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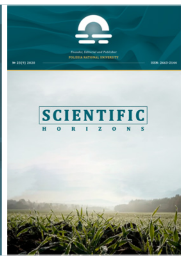

Impact of tillage and fertilisation on organic matter accumulation and soil fertility

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Abstract. The study aimed to determine the effectiveness of traditional, minimum and no-till tillage in combination with organic fertilisation methods, such as green manure, organic compost and green manure. The study was based on field experiments conducted on plots with different soil types, which was used to assess the impact of the applied agricultural technologies in different agroecological conditions. The results showed that no-till with combined fertilisation (NPK + manure) provided the highest increase in soil organic matter (SOM) by 0.7% (up to 3.4% in 2024) and humus by 0.5% (up to 2.6% in the 0-10 cm layer) compared to the control (1.7% SOM for ploughing). The nitrogen (N) content increased by 0.04% (to 0.16%), phosphorus (P) by 7 mg/kg (to 57 mg/kg), and potassium (K) by 20 mg/kg (to 140 mg/kg). Deep ploughing resulted in a loss of SOM (from 2.3% to 1.7%), while minimum tillage-maintained

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SOM at 2.1-3.3%. Organic fertilisers (manure, green manure) stabilised humus with a correlation of $r = 0.85 - 0.90$ ($p < 0.05$), while no-till increased soil moisture by 10-15% and cation exchange by 510%. On fertile soils (Eutric Cambisol), no-till with combined fertiliser increased the SOM by 0.7%, while on sandy soils (Quartzipsamment) organic fertiliser added 0.4%. The ANOVA analysis confirmed the significant effect of tillage ($F = 45.2$, $p < 0.001$) and fertiliser ($F = 38.7$, $p < 0.001$) on the SOM. The seasonal dynamics showed a peak in the spring (3.6% in 2023 for no-till). No-till with combined fertiliser was found to be the most effective. The results obtained can be useful for improving agricultural technologies in the field of organic farming, developing ecological farming systems and formulating practical recommendations for farmers and agronomists on optimal soil resource management

Keywords: agrotechnology; environmental sustainability; the biological activity of agrocenoses; fertility conservation; biogeochemical processes

INTRODUCTION

Soil is the main component of terrestrial ecosystems and maintains a balance between physical, chemical and biological properties. Soil organic matter is central to improving soil structure, water-holding capacity and fertility. Increasing the organic matter content is an important factor in sustainable soil management and maintaining the productivity of agricultural land. In this regard, organic farming is becoming increasingly widespread as an alternative to conventional farming methods aimed at the long-term preservation of soil fertility and environmental sustainability of agricultural landscapes. Organic farming is based on methods such as crop rotation, legume cover crops, green fertilisers and compost, which contribute to the accumulation of organic matter.

The annual growth of organic farming areas in the world is about 0.2 million hectares, which is 0.5% of the total area (Willer *et al.,* 2025). The main feature of organic farming is the exclusion of the use of synthetic fertilisers, pesticides, plant growth regulators and genetically modified organisms (Tanchyk *et al.*, 2024). This approach views the farm as a complete ecosystem in which minerals, organic matter, microorganisms, insects, plants, animals and people interact to form a balanced and stable environment. The impact of tillage systems and fertilisation methods on organic matter accumulation has been the subject of numerous studies. In the study by M. Allam *et al.* (2022), a meta-analysis showed that organic fertilisers increased the organic matter content (Soil organic carbon (SOC)) by 12.9% (up to 20.6% for No-Till (NT)), mineral-organic fertilisers increased yields by 13.4% (Conventional Tillage (CT)) and 12.7% (Reduced Tillage (RT)) in coarse soils, and the best effect of organic fertilisers was observed in legumes (15.2%), which emphasises the importance of adapting fertiliser to the conditions. A nine-year study of rice-wheat rotation by Z. Zhao *et al.* (2021) showed that organic fertilisers (conventional tillage with organic manure (CTOM), reduced tillage with organic manure (RTOM)) increased SOC, its active fractions and macroaggregates (250 μm), with the highest concentration recorded in CTOM, which confirms the effectiveness of organic fertilisation and reduced tillage.

J. Gerke (2022) showed that humus substances (50-80% SOC) improve the availability of phosphorus (P), iron (Fe) and copper (Cu), reduce the toxicity of aluminium (Al), bind heavy metals, and perennial plants and organic fertilisers effectively increase SOC and contribute to CO_2 regulation. According to a study by D. Martin-Lammerding *et al.* (2021), over ten years in a semi-arid agroecosystem, organic fertilisers (ORG) under minimal tillage (MT) increased wheat yields compared to mineral fertilisers (MIN) and provided stable nutrient levels. A. Feilinezhad *et al.* (2022) analysed that minimum tillage with manure application provided the highest maize yield and improved nutrient uptake compared to no-till. A. Morugán-Coronado *et al.* (2022) evaluated the effects of climate, soil and agronomic practices on crop yields under minimum tillage, and the results showed that a combination of organic and mineral fertilisers gave the best results for cereals, while organic fertilisers were sufficient for pulses.

