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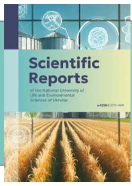

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Structural and aggregate composition of typical chernozem under intercropping and biologically based fertilisation systems

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Abstract. The relevance of this study arises from the urgent need to address the alarming extent of agrophysical soil degradation in Ukraine and to meet the requirements of the European Green Deal by shifting from conventional intensive technologies to environmentally sound practices. These include intercropping and the application of organic fertilisers to achieve land degradation neutrality. The study aimed to investigate the effects of different fertilisation systems on the structural and aggregate composition of typical medium-loam chernozem under spring barley, pea, and a three-component barley-pea-faba bean intercrop. The study employed field methods, laboratory dry sieving of soil samples to determine their structural and aggregate composition, and analytical and statistical methods. The three-component barley-pea-faba bean intercrop produced the most favourable structural condition of typical chernozem among the three cropping treatments under all fertilisation systems. In the 0-30 cm soil layer, the proportion of agronomically valuable aggregates measuring 0.25-10 mm was 10.76% higher under intercropping than under barley and 5.06% higher than under pea. Soil structure under pea was more favourable than under barley monoculture. Among the fertilisation systems, the

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highest structure coefficient was recorded following compost application at a rate equivalent to N50, followed by vermicompost. Lower values were obtained with the combined application of compost, vermicompost, and mineral nitrogen, while mineral fertilisation with N_{50} had the least favourable effect on soil structure. The practical significance of the study lies in demonstrating that organic fertilisers, particularly compost and vermicompost, should be applied to preserve and restore soil structure, whereas the exclusive use of mineral nitrogen fertilisation adversely affects the structural and aggregate composition of the soil

Keywords: soil structure; agronomically valuable aggregates; soil health; pea; faba bean; barley

Introduction

Indicators of soil structural condition are key determinants of soil health, as only well-structured soil can provide optimal conditions for plant growth and development. Soil structure governs water, air, and thermal regimes, the intensity of biological processes, the capacity to accumulate and retain moisture and nutrients, and the efficiency of fertiliser use. A well-developed structure promotes root-system growth and increases the resilience of agroecosystems to drought, heavy rainfall, and other adverse climatic and environmental factors.

Agrophysical soil degradation is a particularly pressing concern for Ukrainian chernozems, which form the basis of the country's land resources and are among the most fertile soils in the world. However, their natural properties are gradually deteriorating as a result of prolonged intensive agricultural use. The principal causes of this form of degradation include the high proportion of cultivated land, excessive mechanical pressure exerted on the soil by modern agricultural machinery, the use of intensive crop-production technologies, failure to follow scientifically based crop rotations, and insufficient application of organic fertilisers. Other contributing factors include the inadequate return of crop residues to the soil and declining organic matter content, both of which adversely affect aggregate formation.

These processes result in the destruction of agronomically valuable aggregates, leading to excessive compaction, poorer aeration, reduced water permeability and water-holding capacity in the fertile soil layer, intensified erosion, and lower crop productivity. Under current climate-change conditions, characterised by increasingly frequent prolonged droughts and intense rainfall events, maintaining an optimal soil structure has become especially important. It is therefore necessary to examine innovative, environmentally sound, and soil-conserving agronomic practices capable of restoring soil structure, improving soil fertility, and supporting the sustainable functioning of agroecosystems.

In the context of Ukraine's alignment with the European Green Deal, changes in crop-production practices are essential to ensure soil regeneration (Achasova & Achasov, 2024). O.L. Tonkha *et al*. (2025) have also reported an intensification of wind erosion, dehumification, and agrophysical soil degradation. R. Tykhenko *et al*. (2025) examined the environmental sustainability of territories in the context of food security and highlighted the need to introduce sustainable technologies in the agricultural sector. At the same time, S.V. Zhuravel *et al*. (2020) emphasised that regenerative agriculture reduces environmental impacts and prevents soil degradation through the application of organic fertilisers. M.V. Yakymovych *et al*. (2025) noted the growing global interest in composting as part of the sustainable development of the agricultural sector. As mineral fertiliser prices continue to rise and the mineral raw materials used in their production are finite, organic fertilisers, particularly manure and compost, represent an environmentally and economically viable alternative (Kelbesa, 2021; Hoque *et al.*, 2022). Based on analyses of nutrient and organic matter content, M. Jakubus & W. Michalak-Oparowska (2022) concluded that converting biowaste into compost and vermicompost is both economically and environmentally justified. These two fertilisers provide organic matter and nutrients, improve the physical and chemical properties of soil, and stimulate soil biological processes. They may therefore be used to enhance soil fertility and crop productivity within the framework of sustainable agricultural development (Amaya-Gómez *et al.*, 2025).

Research into the effects of organic and mineral fertilisers, as well as their combined application in monocrops and intercrops, is therefore important for assessing changes in soil physical properties. This study aimed to evaluate changes in the proportion of structural aggregates in typical chernozem under different mineral and organic fertilisation treatments and in monocrops and a three-component intercrop.

Materials and Methods

The effects of intercropping and different fertilisation systems were studied in 2025 in a field experiment established at the Separate Subdivision of the National University of Life and Environmental Sciences of Ukraine of Ukraine "Agronomic Research Station", located in Vasylkiv District, Kyiv Region. The experiment comprised two factors.

Factor A – cropping system: spring barley monocrop, pea monocrop, two-component intercrops, and a three-component pea-barley-faba bean intercrop. The most contrasting treatments in terms of their effects on soil physical properties were selected for comparison, namely the pea monocrop, barley monocrop, and pea-barley-faba bean intercrop.

