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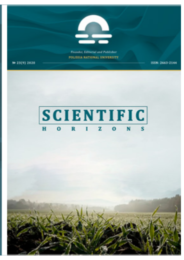

Effect of tillage methods and biological preparations on the structural state of soil

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Abstract. The aim of this study was to evaluate the effects of different primary tillage technologies and the application of biopreparations on the structural condition of chernozem soils in sunflower cultivation. Understanding these effects is essential for optimising soil management practices and enhancing crop productivity. To achieve this goal, the study employed a combination of field, laboratory, and statistical methods. Field methods included the establishment of a stationary experiment using a randomised block design. Laboratory analyses involved the determination of soil particle-size fractions using the dry sieving method. Statistical analysis, specifically analysis of variance, was applied to assess the significance of differences among treatments. The results demonstrated that conventional plowing produced the highest content of large aggregates (>10 mm) in the 0-30 cm soil layer (35.1%). Nevertheless, this method was associated with a relatively low proportion of agronomically valuable 5-3 mm fractions, thereby reducing structural stability against erosive processes. In contrast, chisel subsoiling and deep non-inversion tillage reduced the proportion of large clods while increasing the proportion of optimally sized aggregates by 3.6-8.3% compared to the control. These improvements contributed to a better soil water-air regime and created favorable conditions for sunflower root development. The application of microbial biopreparations (Azotobacter, Bacillus subtilis, Trichoderma, and a microbial consortium) further improved soil structure by decreasing the proportion of oversised clods and enhancing the share of agronomically valuable fractions 0.25-10 mm. The most pronounced effect was recorded during the consortium treatment, which contributed to the formation of a more homogeneous and stable lumpy-grained structure, where the number of agronomically valuable aggregates was 81.5%. The practical significance of this study lies in identifying effective tillage practices and the use of biopreparations to improve the structural condition of typical chernozem under sunflower cultivation.

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The obtained results can be applied in production systems to preserve soil fertility, enhance water use efficiency, and ensure the ecological stability of agroecosystems

Keywords: tillage systems; soil structural-aggregate composition; chernozem; agrophysical propertie; sunflower; biologisation of agriculture

INTRODUCTION

Enhancing soil fertility is a key objective of modern agriculture, as it directly affects the stability and efficiency of crop production. One of the main indicators of soil fertility is its structural status, which determines water retention, aeration, and nutrient availability. In this context, studying the effects of different tillage practices and the application of biopreparations on soil structure is particularly relevant. X. Meng *et al.* (2024) emphasised that reduced-tillage technologies decrease mechanical impact on the soil and ensure a more stable structural condition, positively affecting the soil water regime and the development of crop root systems. Conventional tillage practices, such as moldboard ploughing, can lead to a reduction in soil aggregates, particularly in the upper soil layer. Specifically, W. Paye *et al.* (2024) reported a decrease in the content of 0.25-10 mm aggregates following ploughing to a depth of 25-27 cm. In contrast, the use of alternative tillage methods, such as chisel subsoiling, can positively influence soil structure preservation. For instance, C. Smith and P. Chalk (2021) observed an increase in aggregate content when applying chisel tillage to a depth of 30 cm. Among Ukrainian researchers, O. Poliakov *et al.* (2021) analysed energy efficiency and the impact on soil structure under primary tillage technologies in the southern regions of Ukraine. International studies also emphasise the importance of integrating tillage technologies with biological approaches. A. Sher *et al.* (2021) investigated the combined effects of tillage and drought stress on sunflower productivity, showing that minimal tillage supports better morphophysiological traits compared to conventional tillage under arid conditions. M. Mokgolo *et al.* (2024) reported that the application of organic fertilizers in combination with different tillage systems enhances sunflower yield, indicating a synergistic effect between agrotechnology's and organic inputs. M. Nankova and N. Nenova (2023) noted that soil compaction under minimal tillage reduces leaf area, plant height, and yield, confirming the close relationship between soil structure and crop productivity.