H. Cui *et al.* (2023) studied the effect of different tillage methods and different levels of nitrogen fertilisation on soil fertility and wheat yield. The results showed that alternating deep and rotary tillage with corn straw and 225 kg of nitrogen per ha resulted in the highest level of fertility and yield at low costs. H. Zhang *et al.* (2020) evaluated the long-term (33 years) effects of different tillage methods and straw return on soil aggregate stability, organic carbon and nitrogen, and the results showed that no-till and straw incorporation increased the number of large macroaggregates, their organic carbon (OC) and nitrogen (N) content, improving soil fertility. J. Balik *et al.* (2020) studied changes in SOC content over 26 years of silage maize cultivation. The results showed that mineral nitrogen fertilisation accelerates the mineralisation of stable organic matter, straw application reduces organic matter losses, and manure increases carbon in stable organic matter (CSOM) by 16%. L. Lv *et al.* (2023) assessed the impact of conservation tillage technologies on soil chemical properties through a global meta-analysis, and the results showed that such methods, especially stubble cover, significantly increase the content of organic matter, carbon, and key nutrients, namely nitrogen (N), phosphorus (P), potassium (K), and cation exchange potential in the soil.

Despite numerous studies, there are gaps in understanding the long-term impact of different tillage systems and organic fertilisation on organic matter accumulation in different soil types and climatic conditions. In particular, the optimal combinations of fertilisation and tillage practices that maximise organic carbon storage and improve soil structure remain poorly understood. The study aimed to investigate the impact of different tillage methods (traditional, minimum, zero tillage) and organic fertilisation (green manure, compost, green manure) on the level of organic matter and agrochemical fertility indicators.

MATERIALS AND METHODS

The study of the impact of tillage and fertilisation on the accumulation of organic matter and soil fertility was conducted during 2021-2024 years on the experimental field of the Agricultural Research Institute of Agriculture of Central Ukraine of the National Academy of Agrarian Sciences of Ukraine, in Kryvyi Rih. The study area is characterised by chornozem soils of medium humus content, which provides favourable conditions for the experiment and representative results. The climate of the region is temperate continental, with warm summers and mild winters, which also contributes to the successful cultivation of crops and field research. The study area is characterised by the following soil types: Typical Hapludult (acidic, well-drained soils with low organic matter content); Typical Xerorthent (dry, underdeveloped soils with low fertility); Typical Udipsamment (sandy soils with low humus content); Eutric Cambisol (fertile soils with high nutrient content); Typical Quartzipsamment (sandy soils with a predominance of quartz). The study focused on agronomic tillage systems, including conventional, minimum and no-till methods, as well as various fertilisation schemes, including both organic and mineral fertilisers. The assessment of the dynamics of changes in soil organic matter, humus content, physical and chemical properties of the soil profile, and the effectiveness of different fertilisation systems in a changing climate were emphasised.

The impact of deep ploughing, minimum tillage and no-till on the accumulation of organic matter in the topsoil (0-30 cm) was studied. The effect of mineral and organic fertilisers (nitrogen ammonium nitrate, phosphate superphosphate, potassium chloride) and organic fertilisers (rotted manure and green manure) on changes in humus, nitrogen, phosphorus and potassium content was studied. The experiment was laid out in a randomised quadruplicate design with three tillage options and three fertilisation schemes: deep ploughing (20-25 cm), minimum tillage (10-15 cm), no-till and mineral fertiliser (NPK), organic fertiliser (manure), and combined fertiliser (manure + NPK). Each variant included a control plot without fertilisation. Soil samples were collected in the spring and autumn of each year at depths of 0-10 cm, 10-20 cm and 20-30 cm.

The analyses were performed using a UV-1800 spectrophotometer (Shimadzu, Japan), an electronic balance Radwag AS 220.R2 (Radwag, Poland) and a pH meter pH-150MI (Institute of Electric Welding named after E.O. Paton Institute of Electric Welding, Ukraine), a drying cabinet and analytical chemicals, including potassium sulphate (K_2SO_4), hydrochloric acid (HCl), sulphuric acid (H_2SO_4), nitric acid (HNO_3), hydrogen peroxide (H_2O_2), sodium hydroxide (NaOH), phenolphthalein indicator, calcium chloride ($CaCl_2$), and standardised solutions for photometric determination of nitrogen, phosphorus and potassium. The data were processed using statistical methods of analysis of variation (ANOVA) to assess the significance of the influence of various factors. Plots with homogeneous soil types were selected for the study, which ensured a correct comparison of results between the variants. The sites were selected based on the criteria of equal exposure and the absence of factors that could affect the results, such as excessive moisture or erosion processes. The results of soil analysis were compared between the experimental variants to assess the effectiveness of each tillage and fertilisation system.

Before the experiment, a detailed characterisation of the initial soil properties was carried out. Fertilisers, namely nitrogen (ammonium nitrate), phosphorus (superphosphate) and potassium (potassium chloride), were applied following agronomic recommendations, considering the potential balance of nutrients in the soil. At the same time, the mass, moisture content and degree of decomposition of plant residues were recorded to analyse their impact on the level of organic matter, following the requirements of DSTU 4287:2004 (2005). Soil sampling was carried out three times a year: in April (spring), July (summer) and October (autumn) throughout the study period. This was used to trace the seasonal dynamics of changes in soil fertility indicators and avoid errors associated with weather fluctuations between years. Areas with anthropogenic pollution (industrial or urbanised areas) were excluded, as well as soils that had been severely depleted due to intensive previous use without appropriate fertilisation.