Factor B – fertilisation systems:

- T1 – N_0 (control);
- T2 – N_{50} (mineral nitrogen);
- T3 – N_{50} (compost);
- T4 – N_{25} (compost) + N_{25} (mineral nitrogen);
- T5 – N_{50} (vermicompost);
- T6 – N_{25} (vermicompost) + N_{25} (mineral nitrogen).

Mineral nitrogen was applied in the form of ammonium nitrate. The area of each experimental plot was 15 m^2. Pea and faba bean were sown to a depth of 6-8 cm at seeding rates of 350,000 per hectare and 240,000 per hectare, respectively. Barley was sown to a depth of 3-4 cm at a seeding rate of 1.5 million seeds per hectare. The plots were arranged in a randomised design with three replicates. The soil of the experimental site was a typical medium-loam chernozem containing 3.6% humus, with a neutral soil reaction of pH 6.8 and a base saturation of 93%. Soil samples were collected from the experimental treatments in accordance with DSTU ISO 10381-2:2004 (2004) from the 0-10, 10-20, and 20-30 cm layers. Their structural composition was determined in accordance with DSTU 4744:2007 (2007). The proportion of agronomically valuable aggregates was calculated as the sum of fractions measuring 0.25-10 mm. The structure coefficient (K_{str}) was calculated as the ratio of the proportion of agronomically valuable aggregates to the combined proportion of dusty aggregates smaller than 0.25 mm and cloddy aggregates larger than 10 mm. Statistical analysis was performed using ANOVA. The significance of differences was assessed using Fisher's F-test by comparing with the critical $F_{0.05}$ value at the corresponding degrees of freedom. The significance level was set at $\alpha = 0.05$. For pairwise comparisons of means, the least significant difference was calculated at the significance level (LSD_{05}).

Results

The structural and aggregate composition of the soil varied according to the crops grown and the fertilisation systems applied. Analysis of structural aggregates in the 0-30 cm soil layer showed that, under barley and pea monocrops and the three-component barley-pea-faba bean intercrop, soil structural condition was classified as excellent according to the scale developed by

S.I. Dolgov and P.U. Bakhtin, as the proportion of agronomically valuable aggregates exceeded 60%. This can be attributed to the genetic characteristics and particle-size distribution of the soil, as well as the high organic matter content of typical chernozems (Balaev *et al*., 2023). Among the three cropping treatments, the lowest average proportions of 0.25-10 mm aggregates in the 0-30 cm layer were recorded under spring barley, ranging from 64.6% to 75.0%, whereas the highest values, ranging from 73.7% to 83.3%, were observed under the three-component intercrop. Aggregates measuring 1-5 mm predominated in the typical chernozem, indicating a favourable physical condition of the soil, since aggregates of this size provide suitable conditions for the formation of its water, thermal, and air regimes. Under barley in the control treatment (T1), the proportion of cloddy aggregates in the upper 0-10 cm soil layer was 14.5%, while 1-5 mm aggregates accounted for 31.1% and aggregates smaller than 0.25 mm for 15.2% (Fig. 1).

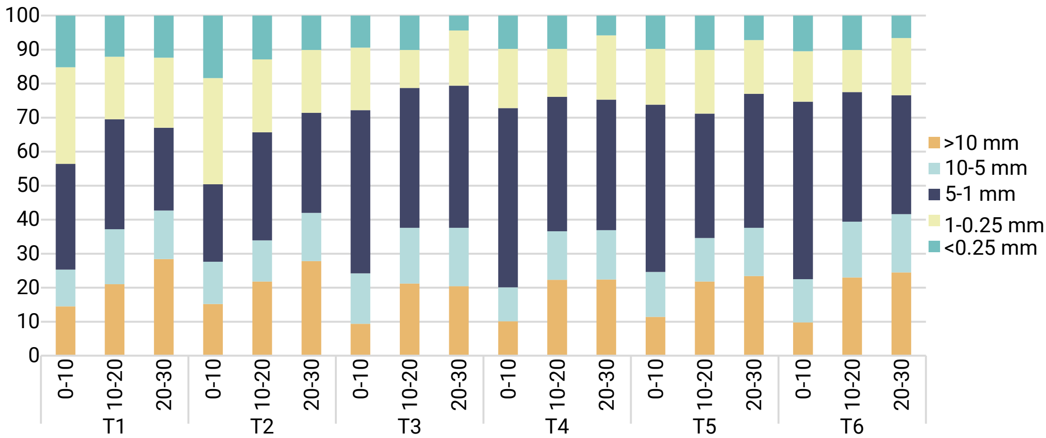

Figure 1. *Structural and aggregate composition of typical medium-loam chernozem under spring barley cultivation in 2025, %*

Note:

Aggregate fraction, mm	LSD_{05} for the fertilisation factor	LSD_{05} for the soil-layer factor	LSD_{05} for the interaction
>10 mm	1.39	0.98	2.41
10-5 mm	1.66	1.18	2.88
5-1 mm	2.98	2.11	5.17
1-0.25 mm	4.46	3.15	7.72
<0.25 mm	1.76	1.24	3.04

Source: developed by the authors

The proportion of cloddy aggregates increased with depth, reaching 21.0% in the 10-20 cm layer and 28.4% in the 20-30 cm layer. No comparable pattern was found for the 1-5 mm fraction. Its proportions in the 0-10, 10-20, and 20-30 cm layers were 31.1%, 32.3%, and 24.3%, respectively. The application of nitrogen in the form of ammonium nitrate caused some deterioration in soil structural condition. In the 0-10 cm layer, the proportion of the 1-5 mm fraction decreased by 8.3% relative to the control, whereas the proportion of dusty aggregates smaller than 0.25 mm increased by 3.2%.