Recently, there has been growing interest in the use of biopreparations, particularly plant-associated microorganisms, which can mitigate the negative effects of abiotic stresses and indirectly influence soil structural condition. Soil bacteria belonging to the PGPR (plant growth-promoting rhizobacteria) group produce phytohormones and secondary metabolites that stimulate root system development, improve the water regime in the rhizosphere, and promote the formation of organo-mineral bonds. These processes, in turn, activate mechanisms that stabilise soil aggregates, directly affecting the structural condition of chernozem soils in sunflower (*Helianthus annuus* L.) cultivation. R. Sammauria *et al.* (2020) reported that the application of microbial biopreparations capable of fixing atmospheric nitrogen, mobilising phosphorus and potassium, producing phytohormones, and stimulating root system development promotes an increase in water-stable aggregates, reduces soil bulk density, and improves field water-holding capacity. P. Yadav *et al.* (2024) confirmed that the use of biopreparations enhances soil structural stability and ensures more efficient water retention, which is critical for root system development and the resilience of soil structure. M. Janmohammadi and N. Sabaghnia (2023) demonstrated that combining biopreparation application with conservation tillage technologies in sunflower crops significantly improves both soil structural properties and crop yield, highlighting the synergistic effect between biologisation and optimisation of agronomic practices.

Regarding biopreparations, recent studies in Ukrainian agricultural practice demonstrate their potential to improve soil properties. In particular, I. Nepran *et al.* (2021) analysed the effectiveness of biologically active substances on soil structure, showing that the application of humic preparations and microbial inoculants stimulates microbial development and positively affects aggregate composition. Research by Ye. Yurkevych *et al.* (2023) demonstrated that the use of the Groundfix preparation enhances crop productivity under different application methods. Additionally, C. Zhang *et al.* (2023) reported that the application of biopreparations can promote the formation of more stable soil aggregates, improving both soil structure and its water-physical properties. Despite these contributions, the combined effects of specific tillage methods (moldboard, chisel, non-inversion, and disk) together with biopreparation application on the structural condition of chernozem under sunflower cultivation in the Left-Bank Forest-Steppe of Ukraine remain insufficiently studied.

Sunflower occupies a leading position among oilseed crops both globally and in Ukraine; however, the stability of its yield largely depends on the structural condition of the soil. Optimisation of tillage systems and the application of biopreparations represent promising strategies for increasing the efficiency of sunflower production, particularly under conditions of climate change and growing demand for environmentally sustainable agriculture. Therefore, the integration of microbial biopreparations with soil-conserving tillage systems provides a promising approach for increasing agroecosystem resilience and improving the structural condition of chernozem soils in sunflower cultivation, supporting the rationale for an integrated management strategy in modern agriculture. Thus, the aim of this study was to determine the impact of selected primary tillage methods and biopreparations on the formation of the aggregate structure of typical chernozem in sunflower (*Helianthus annuus* L.) cultivation.

MATERIALS AND METHODS

The study was conducted in 2023-2024 at the Dokuchaevske experimental field of the State Biotechnological University, located in the Left-Bank Forest-Steppe zone of Ukraine. According to data from the Kharkiv National Agrarian University meteorological station, during the sunflower growing season (May-September) in 2023-2024, total precipitation amounted to 373.1 mm, and the average air temperature was 19.0 °C. The soil cover of the experimental field is represented by typical chernozem heavy loam on loess-like loam (Chernozem Haplic). This soil is characterised by good physical and mechanical, agrochemical, and some chemical properties, fairly high reserves of nutrients available to plants, high humus content, and intensive biological activity. The arable layer of the soil (0-30 cm) contains humus (according to Tyurin (DSTU 7828:2015, 2016)) – 4.9-5.1%, easily hydrolyzable nitrogen (according to Kornfield (DSTU 7863:2015, 2016)) – 81 mg/kg of soil, mobile forms of phosphorus and potassium (according to Chirikov (DSTU 4115:2002, 2003)) – 100 and 200 mg/kg of soil. Content of exchangeable cations: calcium – 37.8%, magnesium – 6.6%, sodium – 0.49%, potassium – 0.5%, hydrogen – 21 mg-equiv./kg soil. The soil reaction – pH: aqueous – 7.0, salt – 5.2-5.6. The experimental plots were arranged using a systematic method with four replicates. The size of the observation plot was 50 m^2.

Experiment A – primary tillage methods:

1. Ploughing with PLN-4-35 at 25-27 cm (control).
2. Chisel local tillage by PC-2.5 at 33-35 cm.
3. Non-moldboard tillage with PRN-31000 at 33-35 cm.
4. Disking by BDM-2.5 at 10-12 cm.

Experiment B – microbial biopreparations:

1. Control (without entry)
2. Azotobacter
3. Bacillus subtilis
4. Trichoderma
5. Microbial consortium (Azotobacter + Bacillus subtilis + Trichoderma).