RESULTS

This section presents the results of an experimental study of the impact of tillage systems (deep ploughing, minimum tillage, no-till) and fertiliser types (mineral, organic, combined) on the accumulation of organic matter, humus content and agrochemical soil fertility indicators over the period of 2021-2024 years. An experiment to study the impact of tillage systems on the accumulation of organic matter (SOM) and humus was conducted for 2021-2024 years based on an experimental field located in the agro-climatic conditions of Kryvyi Rih. The study aimed to determine how different tillage methods affect the accumulation and preservation of organic matter and humus, which are important indicators of soil fertility. Three tillage approaches were used in the study: deep ploughing at 20-25 cm, minimum tillage at 10-15 cm, and no-till. Soil samples for analysis were taken at depths of 0-10, 10-20 and 20-30 cm in spring, summer and autumn, which tracked the seasonal dynamics of indicators.

When comparing the organic matter content in the top 30 cm of soil, it was found that the tillage system significantly affects its concentration. Under deep ploughing, the content of POM was the lowest among all variants and tended to gradually decrease from 2.3% in 2021 (without fertiliser) to 1.7% in 2024. Under combined fertilisation (organic and mineral fertilisers), this figure was higher at 3.5% in 2021 but decreased to 2.9% in 2024. Minimal tillage provided slightly better results in terms of organic matter accumulation. In the variants without fertiliser, the content of SOM varied from 2.5% in 2021 to 2.1% in 2024. When applying the combined fertiliser, maximum values of 3.8% were observed in 2021 and 3.3% in 2024, indicating the effectiveness of the combination of reduced mechanical intervention and nutritional support. The soil was less compacted and easier to penetrate by the root system, which created favourable conditions for crop growth. In the no-till areas, there were also more earthworms, a bioindicator of soil health, which indirectly indicates an increase in biological activity and stabilisation of organic matter (Mirzavand *et al.,* 2022). In addition to quantitative indicators, there was also a noticeable decrease in erosion processes in areas with minimal and no-tillage. The stubble residues on the surface retained moisture reduced the spraying of soil particles during rain and lowered the temperature of the top layer on hot days.

The highest results were recorded with the no-till system. In the no-fertiliser variants, the organic matter content was 2.7% in 2021 and decreased to 2.3% in 2024. When combined fertilisers were used in the first year of the study, the SOM reached 4.0%, and in 2024 it remained at 3.4%. This confirms the positive impact of no-till on the organic part of the soil due to the preservation of plant residues on the surface and minimal disturbance of the soil structure. An analysis of the dynamics of humus content by year and depth showed a general downward trend. On average, the humus content of all variants decreased from 2.4% in 2021 to 2.0% in 2024. The highest concentrations of humus were observed in the topsoil (0-10 cm), especially in the no-till system, where the content varied from 2.8-3.0% in 2021 to 2.4-2.6% in 2024. Under deep ploughing, the same layer saw a decrease from 2.5% to 1.9%, indicating a loss of humus due to intensive mechanical intervention and accelerated mineralisation. At deeper depths (10-20 and 20-30 cm), there was a less pronounced difference between the tillage systems, but the general trend of decreasing humus content was noticeable in all variants.

SOM has become increasingly important scientifically and practically due to the problem of global warming and the potential of the soil environment as a natural reservoir for the accumulation of atmospheric carbon released as CO_2 due to anthropogenic activities (Harenda *et al.,* 2018; Navarro-Pedreño *et al.,* 2021). The most effective measures to increase soil carbon stocks include increasing the level of organic residues and reducing the intensity of organic matter mineralisation processes. The dynamics of organic carbon in the soil profile are determined by the balance between its supply with plant residues and organic fertilisers and its losses caused by the decomposition of SOM, CO_2 emissions, erosion processes and leaching of dissolved organic compounds (Rajpoot *et al.,* 2024). The main sources of organic material returned to the soil system are crop residues and organic fertilisers, including manure. These components contain a wide range of organic compounds that are involved in the formation of microbial structures (Brichi *et al.,* 2023). These structures perform two main functions: first, they contribute to the stabilisation of soil particles, improving the aggregate stability of the soil, and second, they participate in microbial respiration, which causes CO_2 emissions into the atmosphere. Thus, effective management of SOM transformation processes is crucial for maintaining ecological balance, increasing agricultural land productivity and minimising the negative effects of climate change.

Organic carbon (C) is one of the key elements in organic farming systems, as its increased accumulation has a positive impact on the soil carbon balance. A high level of SOM is directly correlated with the application of organic C, which contributes to a long-term increase in its concentration (Dittmar & Lennartz, 2024). The conversion of natural soil ecosystems into agricultural land, especially under active mechanical cultivation, leads to a decrease in soil organic matter content in 60-70% of cases. According to long-term observations, the SOM decreased by 25-40% in arable land compared to virgin meadows and pastures. This phenomenon is since traditional cultivation methods intensify the mineralisation of organic matter compared to natural conditions, and do not contribute to the effective accumulation of organic carbon in the soil profile (Fig. 1). In the transition period from natural vegetation to cultivated agrocenoses, mechanical impact on the soil leads to significant losses of SOM (Filipović *et al.,* 2024). Thus, the introduction of conservation tillage practices is an important measure to reduce the negative impact of agricultural activities on soil organic matter and ensure its long-term preservation and accumulation.