The application of compost at a rate equivalent to N_{50} (T3) improved aggregate composition in the 0-10 cm layer. The proportion of the 1-5 mm fraction increased to 48.0%, while the proportions of cloddy and dusty aggregates decreased by 5.1% and 5.8%, respectively, relative to the control. These differences exceeded the LSD value. Similar changes were observed in the 1,020 cm and 20-30 cm soil layers, where the proportions of cloddy and dusty aggregates decreased compared with both the control and the mineral fertilisation treatment (T2). The 1-5 mm fraction accounted for 41.1% and 41.8% in the 10-20 and 20-30 cm layers, respectively. The combined application of compost and mineral nitrogen (T4) tended to increase the proportion of the 1-5 mm fraction. It reached 52.7% in the upper layer, 39.5% in the middle layer, and 38.4% in the 20-30 cm layer.

The combined vermicompost and mineral fertilisation treatment (T6) promoted the formation of an agronomically valuable soil structure. In the 0-10 cm layer, the 1-5 mm fraction accounted for 52.2%, while cloddy and dusty aggregates accounted for 9.8% and 10.5%, respectively. These values differed only slightly from those obtained under T5. In the 10-20 and 2030 cm layers, the proportions of agronomically valuable aggregates were 66.9% and 68.9%, respectively. A significant interaction between fertilisation treatment and soil layer was established for the >10 mm, 1-5 mm, and <0.25 mm fractions ($p \leq 0.05$), indicating that the effect of fertilisation depended on soil depth. For the 5-10 mm and 0.25-1 mm fractions, the interaction was not significant, which indicates that the two factors affected these parameters independently. Under the pea monocrop, the soil had a more favourable structural and aggregate composition than under spring barley, owing to the beneficial effect of leguminous crops on soil aggregation (Fig. 2).

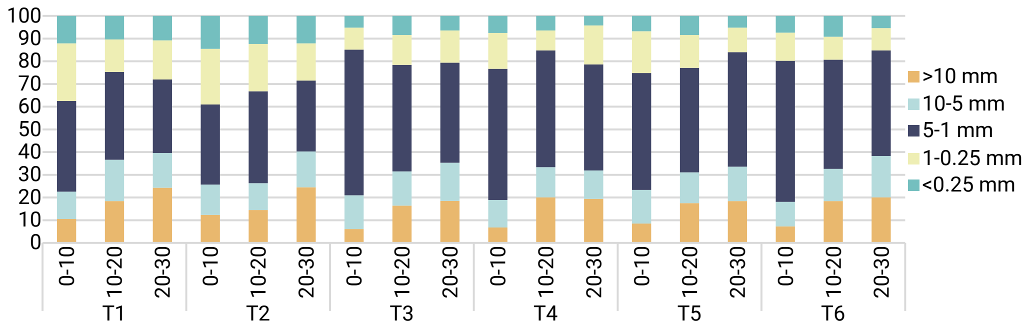

Figure 2. *Structural and aggregate composition of typical medium-loam chernozem under spring barley cultivation in 2025, %*

Note:

Aggregate fraction, mm	LSD_{05} for the fertilisation factor	LSD_{05} for the soil-layer factor	LSD_{05} for the interaction
>10 mm	1.80	1.27	3.12
10-5 mm	1.31	0.93	2.28
5-1 mm	2.54	1.79	4.39
1-0.25 mm	3.27	2.31	5.67
<0.25 mm	1.34	0.95	2.33

Source: developed by the authors

In the control treatment (T1), the proportions of cloddy aggregates and dusty particles in the 0-10 cm layer were 4.0% and 3.1% lower, respectively, than under barley, while the proportion of agronomically valuable aggregates increased accordingly. Under mineral fertilisation (T2), the proportion of agronomically valuable aggregates in the 0-10 cm layer decreased by 4.2% relative to the control because of an increase in the proportions of particles larger than 10 mm and smaller than

0.25 mm. The proportion of 1-5 mm aggregates decreased to 35.3%, compared with 39.9% under T1; in the 10-20 and 20-30 cm layers, this fraction accounted for 40.5% and 31.2%, respectively.

Compost applied at a rate equivalent to N_{50} (T3) had the greatest beneficial effect on soil structure in the 0-10 cm layer, where the proportion of 1-5 mm aggregates reached 64.1%. At the same time, the proportions of cloddy and dusty aggregates decreased to 6.1% and 5.2%, respectively. In the 10-20 and 20-30 cm layers, the 1-5 mm fraction accounted for 46.9% and 44.1%, respectively. Treatment T4, which combined compost with mineral nitrogen, was only slightly less effective than compost alone (T3). In the 0-10 cm layer, the proportions of 1-5 mm, cloddy, and dusty aggregates were 57.8%, 6.8%, and 7.5%, respectively. Similar patterns of aggregate distribution were also observed in the deeper layers.