The study on the effect of biopreparations was conducted under the background of moldboard plowing (PLN-4-35) to a depth of 25-27 cm. The plot area was 30 m², with an accounting area of 10 m². A total of 20 plots (five treatments with four replications) were established, covering a total area of 600 m². The experiment with biopreparations was analysed as an independent single-factor trial in the statistical analysis. The plots were arranged systematically. Effect of biopreparations on soil structure in sunflower Limagrain LG 59580 crops was studied in a randomised block design with four replications. Seed inoculation was performed using four microbial preparations: Azotobacter chroococcum (strain AC-10, Collection № IMV B-7075) – nitrogen-fixing agent; Bacillus subtilis (strain BS-26, IMV B-7324) – phosphate-mobilising bacterium; Trichoderma harzianum (strain TH-17, IMV B-7162) – fungal antagonist; a consortium of the above strains in equal proportions. The preparations were applied as liquid suspensions with a concentration of 1×10^9 CFU/mL. Sterile water with 0.5% humic substances was used as a carrier and natural adhesive. Seeds were sprayed with the suspension 24 hours before sowing at a rate of 10 mL per 1 kg of seed (≈1×10^8 CFU per seed). The inoculation was performed at 20 ± 2°C and relative humidity of 60-70%. Treated seeds were air-dried and stored under ventilated conditions at ≤15°C until sowing. In the consortium treatment, the ratio of Azotobacter:Bacillus:Trichoderma was 1:1:1 in terms of viable cell count. All treatments were applied only under the ploughing background, without additional soil inoculation.

The experimental agrobackground was uniform across treatments: previous crop – winter wheat; mineral fertilisation – $N_{90}P_{60}K_{60}$ kg/ha a.i.; herbicide regime – application of "Euro-Lightning" at 1.0 l/ha in the 3-4 leaf stage. Soil structural–aggregate composition was determined using the sieving method modified by N.I. Savvinov with the definition of the main fractions of structural aggregates: lumpy (size >10 mm), agronomically valuable (10-0.25 mm) and dusty fractions (<0.25 mm) (DSTU 4744:2007, 2008). This method assesses the granulometric composition of soil aggregates by passing soil samples through a series of sieves with different mesh sizes. The material retained on each sieve was weighed, and the percentage of each fraction was calculated, allowing the classification of soil aggregates by size. The statistical assessment of the reliability of the differences in the measurement results was carried out using the least significant difference ($LSD_{0.5}$) by comparing the calculated Fisher criterion with the theoretical one.

RESULTS AND DISCUSSION

The analysis of soil structural condition revealed significant differences in aggregate distribution depending on the tillage method. In the upper 0-10 cm soil layer, the control treatment (ploughing) exhibited the highest proportion of aggregates >10 mm at 42.4%, which is 1.3-20.6% higher than in the other treatments (Table 1), indicating a lower degree of aggregate fragmentation under conventional plowing. Chisel local tillage reduced the proportion of large clods to 36.3%, while non-inversion tillage further decreased it to 21.8%, reflecting more intensive breakdown of large aggregates and the formation of a more uniform structure. The highest content of the agronomically valuable 5-3 mm fraction was observed under non-inversion tillage (18.7%), which is 10% higher than in the control. Disking maintained a high proportion of large aggregates >10 mm (41.1%), similar to ploughing, but exhibited a lower content of fine fractions (<1 mm).