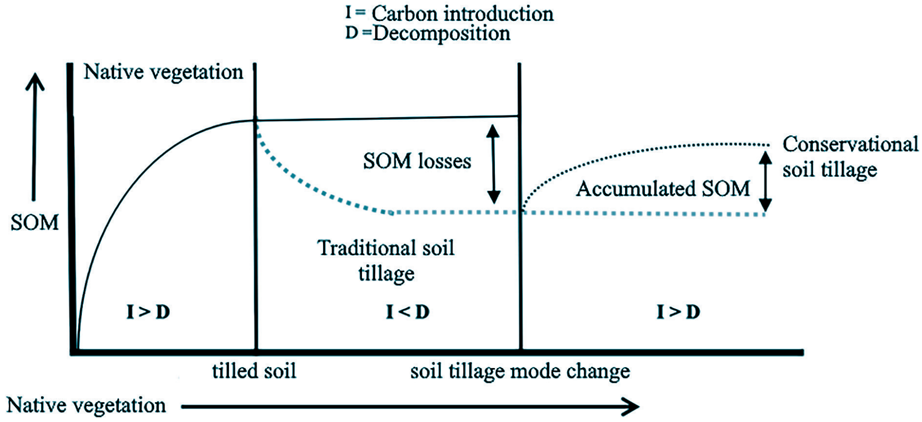

***Figure 1**. The tendency of soil organic matter accumulation from conventional tillage and conservation tillage compared to native soil*
***Source:** compiled by the authors based on A.S.F. de AraÃºjo et al. (2016)*

As organic matter is the main indicator of soil fertility, changes in its content over time can be used to conclude regarding the effectiveness of agricultural practices. In addition, variations in the content of elements such as nitrogen, phosphorus and potassium indicate changes in the physical and chemical properties of soils, which is relevant for the formation of sustainable and productive agroecosystems (Muraru *et al.,* 2021). Accounting for the factors, for further analysis, data characterising changes in soil organic matter and humus content in the period 2021-2024 are presented. These results are presented in Table 1, which shows how different tillage systems and fertilisation options affected the accumulation of organic matter in the soil profile. The dynamics of changes in organic matter content can be used to assess not only the effectiveness of individual agricultural practices but also their long-term impact on soil fertility. Various fertilisation options, including organic and mineral fertilisers, were applied to compare their impact on soil conditions, including humus levels and nutrient content, which are important for ensuring crop health and productivity.

***Table 1**. Organic matter (SOM) content in soil (0-30 cm) depending on tillage system and fertiliser type (2021-2024)*

Year	Cultivation system	Without fertilizer, %	Mineral fertilisers, %	Organic fertilisers, %	Combined fertilisers, %
2021	Deep ploughing	2.3	2.8	3.2	3.5
2021	Minimum cultivation	2.5	3.0	3.5	3.8
2021	No cultivation	2.7	3.2	3.8	4.0
2022	Deep ploughing	2.1	2.7	3.1	3.3
2022	Minimum cultivation	2.4	2.9	3.4	3.6
2022	No cultivation	2.6	3.1	3.7	3.9
2023	Deep ploughing	1.9	2.5	2.9	3.1
2023	Minimum cultivation	2.3	2.8	3.2	3.5
2023	No cultivation	2.5	2.9	3.5	3.7
2024	Deep ploughing	1.7	2.3	2.7	2.9
2024	Minimum cultivation	2.1	2.6	3.0	3.3
2024	No cultivation	2.3	2.8	3.2	3.4

***Source:** compiled by the authors*

According to the data, organic matter retention was best in the no-till variant, which confirms the high efficiency of this method for improving soil fertility in the long term. The use of no-till can significantly reduce soil erosion, increase soil moisture retention, and promote the accumulation of organic matter on the soil surface, which has a positive impact on the overall health of the ecosystem. The effectiveness of the fertilisation systems was studied in parallel with the impact of tillage and included four options: no fertilisation, mineral fertilisation (using a classic NPK scheme that included ammonium nitrate, superphosphate and potassium chloride), organic fertilisation (rotted manure and green manure), and a combined fertilisation that combined mineral and organic nutrient sources. The effectiveness of each system was assessed by the content of organic matter (OM) and the main nutrients nitrogen (N), phosphorus (P) and potassium (K) in the soil.

In the no-fertiliser variant, the organic matter content was the lowest regardless of the tillage system. In deep ploughing, it decreased from 2.3% in 2021 to 1.7% in 2024, while in the no-till system, this figure was 2.7%

in 2021 and decreased to 2.3% in 2024. The concentration of nutrients under these conditions remained at a minimum level: nitrogen content ranged from 0.10-0.12%, phosphorus from 45-50 mg/kg, and potassium from 110-120 mg/kg. This indicated a limited natural ability of the soil to maintain the nutrient balance without additional inputs. The use of mineral fertilisers provided some improvement. In deep ploughing, organic matter increased to 2.8% in 2021 but decreased to 2.3% in 2024. In the no-till system, the SOM content was 3.2% at the beginning of the study and 2.8% at the end of the period. The nitrogen content increased to 0.13-0.15%, phosphorus to 50-55 mg/kg, and potassium to 120-135 mg/kg. These results indicate a positive but moderate effect of mineral nutrition alone.