Vermicompost was less effective than compost but performed better than the other treatments. The proportions of 1-5 mm aggregates were 51.5%, 46.0%, and 50.4% in the 0-10, 1020, and 20-30 cm layers, respectively. These values were 12.6%, 0.9%, and 6.3% lower than those recorded under the compost treatment. The combined application of vermicompost and mineral fertiliser (T6) resulted in a slightly lower proportion of agronomically valuable aggregates than T5. In the 0-10 cm layer, aggregates larger than 10 mm accounted for 7.3%, the 5-10 mm fraction for 10.8%, the 1-5 mm fraction for 62.1%, the 0.25-1 mm fraction for 10.1%, and aggregates smaller than 0.25 mm for 9.2%. The three-component intercrop produced the most favourable structural and aggregate conditions of typical medium-loam chernozem under all fertilisation treatments (Fig. 3).

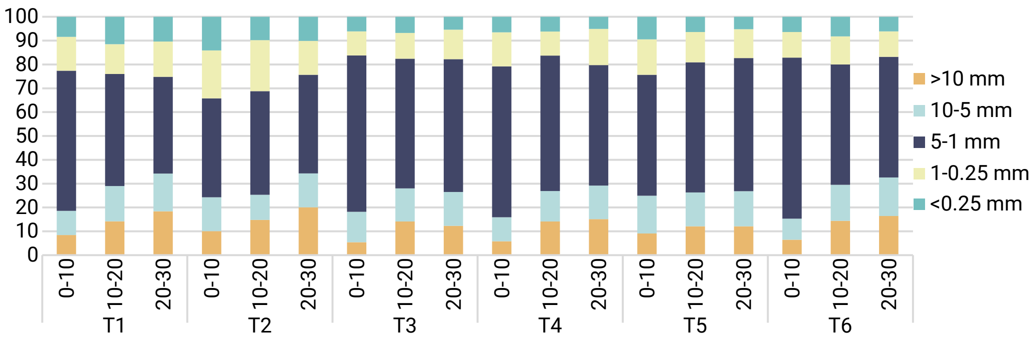

Figure 3. *Structural and aggregate composition of typical medium-loam chernozem under the barley-faba bean-pea intercrop in 2025, %*

Note:

Aggregate fraction, mm	LSD_{05} for the fertilisation factor	LSD_{05} for the soil-layer factor	LSD_{05} for the interaction
>10 mm	1.58	1.12	2.73
10-5 mm	1.55	1.09	2.68
5-1 mm	2.31	1.64	4.01
1-0.25 mm	2.82	2.00	4.89
<0.25 mm	1.04	0.74	1.80

Source: developed by the authors

The beneficial effect of intercropping on soil structure was evident even in the control treatment (T1). In the 0-10 cm layer, the proportion of 1-5 mm aggregates was 58.8%, exceeding the values recorded under all treatments in the barley monocrop. In the upper layer, cloddy and dusty aggregates each accounted for 8.4%. In the 10-20 and 20-30 cm layers, the proportions of 15 mm aggregates were 47.0% and 40.6%, while those of cloddy aggregates were 14.2% and 18.4%, respectively. Analysis of variance for the 0-10 cm layer showed that both cropping system and fertilisation treatment had significant effects on the proportions of agronomically valuable aggregates and dusty particles. The strongest effects were observed for the most valuable 1-5 mm fraction (F = 162.6 for factor A and F = 161.3 for factor B). The significant interaction between the factors (F = 11.26; p < 0.001) indicated that the effect of fertilisation varied substantially among cropping systems.

Table 1. *Results of the analysis of variance for the 0-10 cm soil layer*

Indicator	Pea	Barley	Intercrop	LSD_{05}(A)	F(A); p	LSD_{05} (B), T1-T6 range	F(B); p	F(A × B); p
Cloddy aggregates, %	8.6 ± 2.6	11.7 ± 2.5	7.6 ± 2.1	0.85	54.3; p < 0.001	7.0 (T3) – 12.5 (T2)	28.0; p < 0.001	0.99; p = 0.47 (n.s.)
Agronomically valuable aggregates, %	82.5 ± 5.9	76.1 ± 6.0	84.1 ± 4.7	1.33	83.4; p < 0.001	72.0 (T2) – 86.3 (T3)	68.8; p < 0.001	2.36; p = 0.03
1-5 mm aggregates, %	51.8 ± 11.4	42.7 ± 12.0	57.9 ± 9.7	1.73	162.6; p < 0.001	33.2 (T2) – 60.6 (T6)	161.3; p < 0.001	11.26; p < 0.001
Dusty particles (<0.25 mm), %	8.9 ± 3.6	12.2 ± 3.7	8.5 ± 3.0	0.92	39.9; p < 0.001	6.9 (T3) – 15.7 (T2)	53.7; p < 0.001	2.57; p = 0.02

Source: developed by the authors

In the 10-20 cm layer, factor A continued to exert a very strong effect on all parameters, whereas fertilisation had no statistically significant effect on the proportion of cloddy aggregates (F = 1.69; p = 0.16). The interaction between the factors was not significant for any parameter, indicating that the fertilisation systems produced effects in the same direction irrespective of the crop grown (Table 2).

Table 2. *Results of the analysis of variance for the 10-20 cm soil layer*

Indicator	Pea	Barley	Intercrop	F(A); p	F(B); p	F(A × B); p
Cloddy aggregates, %	17.6 ± 2.4	21.9 ± 1.4	14.0 ± 1.9	86.3; p < 0.001	1.69; p = 0.16 (n.s.)	1.52; p = 0.17 (n.s.)
Agronomically valuable aggregates, %	73.3 ± 2.3	67.3 ± 2.3	78.1 ± 3.6	96.8; p < 0.001	5.50; p < 0.001	1.09; p = 0.39 (n.s.)
1-5 mm aggregates, %	45.3 ± 5.0	36.6 ± 5.0	51.1 ± 5.2	99.1; p < 0.001	17.6; p < 0.001	0.99; p = 0.47 (n.s.)
Dusty particles (<0.25 mm), %	9.2 ± 2.1	10.9 ± 2.1	8.2 ± 2.2	14.5; p < 0.001	11.7; p < 0.001	0.93; p = 0.52 (n.s.)