***Table 1**. Effect of different tillage practices on soil aggregate content*

Soil layer, cm	Content of macroaggregate fractions, %; by diameter, mm							
	>10	10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25
Ploughing with PLN-4-35 at 25-27 cm (control)								
0-10	42.4	11.2	8.0	8.7	8.2	11.3	3.1	4.5
10-20	37.9	8.4	10.7	12.3	9.2	10.8	3.7	4.3
20-30	25.1	10.4	11.9	18.0	15.7	10.9	2.5	4.0
0-30	35.1	10.0	10.2	13.0	11.0	11.0	3.1	4.3
Chisel local tillage by PC-2.5 at 33-35 cm								
0-10	36.3	9.3	10.4	14.7	10.1	12.3	2.1	2.9
10-20	30.4	11.7	12.4	19.3	12.7	9.1	1.6	1.8
20-30	28.6	10.8	11.0	15.8	11.2	13.9	2.8	3.6
0-30	31.8	10.6	11.3	16.6	11.3	11.8	2.2	2.8
Non-moldboard tillage with PRN-31000 at 33-35 cm								
0-10	21.8	11.8	10.0	18.7	16.1	14.7	2.3	2.9
10-20	25.9	14.7	16.6	22.6	10.7	7.3	0.9	0.8
20-30	17.2	16.9	20.3	22.6	10.8	8.3	1.4	1.4
0-30	21.6	14.5	15.6	21.3	12.5	10.1	1.5	1.7
Disking by BDM-2.5 at 10-12 cm								
0-10	41.1	9.4	9.0	12.8	10.6	10.6	1.9	2.7
10-20	19.8	18.2	20.9	20.6	8.5	8.3	1.3	1.5
20-30	37.3	25.3	15.9	11.7	4.4	3.6	0.7	0.6
0-30	32.7	17.6	15.3	15.0	7.9	7.5	1.3	1.6

***Source:** developed by the authors*

More pronounced changes in soil aggregate composition were observed in the 10-20 cm layer under different tillage practices. In the control treatment, the proportion of aggregates >10 mm was 37.9%, whereas it decreased to 25.9% under non-inversion tillage and to 19.8% under disking. In the disking variant, there was a notable increase in the 10-7 mm (18.2%) and 7-5 mm (20.9%) fractions, indicating active fragmentation of structural units in this layer. Chisel local tillage was characterised by an increased content of the 5-3 mm fraction (19.3%), which is 7% higher than in the control. Under non-inversion tillage, the same fraction reached 22.6%, exceeding the control by 10.3%. The results obtained demonstrate that soil tillage systems exert a decisive influence on the structural organisation of the plough layer, particularly in the 20-30 cm horizon. The prevalence of large aggregates (>10 mm) under conventional ploughing indicates the formation of compacted clods, a characteristic feature of inversion tillage, which restricts root penetration and reduces soil porosity. Similar conclusions were reported by V. Steponavičienė *et al.* (2023), who found that ploughed Chernozem soils exhibited increased bulk density and limited aeration compared with non-inversion tillage.

In contrast, the high proportion of 7-5 mm and 5-3 mm aggregates under non-moldboard tillage suggests the development of a more stable and uniform aggregate structure across the profile. B. Liu *et al.* (2024) confirmed that conservation tillage enhances the continuity of soil pore space and promotes aggregate binding through organic carbon stabilisation. The dominance of intermediate fractions under non-inversion systems can thus be attributed to minimal mechanical disturbance combined with the preservation of biological activity, particularly fungal hyphae and bacterial exudates that act as natural aggregating agents. Moreover, A. Vasilchenko *et al.* (2023) demonstrated that reduced tillage fosters greater microbial biomass and enzymatic activity in deeper horizons, which supports the stabilisation of soil aggregates through polysaccharide and glomalin accumulation. The trend observed in this study aligns with the findings of P. Wojewodzki *et al.* (2024), who emphasised that non-inversion tillage increases macroaggregate stability by maintaining higher levels of labile organic matter and hyphal networks. Disking, despite increasing the 10-7 mm fraction, resulted in uneven aggregate distribution, implying that shallow mechanical treatment fails to improve structural integrity in deeper horizons. J. Pöhlitz *et al.* (2022) noted similar effects in light-textured soils, where surface disking improved only the upper layer while leaving subsurface layers compacted. Consequently, the present results confirm that conservation and non-moldboard systems are more effective for maintaining the structural stability of typical chernozem soils than conventional ploughing or shallow disking.

The obtained results demonstrated that ploughing with the PLN-4-35 maintained a predominance of large aggregates (>10 mm) throughout the 0-30 cm layer, reflecting the typical cloddy structure of conventionally inverted soil. This phenomenon is associated with intensive mechanical disturbance and insufficient disintegration of the lower horizons. E. Tobiašová *et al.* (2023) also reported that conventional moldboard systems tend to produce a high share of large, unstable clods in chernozem soils, reducing structural uniformity and aggregate stability. In their study on maize-sunflower rotations, the proportion of aggregates >10 mm exceeded 40%, which is consistent with the present findings. In contrast, the current experiment showed that chisel and non-moldboard tillage promoted the formation of medium-sized aggregates (7-3 mm), contributing to a more favorable soil structure. V. Lozanova and I. Dimitrov (2021) found that chisel loosening at 30-35 cm improved water infiltration by 15% and increased the share of stable aggregates within the 5-3 mm range compared with ploughing. Likewise, L. Wang *et al.* (2023) observed that non-inversion tillage maintained higher aggregate stability in dry continental climates due to reduced mechanical disruption and better root–soil interactions. These trends correspond well with the present study, where non-moldboard tillage resulted in a 4.6% higher content of 5-3 mm aggregates than under ploughing, suggesting enhanced structural uniformity in the 20-30 cm horizon.

