-term experiment, oligonitrophile abundance increased under soybean at N 45-65 kg/ha and almost disappeared under maize at N 120-200 kg/ha. This comparison, made on the same soil, in the same crop rotation and by the same method, supports the use of this group as a bioindicator of nitrogen saturation. A study by M. Tosi *et al*. (2021) showed that it is the cumulative nitrogen load, rather than current application, that determines the structure of the community. A group of researchers led by J. Liu *et al*. (2024) established that excessive doses of nitrogen make the microbial networks of the maize rhizosphere the most complex, yet at the same time the least stable. T. Meng *et al*. (2024) identified a non-linear response of bacterial diversity to increasing nitrogen doses.

The study highlighted the differing ecological effects of soil amendments with varying chemical compositions. Dolomite flour and calcite produced virtually identical responses in the soil solution. However, the abundance of microfungi in these treatments differed by a factor of three. This indicates that the phytosanitary effect of liming is determined not only by the pH level. P. Wenyika *et al*. (2025) also point out that, under certain conditions, liming can increase the abundance of specific groups of fungi. Furthermore, I. Beznosko *et al*. (2022) demonstrated that the quantitative composition of microfungi under cereal crops depends significantly on soil conditions and the cultivation system. Thus, the choice of a soil conditioner for acidic soils should not be based solely on its neutralising potential.

A simultaneous increase in biomass and a decrease in respiration indicate reduced stress on the community. This is how a decline in the metabolic quotient is interpreted by T.-H. Anderson & K.H. Domsch (1993). At the same time, D.A. Wardle & A. Ghani (1995) caution that $qCO_2$ is not a universal index and should be interpreted carefully, because it may increase both under greater stress and when recalcitrant substrates predominate. In the present study, the decrease in $qCO_2$ was accompanied by an increase in biomass and a reduction in the fungal fraction; therefore, its interpretation as reduced stress is justified. R. Dang *et al*. (2024) found that the external supply of nutrients generally increases the efficiency of carbon utilisation by microorganisms. F. Tao *et al*. (2023) regard this efficiency as the leading factor in the accumulation of organic carbon in the soil. For the same stationary experiment, V. Polovyi *et al.* (2023) had previously established a positive organic carbon balance at the calculated fertiliser rates against a background of dolomite flour. The authors' microbiological data explain the biological mechanism behind this phenomenon.

The observed stimulatory effect of balanced mineral nutrition on beneficial bacterial groups is consistent with the results obtained by A. Srour *et al.* (2020) for maize and soya bean rotation on neutral soils. A similar pattern of changes was documented by S. Reznik (2021) for typical chernozems of the Left-Bank Forest-Steppe of Ukraine. The consistency of results across different soil types indicates the universality of the mechanism, which involves the displacement of acidophilic and oligotrophic forms by copiotrophic bacteria as trophic conditions improve. A similar restructuring of the rhizosphere community under different fertilisation regimes was described by S. Hudz & L. Skivka (2020) and V. Polishchuk *et al*. (2025) for cereal crops. The dependence of the direction of soil microbiological processes on the fertilisation regime was also confirmed by I. Malynovska *et al.* (2021) for grassland phytocenoses.

The practical significance of this work lies in the possibility of targeted management of the microbiocenosis. The favourable microbiological background established in variants 3 and 7 is a prerequisite for the subsequent introduction of microbial preparations, as noted by A. Levishko & P. Mamenko (2025). Y. Yu *et al.* (2024) emphasise that the effectiveness of introduced microorganisms depends on the state of the indigenous community and the trophic conditions of the soil. It has been shown that the level of nitrogen supply directly shapes the bacterial diversity of the maize rhizosphere. At the same time, variants 4 and 6 demonstrate the ecological risks of nutrient imbalance. They are accompanied by the depletion of phosphorus reserves and the suppression of soil-specific forms of microorganisms. A limitation of this study is the use of culture-based methods. These cover only a small fraction of the soil microbiome. N. Fierer *et al.* (2021) emphasise that this is a widely recognised problem in microbiological soil diagnostics. However, for a comparative assessment of field trial options, the ecological-trophic group approach remains informative and accessible, as demonstrated in the work by A. Levishko *et al*. (2026). The results obtained provide grounds for considering the targeted management of the microbiological state of the soil as a promising direction for optimising the fertilisation system and enhancing the ecological stability of the agrocenosis.