Source: developed by the authors

In the deepest layer examined, at 20-30 cm, the effect of cropping system on the proportion of dusty particles was no longer significant (p = 0.41). At this depth, the dusty fraction was determined solely by the fertilisation system (F = 29.6; p < 0.001), rather than by factor A (Table 3).

Table 3. *Results of the analysis of variance for the 20-30 cm soil layer*

Indicator	Pea	Barley	Intercrop	F(A); p	F(B); p	F(A × B); p
Cloddy aggregates, %	20.9 ± 3.2	24.5 ± 3.3	15.7 ± 3.3	98.0; p < 0.001	22.3; p < 0.001	0.70; p = 0.72 (n.s.)
Agronomically valuable aggregates, %	71.8 ± 5.9	67.8 ± 5.7	77.2 ± 5.4	131.0; p < 0.001	95.2; p < 0.001	3.13; p = 0.006

***Table 3.** Continued*

Indicator	Pea	Barley	Intercrop	F(A); p	F(B); p	F(A × B); p
1-5 mm aggregates, %	41.9 ± 8.0	34.7 ± 6.5	49.1 ± 6.6	147.2; $p < 0.001$	68.1; $p < 0.001$	2.56; $p = 0.02$
Dusty particles (<0.25 mm), %	7.35 ± 3.4	7.75 ± 3.2	7.05 ± 2.5	0.92; $p = 0.41$ (n.s.)	29.6; $p < 0.001$	1.26; $p = 0.29$ (n.s.)

Source: developed by the authors

As in the barley and pea monocrops, the application of mineral nitrogen alone (T2) adversely affected soil structure in the 0-10 cm layer. The proportion of 1-5 mm aggregates decreased to 41.5%, while the proportions of aggregates smaller than 0.25 mm and cloddy aggregates increased to 14.1% and 10.1%, respectively. In the 10-20 and 20-30 cm layers, the 15 mm fraction accounted for 43.5% and 41.4%, respectively. It is important to note that mineral nitrogen application alone increased the proportion of 0.25-1 mm aggregates by 5.9%, 8.9%, and 6.6% relative to the control in the 0-10, 10-20, and 20-30 cm layers, respectively. This indicates that the continued use of this fertilisation system may increase the proportion of fine particles and thereby contribute to the deterioration of soil structure.

Compost applied at a rate equivalent to N_{50} (T3) increased the proportion of 1-5 mm aggregates in the 0-10 cm layer to 65.6%, while reducing the proportions of cloddy and dusty aggregates to 5.4% and 6.1%, respectively. The 1-5 mm fraction accounted for 54.4% in the 1020 cm layer and 55.7% in the 20-30 cm layer. The corresponding proportions of cloddy aggregates were 14.1% and 12.3%. The value recorded in the 20-30 cm layer was the lowest among all cropping and fertilisation treatments examined. Treatment T4, which combined compost and mineral nitrogen, produced slightly lower proportions of agronomically valuable aggregates, including the 1-5 mm fraction. In the 0-10 cm layer, 1-5 mm aggregates accounted for 63.3%, aggregates larger than 10 mm for 5.8%, and aggregates smaller than 0.25 mm for 6.5%. In the 1020 and 20-30 cm layers, the proportions of 1-5 mm aggregates were 56.8% and 50.5%, while those of cloddy aggregates were 14.1% and 15.1%, respectively.

Vermicompost application (T5) promoted a more uniform distribution of structural aggregates throughout the soil profile. Compared with the compost treatment (T3), differences in the proportions of cloddy and dusty aggregates were observed only in the 0-10 cm layer, where their values were 3.0% and 3.4% higher, respectively. No substantial differences between T3 and T5 were found in the 10-20 and 20-30 cm layers. The highest proportion of 1-5 mm aggregates in the intercrop was recorded under T6, which combined vermicompost and mineral nitrogen. In the 010 cm layer, this fraction accounted for 67.6%, the highest value among all treatments in the experiment. In the 10-20 and 20-30 cm layers, the corresponding values were 50.5% and 50.6%.

In the control treatment, the proportion of cloddy aggregates in the 0-10 cm layer was 14.5% under barley, 10.5% under pea, and 8.4% under the intercrop. A similar pattern was observed under the treatments involving organic fertilisers (T3, T4, T5, and T6): the proportions of cloddy and dusty aggregates decreased in the upper soil layer, while the proportion of 1-5 mm aggregates increased. Under the compost treatment (T3), the latter rose from 48.0% under barley to 64.1% under pea and 65.6% under the intercrop. Changes in soil structural condition were also observed in the deeper layers. In the 20-30 cm layer under T3, the proportion of 1-5 mm aggregates was 41.8% under barley, 44.1% under pea, and 55.7% under the intercrop. The corresponding proportions of aggregates larger than 10 mm were 20.4%, 18.5%, and 12.3%. Thus, intercropping provided more favourable conditions for the formation of soil structure throughout the 0-30 cm layer of typical medium-loam chernozem under the conditions of the Forest-Steppe zone of Ukraine. Mineral nitrogen application under T2 impaired soil structure relative to the control in all three cropping systems. In the 0-10 cm layer, the proportion of the dusty fraction increased relative to the control, reaching 18.4% under barley, 14.5% under pea, and 14.1% under the intercrop.