Disking to 10-12 cm produced a markedly different pattern. In this treatment, the upper layers (0-10 cm) contained a higher proportion of agronomically valuable aggregates (0.25-10 mm), whereas the deeper layers showed structural degradation. Similar outcomes were described by T. Das *et al.* (2021), who noted that shallow disking tends to over-pulverise surface soil while leaving compacted subsurface layers. M. Ramadhan (2021) also confirmed that excessive fragmentation of the topsoil under disking leads to unstable aggregate formation and increased erosion risk. The current results support these observations, demonstrating a decline in structural quality with depth under disking. The structural coefficient obtained in the present research ranged from 1.3 to 1.6 in the top 0-10 cm layer under ploughing and disking, indicating a satisfactory but not optimal structure. M. Voitovyk *et al.* (2024) in long-term experiments at Bila Tserkva National Agrarian University similarly found that different tillage methods significantly influence soil aggregation dynamics in sunflower agroecosystems. Their results revealed that both ploughing and deep non-moldboard tillage increased the proportion of agronomically valuable aggregates (0.25-10 mm) by approximately 6% at the beginning of the vegetation period, followed by a decline by harvest time due to structural re-compaction. This pattern mirrors the findings of the current study. The increased content of >10 mm and <0.25 mm fractions at the end of the growing season may indicate partial degradation of aggregate stability under repeated mechanical and environmental impacts. Overall, the comparison of results confirms that moderate loosening without inversion, combined with controlled mechanical load, ensures optimal aggregate distribution and water stability in typical chernozem soils. These structural improvements can create favorable conditions for sunflower root growth and moisture retention, thereby supporting sustainable soil management and long-term productivity.

The study revealed significant differences in the content of agronomically valuable aggregates sized 10-0.25 mm depending on the primary tillage system (Fig. 1). In the plowing treatment (control), the total proportion of these aggregates in the 0-30 cm layer was 62.6%. Under chisel tillage, a notable increase was observed, with the content of 0.25-10 mm aggregates averaging 4.0% higher than the control, indicating a more balanced structural condition of the arable layer. Deep non-moldboard tillage had the most favorable effect on aggregate formation across all soil layers, with the mean proportion reaching 77.2%, which exceeded the control by 14.6%. The greatest increases were recorded in the 0-10 cm surface layer (76.5%) and the 20-30 cm layer (81.7%). These results confirm the effectiveness of this tillage practice in increasing the share of aggregates optimal for soil physical properties, thereby improving water infiltration, aeration, and creating favorable conditions for sunflower root system development.

In the disking variant, soil structure was characterised by high variability. On average, aggregates in the 0.25-10 mm range accounted for 66.2%, a proportion comparable to that observed under chisel local tillage but with more pronounced differences between soil layers. In the 10-20 cm soil layer, the share of these aggregates increased to 79.3%, whereas in the 20-30 cm soil layer it sharply decreased to 62.2%. This pattern indicates structural heterogeneity and greater susceptibility of aggregates to breakdown in deeper soil layers. To assess the statistical significance of the differences, an approximate least significant difference (LSD_{05}) was used: 0-10 cm – 6.3, 10-20 cm – 7.0, 20-30 cm – 7.2, 0-30 cm – 6.8. The differences between the non-inversion tillage (PRN-31000) and plowing (PLN-4-35) exceeded the LSD in all layers, indicating their statistical significance within the experiment. Differences between chisel and disk tillage were less pronounced and, in some cases, did not exceed the LSD.