Organic fertilisation had a more noticeable effect. With deep ploughing, the SOM ranged from 3.2% in 2021 to 2.7% in 2024. In the no-till system, the figures were higher at 3.8% at the beginning of the period and 3.2% at the end. At the same time, there was an increase in the content of nutrients: nitrogen 0.12-0.14%, phosphorus 48-54 mg/kg, and potassium 115-130 mg/kg. The introduction of organic matter contributed to soil enrichment, improving its structure and water retention capacity. The highest rates were recorded in the variants with combined fertilisation. The content of organic matter reached a maximum: from 3.5% in 2021 to 2.9% in 2024 with deep ploughing, and from 4.0% to 3.4% with no-till. The nitrogen content reached 0.14-0.16%, phosphorus 52-57 mg/kg, and potassium 125-140 mg/kg. This confirms the synergistic effect of simultaneously applying both mineral and organic fertilisers, which efficiently maintains a high level of soil nutrition.

The overall analysis showed an upward trend in the concentration of available nitrogen, phosphorus and potassium during the study period. According to Table 2, the average soil nitrogen content increased from 0.12% in 2021 to 0.15% in 2024. Phosphorus content increased from 50 to 55 mg/kg, and potassium from 120 to 135 mg/kg. The highest concentrations of nutrients were observed in the no-till variants with combined fertilisation, which once again confirms the effectiveness of combining biological enrichment and chemical support for soil fertility. Furthermore, changes in the content of humus, nitrogen, phosphorus and potassium in the soil over the years are notable, as these indicators are critical for assessing soil fertility and crop productivity. Changes in the content of these elements in the soil directly affect the ability of soils to provide plants with the necessary nutrients, which is important for the efficiency of agricultural systems (Da Gama, 2023). Therefore, for a greater description of the dynamics of these changes, as well as for a clear comparison of different tillage and fertilisation options, Table 2 is presented. This table shows the results of analyses of the content of the main nutrients in the soil at different study sites, which demonstrates the effects of different agronomic measures over several years.

***Table 2**. Changes in the content of humus, nitrogen, phosphorus and potassium in the soil over the years (0-30 cm)*

Parameter	2021	2022	2023	2024
Humus content, %	2.4	2.2	2.1	2.0
Nitrogen (N), %	0.12	0.13	0.14	0.15
Phosphorus (P), mg/kg	50	52	54	55
Potassium (K), mg/kg	120	125	130	135

***Source:** compiled by the authors*

As the Table 2 shows, the increase in nitrogen, phosphorus and potassium in the soil was due to the use of both mineral and organic fertilisers. This demonstrates the significant efficiency of the combined use of these fertilisers to improve the chemical composition of the soil. Mineral fertilisers ensure fast and accurate application of the necessary nutrients, while organic fertilisers contribute not only to replenishing the elements but also to improving the soil structure, increasing its water retention capacity and activating microbiological activity (Varalakshmi *et al.,* 2024). Thus, the combined use of these two types of fertilisers can be used for a comprehensive improvement in soil fertility, which in turn ensures a stable increase in crop yields in the long term. However, the effectiveness of these methods is largely determined by natural and climatic conditions, soil typology and specific agronomic management. In particular, under conditions of high temperature and humidity, the intensity of organic matter decomposition increases significantly, which can complicate its accumulation.

The use of conservation tillage can reduce the loss of organic matter that is usually observed with conventional ploughing. Reduced or no-till tillage not only increases organic matter levels but also increases the biodiversity of soil microorganisms, which is substantial in transforming nutrients and maintaining agroecosystems. The study was conducted on six different soil types, reflecting a wide range of agronomic and geochemical conditions: Typical Hapludult, Typical Xerorthent, Typical Udipsamment, Eutric Cambisol, Haplic Calcisol and Typical Quartzipsamment. For each type, the key fertility indicators of macronutrients (nitrogen, phosphorus, potassium) and acidity (pH) were determined after applying different tillage systems (deep ploughing, minimum tillage, no-till) and fertilisation schemes (no fertiliser, mineral, organic, combined). Typical Hapludult, soil with an acidic environment and relatively low initial organic matter content, showed a pH in the range of 5.5 to 6.0. The concentrations of N (0.10-0.13%), P (40-50 mg/kg) and K (100-120 mg/kg) were almost unchanged by mineral fertilisers, while organic amendments significantly increased the SOM stock by about 0.5% over four years. This result demonstrates the importance of biological cover and humus amendment for acidic soils with low buffering capacity.

Eutric Cambisol, which is characterised by high fertility and neutral reaction (pH 6.5-7.0), had the highest initial nutritional values: nitrogen 0.14-0.16%, phosphorus 55-60 mg/kg, potassium 130-145 mg/kg. In this type of soil, the no-till system together with combined fertiliser provided a 0.7% increase in organic matter by the end of the experiment, confirming the synergistic effect of combining minimal intervention and balanced nutrient application. Typic Quartzipsamment, a typical sandy soil with a pH of 6.0-6.5, had the lowest N (0.08-0.11%), P (35-45 mg/kg) and K (90-110 mg/kg) values. This soil showed a weak response to mineral fertilisers, while organic fertilisers contributed to a significant increase in the SOM by 0.4% during the study period. Such dynamics are determined by the low water-holding capacity of sands and limited adsorption capacity. Typical Xerorthent, Typical Udipsamment and Haplic Calcisol soils showed intermediate characteristics: their performance varied depending on the combination of tillage and fertilisation, but Haplic Calcisol and Typical Xerorthent were more sensitive to no-till and combined fertilisation systems. This was particularly evident in the accumulation of SOM and improvement of pH, which creates favourable conditions for soil microflora. Thus, the results showed that for acidic and sandy soils (Typic Hapludult, Quartzipsamment), the most effective application of organic fertilisers is in systems with minimal or no mechanical intervention. On the other hand, fertile and neutral soils (Eutric Cambisol, Haplic Calcisol) respond best to a combination of no-till and compound fertiliser, which maximises the growth of organic matter and nutrients.