Two interrelated parameters were used to assess the structural condition of the 0-30 cm layer of typical chernozem: the K_{str}, calculated according to the method of M.I. Savvinov as the ratio of the sum of agronomically valuable aggregates to the combined proportion of cloddy and dusty aggregates, and the percentage of agronomically valuable aggregates. The results are presented in Figure 4.

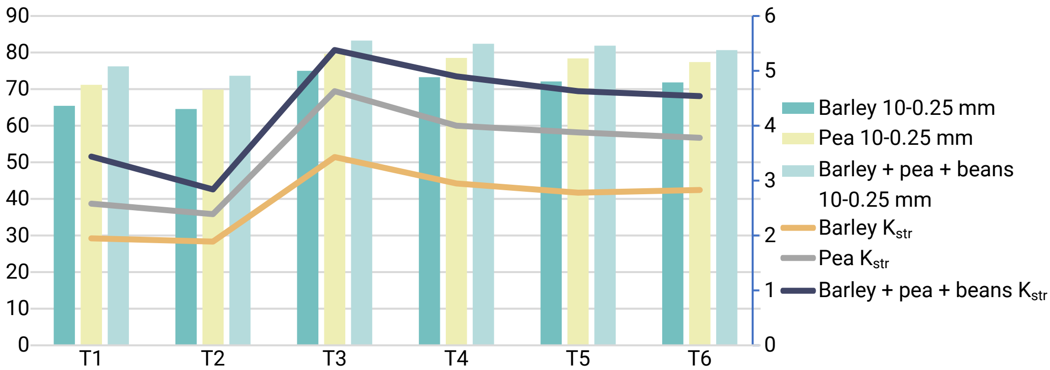

Figure 4. *Proportion of agronomically valuable aggregates (%) and structure coefficients in the 0-30 cm layer of typical medium-loam chernozem, 2025*

Source: developed by the authors

Under spring barley in the control treatment, the K_{str} of typical chernozem was 1.95, while agronomically valuable aggregates accounted for 65.47%. The application of mineral nitrogen alone at a rate of N_{50} under T2 slightly impaired soil structural condition: K_{str} decreased to 1.89, and the proportion of agronomically valuable aggregates declined to 64.60%. Thus, the use of mineral nitrogen alone was ineffective in maintaining the structural condition of typical chernozem under spring barley.

Compost application under T3 produced the greatest improvement in soil structural parameters among all fertilisation treatments under barley. The K_{str} increased to 3.43, which was 75.9% higher than in the control, while agronomically valuable aggregates accounted for 75.03%, exceeding the values recorded under T1 and T2 by 9.56% and 10.97%, respectively. The combined application of compost and mineral nitrogen under T4 resulted in lower values: K_{str} was 0.48 lower, and the proportion of agronomically valuable aggregates was 1.76% lower than under T3. Nevertheless, these values indicated an excellent soil structural condition. Vermicompost produced a K_{str} value of 2.78 and a proportion of agronomically valuable aggregates of 72.10%, both slightly lower than those recorded under the compost treatment (T3). Under T6, which combined N_{25} from vermicompost with N_{25} from mineral nitrogen, K_{str} was 2.83, while the proportion of agronomically valuable aggregates was almost identical to that under T5.

The structural parameters recorded under pea demonstrated its beneficial effect on the physical condition of the soil. In the control treatment, K_{str} was 2.58, which was 0.63 higher than under barley, while the proportion of agronomically valuable aggregates exceeded the corresponding value under barley by 5.70%. This indicates the beneficial effects of the legume root system and symbiotic nitrogen fixation on soil aggregation.

As under barley, mineral nitrogen application under pea caused both parameters to deteriorate: K_{str} decreased to 2.39, and the proportion of agronomically valuable aggregates declined to 69.90%. Compost application under T3 produced the highest K_{str} value among all pea monocrop treatments, reaching 4.63, an increase of 2.05 relative to the control. Under T4, this parameter was 4.00. Based on a review of the relevant literature, W. Kelbesa (2021) found that compost application improves the physical, chemical, and biological indicators of soil fertility, as well as soil organic matter content. He concluded that compost reduces soil bulk density, increases aggregate stability, and improves soil water properties, which is consistent with the findings of the present study. Vermicompost application under T5 resulted in agronomically valuable aggregates accounting for 78.40%, significantly exceeding the values recorded in the control and mineral fertilisation treatments, although remaining below that obtained under T3. Treatment T6, which combined vermicompost and mineral fertilisation, produced results under barley that were almost equivalent to those of T5.

The three-component intercrop provided the most favourable structural condition of typical chernozem among all three cropping systems under every fertilisation treatment. In the control, K_{str} was 3.44, exceeding the values recorded under all fertilisation treatments in the barley monocrop. Under T1, agronomically valuable aggregates accounted for 76.23%, which was 10.76% higher than under barley and 5.06% higher than under pea. The application of mineral nitrogen caused the greatest reduction in K_{str} among all cropping systems, lowering it to 2.84. The proportion of agronomically valuable aggregates decreased to 73.67%. Compost application under T3 produced the highest values: K_{str} reached 5.38, while agronomically valuable aggregates accounted for 83.30%. Under T4, the corresponding values were 4.90 and 82.40%. Vermicompost applied to the intercrop produced a K_{str} value of 4.63 and a proportion of agronomically valuable aggregates of 81.87%, while under T6 these values were 4.54 and 80.67%, respectively.