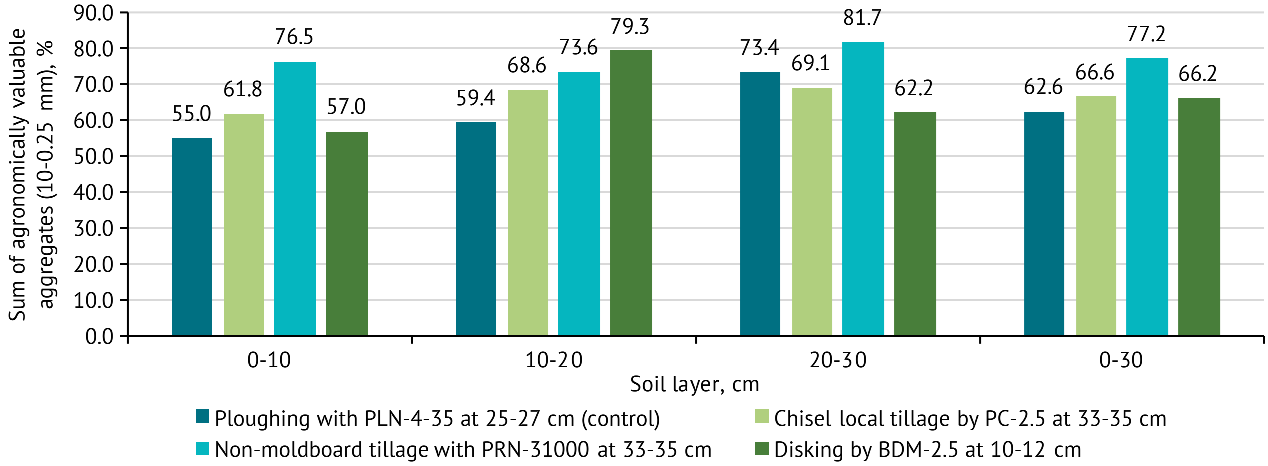

***Figure 1**. The content of agronomically valuable aggregates with a size of 0.25-10 mm, %*
***Source:** developed by the authors*

The results corroborate findings by I. Engell *et al.* (2022) and G. Kovács *et al.* (2023), who reported that conservation and non-inversion tillage maintain better aggregate stability and organic matter retention compared with conventional ploughing. Thus, the use of non-moldboard tillage in sunflower cultivation provides measurable improvements in the structural condition of typical chernozem soils. The obtained results demonstrate that different tillage systems substantially affect the proportion of agronomically valuable aggregates (0.25-10 mm), reflecting their influence on the physical and structural state of the chernozem. The higher proportion of such aggregates under non-moldboard tillage suggests improved soil aggregation and stability, which are critical indicators of soil quality and resilience to degradation. Similar outcomes were reported by Y. Kravchenko *et al.* (2022), who found that non-inversion tillage promoted the accumulation of medium-sized aggregates and enhanced aggregate-associated organic carbon in loamy chernozems. The authors explained this by reduced mechanical disturbance and greater microbial activity in the rhizosphere, which facilitated the cementation of particles into stable structural units. According to M. Malobane *et al.* (2021), chisel and strip tillage systems increase the proportion of water-stable macroaggregates compared to conventional ploughing by 8-15%, owing to the conservation of crop residues and improved pore connectivity. The moderate rise in aggregates of 0.25-10 mm observed in this experiment under chisel tillage (by 4.0% relative to control) corresponds well with their conclusions, confirming that partial soil loosening without inversion supports aggregate regeneration while maintaining aeration and moisture balance.

The pronounced improvement in aggregate formation under deep non-moldboard tillage aligns with findings by C. Wortmann and Y. Dang (2020), who observed enhanced aggregate stability and porosity in deep-loosened chernozem horizons due to reduced plow pan formation and increased biological aggregation. This indicates that loosening without soil turnover fosters a gradual reconstruction of natural structural horizons, which in the following study resulted in a 14.6% higher content of agronomically valuable aggregates compared to plowing. However, E. Farahani *et al.* (2022) reported that in some coarse-textured soils, excessive loosening can lead to temporary structural instability if organic matter is insufficient to sustain aggregate cohesion. This observation partly explains the variability seen in disking treatment in this article, where structural heterogeneity was apparent – especially the sharp decline of aggregates in the 20-30 cm layer – indicating the limited efficiency of shallow disk tillage for deeper profile improvement. The obtained patterns are consistent with the conclusions of A. Alinejadian-Bidabadi *et al.* (2021), who emphasised that soil aggregation is a dynamic process strongly governed by tillage intensity, residue management, and microbial activity. According to these authors, stable aggregates of 0.25-10 mm represent the optimal structural class for balancing aeration, water infiltration, and mechanical strength-parameters that determine the effective rooting of crops such as sunflower (*Helianthus annuus* L.). Thus, the increase in this fraction under non-inversion and chisel tillage in the following experiment indicates not only enhanced soil physical quality but also the potential for improved root development and yield stability.