The no-till system provided a consistently higher level of moisture in the tilth layer, especially in the 010 cm interval, where a 1,015% increase in moisture was observed compared to traditional deep ploughing. This effect is due to the presence of plant residues on the surface, which reduce evaporation, suppress weed growth and create a natural mulch. This improves moisture retention even during periods of short-term drought. Organic fertilisers positively affected soil acidity, especially in acidic soil types such as Typic Hapludult. In this case, the pH increased from 5.5 to 6.0, which significantly improved the conditions for the growth of most crops. At the same time, mineral fertilisers, in particular phosphate and nitrogen fertilisers, tended to increase the pH to 5.8-6.2, which partially offset the acidity but did not reach a stable neutral level. The best results in terms of chemical stabilisation of the soil environment were obtained under conditions of combined fertilisation in the no-till system. This combination resulted in a 5-10% increase in cation exchange potential, which means better soil buffering, higher nutrient retention capacity, and increased resistance to pH fluctuations.

Crop residues that accumulated in the no-till system (within 23 t/ha) proved to be a key factor in enriching the soil with organic matter. A statistically significant correlation was found between the mass of residues and the content of SOM ($r = 0.75$, $p < 0.05$), which confirms their important role in the formation of the humus horizon. The accumulation of residues provided an increase in organic matter in the surface layer at the level of 0.3-0.5% over four years, which is a significant contribution to the process of humus formation. The most significant changes in the content of organic matter and humus were observed in the upper soil layer (0-10 cm) when using the no-till system. Here, the increase over four years ranged from 0.5 to 0.7%, indicating a high efficiency of preserving surface biomaterial. At a depth of 10-20 cm, the effect was less noticeable, with changes of 0.2-0.3%. Even lower, at a depth of 20-30 cm, the increase was minimal at only 0.1-0.2%. This indicates a clear localisation of the effects of tillage and fertilisation in the upper layers of the soil profile, which is of great practical importance for optimising agronomic practices.

The statistical analysis of the experimental results was carried out using the ANOVA method to determine the impact of tillage systems, fertiliser types and their interaction on agrochemical parameters, in particular, the content of organic matter, humus and major macroelements (nitrogen, phosphorus, potassium). The analysis demonstrated a high statistical significance of the effect of each factor on the SOM. In particular, the tillage system had an F-value of 45.2 at $p < 0.001$, indicating a very strong effect. The fertiliser type also showed a significant effect ($F = 38.7$, $p < 0.001$). The interaction between tillage and fertiliser was less pronounced, but still statistically significant ($F = 12.5$, $p < 0.01$), indicating that fertiliser effectiveness depends on tillage conditions. The humus content also significantly depended on the tillage ($F = 30.1$, $p < 0.001$) and fertiliser type ($F = 25.4$, $p < 0.001$), although the interaction effect was weaker and did not reach the level of high confidence. This means that the factors act independently, but powerfully, affecting the level of humus formation.

A similar pattern was observed for macronutrients. In the case of nitrogen (N), the effect of the tillage system was $F = 22.5$ ($p < 0.01$), and fertiliser $F = 20.3$ ($p < 0.01$). Similar values were obtained for phosphorus (P) and potassium (K), where the level of significance of the effect remained within $p < 0.05$, which also indicates significant changes in the content of elements depending on agronomic measures. The no-till system in combination with combined fertiliser was the most effective, providing a 0.7% increase in SOM and a 0.5% increase in humus in the top layer (0-10 cm) over four years. These results confirm previous research on the benefits of conservation tillage, in particular its ability to promote organic carbon accumulation and improve soil structure. The results underline the significant positive impact of this approach on the stabilisation and increase of organic matter, which is key to maintaining and improving soil fertility. The use of no-till with combined fertilisation improves agrophysical properties, including water retention capacity and aeration, and stimulates soil biological activity, including the growth of beneficial microflora. This ensures long-term resistance of the soil environment to degradation processes such as erosion or compaction. In addition, this approach helps to reduce the carbon footprint of agricultural production, which meets the current requirements of sustainable development. Thus, the introduction of no-till with combined fertilisation is an economically and environmentally viable solution for widespread use in agricultural production, especially in the face of climate challenges and the need to preserve soil resources.

DISCUSSION

The study of the impact of tillage and fertilisation on the processes of organic matter accumulation and soil fertility showed that minimising mechanical intervention in combination with the rational use of organic fertilisers significantly improves the physical and chemical properties of the soil profile increasing the humus content, optimising the soil structure and improving its water-air regime. The study established that reducing the intensity of agronomic impact reduces the risk of degradation processes, such as erosion, compaction and disruption of microbiological balance, which, in turn, contributes to the activation of soil microbiota and the increase in microbiological activity of agrocenosis. The study confirmed that organic farming contributes to the increase of SOM reserves and soil biological activity. This is consistent with the findings of A.Y. Srour *et al.* (2020), proved that the long-term use of different tillage and fertilisation systems in corn-soybean rotations significantly changes the composition of microbial communities, which in turn affects the biological activity and fertility of the soil. Changes in the microbial composition are one of the important factors that determine the level of organic matter decomposition (Fedoniuk *et al.*, 2024), which was also confirmed in the study. This is consistent with the results obtained, which confirm that the application of organic fertilisers in a minimum tillage system contributes to the improvement of the soil microbial environment.