Comparison of soil samples from the monocrops and the three-component intercrop showed that, in the control treatment (T1), the difference in K_{str} between the intercrop and the barley monocrop was 1.49 units, while the difference between the intercrop and the pea monocrop was 0.86 units. The intercrop exceeded barley and pea in the proportion of agronomically valuable aggregates by 10.76% and 5.06%, respectively. Compost was the most effective organic fertilisation treatment. Under this treatment, the intercrop exceeded barley by 1.95 units in Kstr and by 8.27% in the proportion of agronomically valuable aggregates. Its advantage over pea under T3 was smaller, amounting to 0.75 units for K_{str} and 3.63% for agronomically valuable aggregates. These findings therefore demonstrate the beneficial effect of legumes on the structural and aggregate composition of soil.

Discussion

Intercropping is a relatively new practice in the Ukrainian agricultural sector and therefore requires investigation not only in terms of crop productivity but also with regard to its effects on soil fertility indicators. Intercrops can enhance the resilience of agroecosystems because they improve such soil physical properties as bulk density, structure, and water-holding capacity (Xu *et al.*, 2021). The statistical model applied to the soil structural and aggregate data showed that factor A, cropping system, affected soil structure. In every soil layer examined, the barley-pea-faba bean intercrop produced the most favourable structure, with the lowest proportion of cloddy aggregates and the highest proportion of agronomically valuable aggregates, including the largest share of the most valuable 1-5 mm fraction. This fraction accounted for 49-58% under the intercrop, compared with 35-43% under the barley monocrop. The barley monocrop had the highest proportions of cloddy and dusty particles and, consequently, the lowest proportion of agronomically valuable aggregates. The pea monocrop occupied an intermediate position and was slightly less favourable than the intercrop. Differences among the levels of factor A were significant ($p < 0.001$) in all cases except for the proportion of dusty particles in the 20-30 cm layer. V. Anthony *et al.* (2025) noted that soil structure is crucial for creating a favourable environment for plant roots and facilitating water infiltration. Comparison of the monocrops with the three-component mixture confirmed their substantial effects on the structural and aggregate composition of typical chernozem. Under T1, without fertiliser application, the 1-5 mm fraction in the 0-10 cm layer accounted for 31.1% under barley and 39.9% under pea, whereas it reached 58.8% under the three-component intercrop. Thus, combining crops within the same field increased the proportion of these aggregates by 27.7% compared with the barley monocrop and by 18.9% compared with the pea monocrop. The synergistic effect of the three crops in the intercrop exceeded even the natural advantage of legumes over cereals. H.-Y. Ma *et al.* (2024) attributed this effect to the root architecture formed in cereal-legume intercropping systems. The resulting root network creates soil pores and physically binds soil particles, thereby promoting aggregate formation, which supports the findings of the present study. In addition, differences in root exudates stimulate greater soil microbial diversity. L. Hu *et al.* (2022) also highlighted the exceptional role of legume roots in intercrops, noting that they promote aggregate formation and reduce the decomposition of organic carbon.

Mineral nitrogen fertilisers have traditionally been widely used in Ukraine. However, K. Jayaswal *et al.* (2023) showed that vermicompost may serve as a potential substitute for synthetic mineral fertilisers because it improves soil fertility and crop yields. W.A. Kelbesa (2021) noted that conventional organic fertilisers, such as manure, release nutrients, particularly nitrogen, slowly after application to the soil. Composting therefore warrants particular attention because it can increase the availability of nutrients to plants. Nevertheless, data on possible changes in soil structure following compost application remain limited. An analysis of studies assessing compost effectiveness showed that 71% examined changes in nutrient content and availability, whereas only about 10% addressed the effects of compost on soil structure.

The present study revealed a tendency towards deterioration in soil structural condition in the unfertilised control and under mineral nitrogen treatment T2. By contrast, treatments T3-T6, particularly T3, T4, and T6, consistently improved aggregate composition: the proportions of agronomically valuable aggregates and the most valuable 1-5 mm fraction increased, while cloddiness and particle dispersion decreased. The fertilisation system had a significant effect on agronomically valuable aggregates, the 1-5 mm fraction, and dusty particles in all soil layers ($p \leqslant 0.001$). The only exception was the proportion of cloddy aggregates in the 10-20 cm layer, where the effect of fertilisation was not statistically significant ($p = 0.16$).

Vermicompost improved the structural and aggregate composition of typical chernozem compared with both the control and mineral fertilisation, although its effects were slightly less pronounced than those of compost. These findings are consistent with those of F. Sayed Aboud *et al.* (2021), who reported that applying vermicompost at 6 tonnes per ha improved soil physical properties and organic matter content. A. Gazi (2024) also concluded that vermicompost has beneficial effects on soil structure, water-holding capacity, and microbial activity. The study emphasised that vermicompost is an effective means of improving soil quality and crop productivity while reducing the adverse effects of intensive crop-production technologies. As it is produced from organic waste, vermicompost also contributes to environmental sustainability, which is particularly important in the context of Ukraine's alignment with the European Green Deal. Significant interactions were observed mainly in the upper 0-10 cm and deepest 20-30 cm layers for the 0.25-10 mm and 1-5 mm aggregate fractions, with p-values ranging from 0.03 to <0.001. This indicates that the effectiveness of a particular fertilisation treatment depended on the cropping system. The selection of an optimal nutrient-management system should therefore be differentiated according to cropping system. In the intermediate 10-20 cm layer, the interaction between the factors was not statistically significant, indicating that their effects were additive.