The application of biopreparations had a distinct effect on the distribution of soil aggregate fractions in the 0-30 cm layer compared to the control. In the control treatment, the proportion of agronomically valuable aggregates (10-0.25 mm) averaged 62.6%, with a relatively high share of large clods (>10 mm, 25.0%) (Fig. 2). To assess the statistical significance of the differences, an approximate least significant difference (LSD) of 7.9% was applied. Considering this LSD_{05}, none of the treatments exceeded it relative to the control, indicating that the increase in the proportion of agronomically valuable aggregates was not statistically significant within the experiment. However, a tendency toward improved soil structure was observed with the application of Bacillus subtilis, Trichoderma, and a microbial consortium, which may have practical relevance with long-term use.

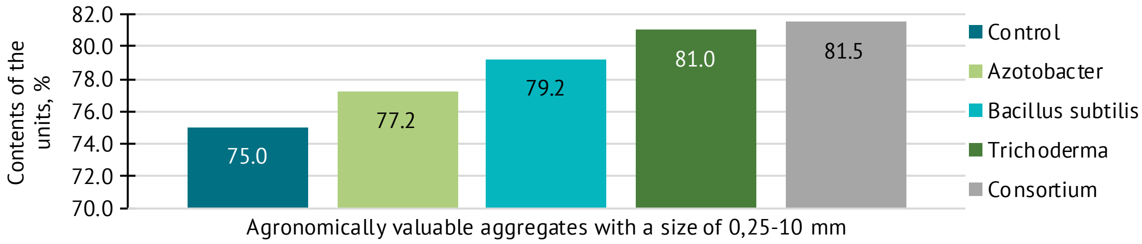

***Figure 2**. Effect of biopreparation application on soil structural condition in sunflower crops in the 0-30 cm layer*
***Source:** developed by the authors*

The obtained results clearly demonstrate that microbial inoculation modifies the soil's aggregate-size distribution by shifting it toward a finer and more stable structural state. Similar structural transformations were reported by B. Liu *et al.* (2024), who found that inoculation with Azotobacter chroococcum increased the proportion of microaggregates (2-1 mm) and enhanced soil aggregate stability through the accumulation of extracellular polysaccharides that cement mineral particles together. This agrees with the following findings, where Azotobacter inoculation increased the share of 1-2 mm aggregate to 17.5% compared to the control, indicating active biogenic aggregation processes. According to A. Ortiz and E. Sansinenea (2022), Bacillus subtilis strains secrete organic acids and biofilms that bind soil particles and stabilise medium-size fractions, particularly in the 3-5 mm range. A similar mechanism likely operated in the experiment in this article, where the 5-3 mm and 2-1 mm fraction under Bacillus subtilis treatment rose to 16.0% and 18.2%, respectively, suggesting enhanced formation of agronomically valuable aggregates.

The stronger effect observed under Trichoderma and microbial consortium treatments aligns with the conclusions of V. Bolokhovsky *et al.* (2024), who demonstrated that multi-strain inoculants based on Trichoderma harzianum intensify soil aggregation by stimulating fungal hyphal growth and increasing glomalin-related soil proteins. These biopolymers act as natural "glues," stabilising fine and medium-sized aggregates while reducing the presence of large clods. In this study, this mechanism was reflected in a decrease of large aggregates to 18.5-19.0% and an increase of 5-3 mm and 2-1 mm fraction up to 17.2-19.6%, indicating the development of a more uniform cloddy-granular structure. Comparable observations were made by A. Ansabayeva *et al.* (2025), who reported that integrated bioformulations containing Azotobacter, Bacillus, and Trichoderma enhanced soil porosity, aeration, and moisture retention by promoting the aggregation of soil particles into stable structural units. The results if this article confirm these conclusions, showing a consistent transition from a course, cloddy structure toward a finely aggregated one, which supports improved water infiltration and sunflower root growth. Thus, microbial inoculation, particularly using multifunctional consortia, can be regarded as a promising biotechnological tool for improving soil physical quality and structural resilience.