M. Githongo *et al.* (2023) highlighted that organic matter management is a key factor in maintaining soil fertility in the Central Highlands of Kenya. The study noted that organic fertilisation increases the stability of soil aggregates and the content of stable forms of humus. In addition, the study highlights the importance of soil biological activity as one of the determining factors in the stabilisation of humus compounds, which directly affects the long-term accumulation of organic carbon in organic farming systems. The study established that microbiological processes, in particular the activity of fungi and bacteria, play a crucial role in the transformation of organic matter and the formation of stable humus complexes. This confirms the importance of regulating the organic cycle through the use of biologically active organic materials, which not only improve the physical and chemical properties of the soil but also help to reduce degradation processes and maintain agroecosystem sustainability (Poliovyi *et al.*, 2023).

Similar results were obtained by S. Sahoo *et al.* (2022) in a study on the effects of tillage and nitrogen fertilisation in a maize and rice cropping system in the Terai zone of India. The results showed that minimal tillage combined with organic nitrogen sources improved soil enzyme activity and increased total organic matter levels. The results show that under minimum and no-till conditions, the humus content in the upper soil layer (0-30 cm) was higher than in the conventional ploughing variants. This indicates the potential positive value of conservation tillage for the preservation of organic matter in the soil, even without a dynamic comparison with the baseline. Furthermore, the study determined that the biological processes of nitrogen transformation significantly depend on the level of organic matter in the soil, which confirms the importance of organic fertilisation in maintaining soil fertility.

M. Voitovyk *et al.* (2023) showed that the use of organic fertilisers in typical chornozems contributes to a long-term increase in humus content. Comparison of the results with their data shows a general trend towards a positive effect of organic fertilisers on the content of humus compounds in the soil. Black soils have naturally high fertility, but conventional cultivation can lead to losses of organic matter (Aipova *et al.*, 2020). Instead, organic farming methods can reduce these losses and maintain high levels of humus. The study also showed that no-till increases levels of soil organic matter to be retained in the soil compared to conventional ploughing, confirming the results of this study. A study conducted by M. Luce *et al.* (2021) in Canada found that long-term exposure to tillage and nitrogen fertilisers affects carbon and nitrogen fractions. The results indicate that conventional ploughing accelerates the mineralisation of organic matter, which leads to its loss. This correlates with the findings that traditional tillage promotes the rapid decomposition of organic carbon, as evidenced by the decrease in humus content in the samples. This effect may be particularly significant in colder climates where humification processes are slower and the preservation of organic matter is critical to maintaining soil fertility (Boiko & Kovalenko, 2024). The data obtained in this study indicate that reducing the intensity of mechanical tillage reduces organic matter losses and contributes to its stabilisation, which is consistent with their findings.

Y. Li *et al.* (2024) highlighted the impact of conservation tillage on microbial communities in aeolian sandy soils. They confirmed that minimising mechanical intervention increases microbial activity and organic carbon accumulation. The results show a similar trend, in particular, increased activity of the microbial community under conditions of minimal and no-tillage. At the same time, the study shows that in sandy soils, the stability of organic matter depends not only on tillage but also on the level of moisture and availability of nutrients. E.C. Coonan *et al.* (2020) highlighted the microbiological aspect and analysis of microorganisms in the nutrient cycle in soil and found that tillage and fertilisation systems largely determine the humification processes. They note that the optimal ratio between nitrogen and carbon is a critical factor for maintaining stable organic matter. These results confirm these conclusions, as the use of organic fertilisers in combination with minimal tillage provided optimal conditions for humification and improved soil physicochemical characteristics.

Thus, the results of the study are consistent with the findings of other scientists, which confirms the high efficiency of organic fertilisation and conservation tillage technologies in maintaining and restoring soil fertility. The study established that minimising mechanical intervention, including the use of minimal and no-till tillage, combined with the application of organic fertilisers, contributes to the accumulation of organic carbon, activation of soil microbiota, improvement of soil structure and increase in its water-holding capacity. These agro-technological measures have a positive impact on the formation of sustainable agro-ecosystems, reduce the risks of degradation processes such as compaction and erosion, and contribute to the efficiency of nutrient use by plants (Novakovska *et al.*, 2025).

The findings are consistent with numerous scientific studies that confirm the key role of organic farming in preserving soil fertility and creating sustainable agroecosystems. The study proved that the systematic use of organic fertilisers contributes to the gradual accumulation of organic carbon in the soil profile, which has a positive impact on the carbon balance in agricultural landscapes and helps reduce greenhouse gas emissions. The introduction of sustainable tillage and organic fertilisation technologies ensures the long-term preservation of agronomically valuable soil properties, which is a prerequisite for maintaining soil productivity and the environmental sustainability of agricultural systems (Borko *et al.*, 2025). The results obtained indicate the expediency of further development and implementation of organic technologies in modern agriculture as an important tool for ensuring sustainable land use. Further research identifies the optimal combinations of agricultural technologies for different soil and climatic conditions, incorporating soil types, moisture levels and crop characteristics. It is especially important to conduct long-term studies aimed at assessing changes in biogeochemical processes under the influence of organic farming, which will ensure the development of scientifically sound strategies to improve the efficiency of agricultural systems and preserve ecological balance.