## CONCLUSIONS

The study demonstrated that the integrated application of fertilisers and soil amendments eliminates acid stress as the principal limiting factor for the development of the microbiota of acidic sod-podzolic soil. The soil solution pH increased from 4.09 to a range of 5.48-6.20, while hydrolytic acidity decreased 2.1- and 2.9-fold. Removal of this limitation initiated a consistent restructuring of the microbial community in the maize rhizosphere from a fungal-oligotrophic to a bacterial-eutrophic type. The abundance of ammonifiers increased 2.9- and 3.8-fold, while the bacterial-fungal ratio increased from 118 to 938. This demonstrates a shift in the pathway of organic matter decomposition from fungal to a more energy-efficient bacterial type. The structural restructuring of the community was accompanied by an increase in its functional efficiency. Microbial biomass increased to 128.95 μg C/g soil, while $CO_2$ emission simultaneously decreased to 14.2 mg/kg per day. The specific metabolic quotient decreased from 183.8 to 111.1 mg $CO_2$ per 1 g biomass carbon. This combination indicates reduced stress on the microbial community and a decrease in unproductive carbon losses from the agrocenosis. Accordingly, the direction of microbiological processes shifted from a coprotrophic-mineralising to a eutrophic-immobilising regime. Hydrolytic acidity was identified as the principal regulator of this transition, with correlation coefficients of +0.92 and +0.96 for the oligotrophy and mineralisation indicators, respectively. Thus, the acid-base status of the soil should be regarded as a key regulator of the biological regime of the maize agrocenosis.

The results obtained have independent diagnostic significance. The abundance of oligonitrophiles decreased 7.7-fold and proved to be the most sensitive of the indicators studied. Within the same long-term experiment, this group increased under soybean at N 45-65 kg/ha and almost disappeared under maize at N 120-200 kg/ha; therefore, its abundance was proposed as a bioindicator of nitrogen saturation in the agrocenosis. Furthermore, the ecological effects of soil amendments of different chemical compositions proved to be inconsistent. Whilst the soil solution reacted in virtually the same way, the abundance of microfungi in the dolomite flour treatment was 3.0 times lower than in the calcite treatment. This implies that the phytosanitary effect of liming is not limited solely to pH levels and depends on the chemical composition of the soil amendment.

The most favourable ecological conditions for the microbial community were established through a combination of the after-effect of dolomite flour with the recommended dose of mineral fertilisers and two applications of foliar feeding with a microfertiliser. In contrast, unbalanced fertilisation was accompanied by the suppression of soil-specific forms of microorganisms and the depletion of the soil's phosphorus reserves. The results obtained justify the need for microbiological monitoring as an essential element of maize cultivation technology on the acidic soils of Polissia. The favourable biological background that has been established is a prerequisite for the further introduction of microbial preparations into such agrocenoses.

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## CONFLICT OF INTEREST

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# Формування мікробіоценозу кислого дерново-підзолистого ґрунту в ризосфері кукурудзи за інтегрованого застосування добрив та меліорантів

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**Анотація.** У роботі вивчався вплив сумісного застосування меліорантів та добрив на формування та функціонування мікробіоценозу ризосфери кукурудзи за умов дерново-підзолистого ґрунту. Метою роботи було визначити вплив комплексного застосування добрив і меліорантів на структурно-функціональні характеристики мікробіоценозу дерново-підзолистого ґрунту в ризосфері кукурудзи та обґрунтувати мікробіологічні показники для екологічної біоіндикації стану агроценозу. Польові дослідження було проведено упродовж 2025 року у стаціонарному досліді Інституту сільського господарства Західного Полісся Національної академії аграрних наук України. Дослід включав 8 варіантів, що поєднували залишковий вплив вапнування доломітовим борошном або вапняком із диференційованим внесенням мінеральних добрив та дворазовим позакореневим підживленням мікродобривом. Чисельність еколого-трофічних груп мікроорганізмів визначали методом посіву на селективні агаризовані середовища, мікробну біомасу регідратаційним методом, емісію $CO_2$ адсорбційним методом. Встановлено, що реакція ґрунтового розчину зросла від 4,09 до діапазону від 5,48 до 6,20, а гідролітична кислотність знизилася у 2,1 та 2,9 раза. Чисельність амоніфікаторів зросла у 2,9 та 3,8 раза і досягла 27,61 млн КУО/г ґрунту. Чисельність мікроміцетів за поєднання доломітового борошна з добривами знизилася у 2,1 раза до 28,80 тис. КУО/г ґрунту. Найбільшу амплітуду змін виявлено для олігонітрофілів, чисельність яких зменшилася у 7,7 раза. Мікробна біомаса зросла до 128,95 мкг С/г ґрунту за одночасного зниження емісії $CO_2$ до 14,2 мг/кг за добу, а питомий метаболічний коефіцієнт зменшився від 183,8 до 111,1 мг $CO_2$ на 1 г вуглецю біомаси. Мікробіоценоз перейшов від грибно-олігoтрофного до бактеріально-евтрофного типу з коефіцієнтом олігoтрофності від 0,08 до 0,15 та коефіцієнтом мінералізації від 0,14 до 0,24. Провідним регулятором цього переходу виявилася гідролітична кислотність ґрунту, коефіцієнти кореляції з якою становили 0,92 та 0,96. Практична цінність роботи полягає в обґрунтуванні чисельності олігонітрофілів як біоіндикатора азотного насичення агроценозу кукурудзи, а також у виявленні переваги магнієвмісного меліоранту для контролю грибної мікробіоти кислих ґрунтів Полісся

**Ключові слова:** ґрунтовий мікробіом; таксономічна структура; біоіндикація; мікробна біомаса; олігoтрофи