CONCLUSIONS

The study results demonstrated that primary tillage technology significantly influences the formation of soil structure in sunflower (*Helianthus annuus* L.) cultivation. Conventional moldboard plowing (PLN-4-35 at 25-27 cm) produced the highest proportion of large aggregates (>10 mm) in the 0-30 cm layer (35.1%), but this was accompanied by a lower content of agronomically valuable 5-3 mm fractions, which may reduce structural resistance to water erosion. Chisel subsoiling (PC-2.5 at 33-35 cm) and deep non-inversion tillage (PRN-31000 at 33-35 cm) reduced the proportion of large clods and increased the 5-3 mm fraction by 3.6-8.3% compared to the control, creating more favorable conditions for root growth and water infiltration. Disking (BDM-2.5 at 10-12 cm) increased the proportion of medium aggregates (10-5 mm) in the upper horizon but showed limited effect on deeper layers, which may limit its long-term effectiveness.

Based on statistical assessment using the least significant difference (LSD_{05}), deep non-inversion tillage (PRN-31000) significantly improved the overall proportion of agronomically valuable aggregates in the 0-30 cm layer (77.2%) compared to conventional plowing – 62.6%, whereas differences between chisel and disking treatments were less pronounced and mostly did not exceed the LSD_{05} threshold – 6.3-7.2%, indicating non-significant effects. The application of microbial biopreparations contributed to improving soil structural status in sunflower crops. Their use led to a reduction in oversised aggregates (>10 mm) and a simultaneous increase in agronomically valuable fractions (0.25-10 mm), particularly in the 5-3 mm and 2-1 mm range. Among the treatments, the microbial consortium exhibited the most pronounced effect, yielding the highest proportion of optimally sized aggregates (81.5%) and promoting a more homogeneous and stable granular–cloddy structure. However, LSD_{05} analysis (7.9%) indicated that differences from the control were not statistically significant, suggesting that while trends were positive, further research is required to confirm significance.

In summary, deep non-inversion and chisel tillage were the most effective mechanical methods for maintaining chernozem fertility and promoting a stable cloddy structure under the experimental conditions. The integration of microbial biopreparations can enhance soil porosity, water infiltration, and aeration, creating favorable conditions for sunflower root development. Future studies should investigate the long-term effects of combined tillage and biopreparation applications on soil structural dynamics, biological activity, and sunflower yield under changing climatic conditions, with particular attention to microbiological processes within different structural fractions and their role in stabilising soil organic matter.

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CONFLICT OF INTEREST

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Вплив способів обробітку ґрунту та біопрепаратів на структурний стан ґрунту

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Анотація. Мета дослідження полягала у визначенні впливу різних технологій основного обробітку ґрунту та застосування біопрепаратів на структурний стан чорнозему у посівах соняшнику. У дослідженні були використані такі методи: польовий (закладка стаціонарного досліду за схемою рендомізованих блоків), лабораторний (визначення фракційного складу ґрунту методом сухого просіювання), статистичний (дисперсійний аналіз для оцінки достовірності різниць між варіантами). Отримані результати показали, що традиційна оранка забезпечує найвищий вміст великих агрегатів (>10 мм) у шарі 0-30 см (35,1 %), проте характеризується відносно низьким вмістом агрономічно цінних фракцій 5-3 мм, що зменшує стійкість структури до впливу ерозійних процесів. Чизельний локальний та безполицевий глибокі обробітки сприяли зниженню частки великих грудок і підвищенню вмісту оптимальних за розміром агрегатів на 3,6-8,3 % у порівнянні з контролем, що забезпечує кращий водно-повітряний режим і сприятливі умови для розвитку кореневої системи соняшнику. Застосування мікробних біопрепаратів сприяло подальшому покращенню структури ґрунту за рахунок зменшення частки брилистих фракцій та збільшення частки агрономічно цінних розміром 0,25-10 мм. Найбільш виражений ефект було зафіксовано при обробці консорціумом, що сприяло формуванню більш однорідної та стабільної грудкувато-зернистої структури, де кількість агрономічно цінних агрегатів склала 81,5 %. Практична цінність роботи полягає у визначенні ефективних прийомів обробітку ґрунту та застосування біопрепаратів для поліпшення структурного стану чорнозему типового в посівах соняшнику. Отримані результати можуть бути використані у виробничих умовах для збереження родючості ґрунтів, підвищення ефективності використання вологи та забезпечення екологічної стійкості агроекосистем

Ключові слова: системи основного обробітку; структурно-агрегатний склад ґрунту; чорнозем; агрофізичні властивості; соняшник; біологізація землеробства