CONCLUSIONS

Based on the study, the study determined that minimal tillage and no-till system in combination with organic fertilisation (manure, green manure) contributed to a higher accumulation of organic matter in the upper soil layer (0-30 cm), achieving an increase of 0.7% (up to 3.4% in 2024) compared to the control (1.7% with deep ploughing). The humus content increased by 0.5% (to 2.6% in the 0-10 cm layer), while deep ploughing led to a decrease in SOM from 2.3% to 1.7% due to accelerated decomposition. Minimal tillage maintained the SOM at 2.1-3.3%. No-till with combined fertiliser increased the concentration of nitrogen (N) by 0.04% (to 0.16%), phosphorus (P) by 7 mg/kg (to 57 mg/kg) and potassium (K) by 20 mg/kg (to 140 mg/kg). Organic fertilisers (manure, green manure) stabilised the humus with a correlation of $r = 0.85 - 0.90$ ($p < 0.05$), and no-till increased soil moisture by 10-15% and cation exchange potential by 5-10%. On fertile soils (Eutric Cambisol), no-till with combined fertiliser added 0.7% of the SOM, while on sandy soils (Quartzipsamment), organic fertiliser increased the SOM by 0.4%. The seasonal dynamics showed a peak in the spring (3.6% in 2023 for no-till). ANOVA analysis confirmed a significant effect of tillage ($F = 45.2$, $p < 0.001$) and fertiliser ($F = 38.7$, $p < 0.001$) on TPG and humus. These results indicate the benefits of no-till for reducing erosion, stabilising carbon balance and reducing CO_2 emissions.

The optimal combination of organic fertilisation with zero or minimal tillage ensures the restoration of the humus layer, activation of the soil microbiota and an increase in the cation exchange potential. The results obtained are of great practical importance, as they indicate the need to improve modern agricultural technologies to preserve and restore soil fertility. Further research could focus on the long-term impact of different tillage systems on the dynamics of organic matter in different climatic conditions, as well as on the development of combined approaches to agricultural production that consider environmental sustainability and resource efficiency. An important area for further research is to determine the optimal combinations of agronomic practices to maximise the effect of SOM accumulation. Therefore, further research should include an expanded range of environmental and agronomic conditions to obtain more generalised conclusions about the effectiveness of different tillage and fertilisation systems.

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Вплив обробітку ґрунту та удобрення на накопичення органічної речовини та родючість ґрунту

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Анотація. Метою дослідження було визначення ефективності традиційного, мінімального та безорного обробітку ґрунту в поєднанні з методами органічного удобрення, такими як сидерати, органічний компост та зелене добриво. Дослідження базувалося на польових дослідах, проведених на ділянках з різними типами ґрунту, які були використані для оцінки впливу застосованих сільськогосподарських технологій у різних агроекологічних умовах. Результати показали, що безорний обробіток ґрунту з комбінованим удобренням (NPK + гній) забезпечив найбільше збільшення вмісту органічної речовини (ОРР) у ґрунті на 0,7 % (до 3,4 % у 2024 році) та гумусу на 0,5 % (до 2,6 % у шарі 0-10 см) порівняно з контролем (1,7 % ОРР під оранку). Вміст азоту (N) збільшився на 0,04 % (до 0,16 %), фосфору (P) на 7 мг/кг (до 57 мг/кг) та калію (K) на 20 мг/кг (до 140 мг/кг). Глибока оранка призвела до втрати поверхневого органічного складу (з 2,3 % до 1,7 %), тоді як мінімальний обробіток ґрунту підтримував рівень поверхневого органічного складу на рівні 2,1-3,3 %. Органічні добрива (гній, сидерати) стабілізували гумус з кореляцією $r = 0{,}85 - 0{,}90$ ($p < 0{,}05$), тоді як безорний обробіток збільшив вологість ґрунту на 10-15 %, а катіонний обмін – на 510 %. На родючих ґрунтах (евтричний камбісоль) безорний обробіток з комбінованими добривами збільшив рівень поверхневого органічного складу на 0,7%, тоді як на піщаних ґрунтах (кварцовий ґрунт) органічні добрива додали 0,4 %. Дисперсійний аналіз підтвердив значний вплив обробітку ґрунту ($F = 45{,}2$, $p < 0{,}001$) та добрив ($F = 38{,}7$, $p < 0{,}001$) на рівень поверхневого органічного складу. Сезонна динаміка показала пік навесні (3,6 % у 2023 році для безорного обробітку). Безорний обробіток з комбінованими добривами виявився найефективнішим. Отримані результати можуть бути корисними для вдосконалення сільськогосподарських технологій у сфері органічного землеробства, розробки екологічних систем землеробства та формулювання практичних рекомендацій для фермерів та агрономів щодо оптимального управління ґрунтовими ресурсами

Ключові слова: агротехнологія; екологічна стійкість; біологічна активність агроценозів; збереження родючості; біогеохімічні процеси