The findings therefore demonstrate the beneficial effects of compost and vermicompost on soil structural condition, as determined by dry-sieving analysis. Using a different method, namely X-ray computed tomography, Ö. Sari *et al*. (2025) found that composting and vermicomposting promoted the development of a more complex and diverse pore system and improved soil structure and porosity. By contrast, P.-A. Rivier *et al*. (2022) concluded that organic fertiliser application caused a slight decline in the aggregation of loamy soil but increased the stability of both micro- and macroaggregates in sandy soil, even within a single growing season. Further research into the effects of these fertilisers on different soil types is therefore warranted.

Combining intercropping with organic fertiliser application is an effective means of improving the structural condition of typical chernozem. This is supported by K. Keshyagol *et al*. (2026), who found that cover crops, mulching, green manures, vermicomposting, and biochar application increased soil organic matter stocks and improved soil structure by 10-30% over extended periods. They also reported that combinations of regenerative practices produced the greatest average improvements in the principal indicators, with soil organic matter content increasing by approximately 25% and crop yield by 28%. In terms of their effects on soil physical condition, the combined organic and mineral nitrogen treatments T4 and T6 were consistently less effective than the organic-only treatments T3 and T5, but substantially outperformed both the unfertilised control and the mineral nitrogen treatment.

Conclusions

The study examined the effects of different fertilisation systems on the structural and aggregate composition of soil under barley and pea monocrops and a three-component barley-pea-faba bean intercrop. Soil structural condition was classified as excellent under all treatments in the two-factor experiment. The dry-sieving results revealed a consistent hierarchy in the development of agronomically valuable soil structure across all soil layers and fertilisation treatments: three-component intercrop > pea monocrop > barley monocrop.

According to their effects on K_{str} and the proportion of agronomically valuable 0.25-10 mm aggregates in typical medium-loam chernozem, the fertilisation treatments were ranked as follows: compost > vermicompost > N_{25} compost + N_{25} mineral nitrogen > N_{25} vermicompost + N_{25} mineral nitrogen > unfertilised control > N_{50} mineral nitrogen. The differences were statistically significant, as they exceeded the LSD_{05} value. Changes in aggregate composition varied among the cropping systems. Under barley, organic fertilisers, including compost and vermicompost, had the greatest effect on the proportions of different aggregate fractions in the 010 cm layer. Under pea, their effects extended to a depth of 20 cm, whereas under the intercrop, the differentiated distribution of plant roots resulted in changes throughout the 0-30 cm layer.

In all three cropping systems, mineral nitrogen application under T2 adversely affected the structural and aggregate composition of the soil by increasing the proportion of dusty particles smaller than 0.25 mm and reducing the proportion of agronomically valuable aggregates. The greatest dispersion of the upper soil layer was recorded under T2 in the barley monocrop, where dusty particles accounted for 18.4%. Treatments T3-T6 significantly reduced the proportion of microaggregates to 4.2-6.8%, indicating improved aggregate stability and soil structure under the factors studied. Farmers who rely exclusively on mineral fertilisers should therefore consider alternative fertilisation systems involving organic amendments to prevent the development of agrophysical soil degradation.

The agrophysical condition of soils remains an important area of research. Future studies should examine the effects of intercropping and the biological improvement of fertilisation systems on different soil types across other soil and climatic zones.

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Conflict of Interest

None.

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Структурно-агрегатний склад чорнозему типового за сумісного вирощування культур і біологізації систем удобрення

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Анотація. Актуальність роботи зумовлена необхідністю подолання загрозливими масштабами агрофізичної деградації ґрунтів України та виконання вимог Європейської зеленої угоди шляхом переходу від традиційних інтенсивних технологій до екологічно безпечних практик – зокрема, впровадження сумісних посівів і застосування органічних добрив для досягнення нульового рівня деградації земель. Метою статті було дослідження впливу різних систем удобрення у посівах ячменю ярого, гороху та в сумісному посіві ячменю, гороху і бобів на структурно-арегатний склад чорнозему типового середньосуглинкового. Методологія У роботі використовували польовий, лабораторний метод сухого просіювання зразків грунту для визначення структурно-агрегатного складу, аналітичний і статистичний методи. Було встановлено, що трьохкомпонентний сумісний посів ячменю, гороху і бобів забезпечив найкращий структурний стан чорнозему типового серед усіх трьох варіантів культур для всіх систем удобрення. За вмістом агрономічно цінних агрегатів розміром 0,25-10 мм перевага інтеркропінгу порівняно з ячменем становила 10,76 %, над горохом – 5,06 % у шарі 0-30 см. За вирощування гороху структурний стан ґрунту був кращим порівняно з монопосівом ячменю. Серед систем удобрення найвищий коефіцієнт структурності встановлений при внесення компосту у розрахунку на N_{50}, поступався варіант із вермикомпостом, нижчі значення отримали на варіантах сумісного внесення компосту, вермикомпосту та мінеральної форми азоту, найгіршим варіантом за впливом на структуру ґрунту був варіант мінерального удобрення N50. Практичне значення роботи полягає у тому, що для збереження та відновлення структури ґрунту потрібно застосовувати внесення таких органічних добрив як компост і вермикомпост, а також те, що використання винятково мінерального азотного удобрення погіршує стуктурно-агрегатний склад ґрунту

Ключові слова: структура ґрунту; агрономічно цінні агрегати; здоров'я ґрунту; горох; боби; ячмінь