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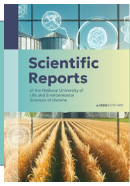

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Winter wheat productivity under conditions of uneven fertiliser distribution during application

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Abstract. The rational use of mineral fertilisers, given their uneven distribution, is an important factor in improving plant nutrition and achieving high yields of winter cereals. The aim of the study was to determine the effect of uneven distribution of mineral fertiliser granules during pre-sowing application on the productivity of winter wheat. The research was conducted in a four-fold field experiment on dark grey podzolised soil using nine fertiliser distribution options, including a control (100%) and deviations of ±10-25%. It was found that the rate of phosphorus and potassium fertilisers, which exceeded by 10-15% on dark grey podzolised soil, did not have a positive effect on the growth of the aboveground part and root system of winter wheat. It was found that increasing the uniformity of fertiliser distribution had a positive effect on the biometric indicators of plants, in particular height, mass of the aboveground and root parts, which contributed to higher yields and higher grain quality indicators. The maximum growth rates of the aboveground mass of plants were characteristic of the tillering phase. A deviation of 10-25% from the optimal fertiliser rate resulted in deviations in the indicators compared to the control by 10-72% in the tillering phase, 6.4-25% in the stem elongation phase, and 38-46% in the heading phase, respectively. The productivity analysis showed that only a 15% and 25% reduction in the fertiliser rate resulted in a significant decrease in winter wheat yield. The highest yield (10.4 t/ha) was obtained with the use of $N_{38}P_{98}K_{98}$ in pre-sowing

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application. Increasing the fertiliser rate to 110-120% resulted in an increase in protein content to 13.6-14.0%, which is 0.3-0.5% higher than the control. The results of the effect of fertiliser unevenness on crop yield formation can be used in precision farming

Keywords: yield; experimental plots; above-ground mass; root system; precision farming

Introduction

Winter wheat is one of the most important grain crops in global and national agricultural production, ensuring food security and accounting for a significant share of cultivated land. The high productivity of this crop is closely linked to the efficiency of the nutrition system, in particular the application of mineral fertilisers. In modern precision farming, increasing attention is being paid to the problem of spatial heterogeneity of soil agrophysical properties, which, in turn, causes uneven absorption of nutrients by plants and affects yield levels. The distribution of fertilisers across the field is a critical factor in ensuring uniform crop development, but in practice, there is often significant variability in their application due to both technical limitations and the characteristics of the terrain, granulometric composition and soil moisture. This requires a scientific analysis of the impact of such differences on crop productivity, taking into account modern approaches to nutrient management in the field.

As a leader among agricultural exporters, Ukraine has proven itself to be a country that is resilient to difficult circumstances and harsh conditions. The growth in the production of high-quality agricultural products, and for wheat in particular the harvesting of strong and valuable varieties, is in line with the main directions of state policy on food security and the country's export potential (Pustovit *et al.*, 2024). The productivity of winter wheat largely depends on effective plant nutrition management, which includes the rational use of mineral fertilisers. Effective fertiliser management is an important aspect that affects the range of wheat productivity. Applying fertilisers to the soil for subsequent uptake by plants is a method of increasing crop yields. The uniform distribution of fertiliser particles and the amount of fertiliser depend on the parameters of the pin and the speed of the operation. The uniformity of application (coefficient of variation) in both the transverse and longitudinal directions was in the range of 11.2-13.1% and 2.9-15.3%, respectively. The accuracy of the prototype was quantitatively determined as the percentile ratio of the collected amount of fertiliser to the desired amount per unit area. The application accuracy ranged from 81.9% to 97.4% in the working speed range (Sugirbay *et al.*, 2020).

According to the results of studies by Y. Wang *et al.* (2023), uneven distribution of fertilisers causes significant variations in wheat yields in different parts of the field. It has been proven that differential fertiliser application reduced the use of nitrogen (N), phosphorus (P) and potassium (K) fertilisers by 22.90-43.95%, 59.11-100% and 8.21-100%, respectively, and increased the efficiency of N, P and K use by 12.27-28.71, 89.64-176.85 and 5.48-266.89 kg/kg, respectively, without loss of yield. The results of the study indicate that fertiliser management has great potential for saving fertilisers, significantly increasing farmers' net income, reducing environmental pollution, and promoting sustainable resource use.

Studies by Z. Jiang *et al.* (2024) show that, in addition to the heterogeneity of fertiliser application, crop productivity is influenced by the combination of nutrient distribution in the study area and nutrient distribution in the meridional, mesmeridional and septentrional segments. A clear latitudinal dichotomy was also observed, delineating areas with excess and deficiency of nutrients in the soil. A. Aleminew *et al.* (2020) proved that the sensitivity of winter wheat to fertilisers varied depending on different areas of the map with stable intra-field heterogeneity. In the low fertility zone, increasing fertiliser application from 50 kg/ha^{-1} to 350 kg/ha^{-1} of ammonium nitrate (from 17.2 to 120.4 kg/ha^{-1}N) resulted in a 26% increase in wheat yield, compared to 50% in the optimal zone and 74% in the high fertility zone. A stable map of intra-field heterogeneity based on large satellite data can be used to intensify precision farming.

Uneven distribution of fertilisers at the time of application can have a significant impact on nutrient use efficiency, yield and economic benefits. The work of X. Wang *et al*. (2024) studied the biosynthesis of lignin in stems, which determines the level of resistance to lodging. Optimising fertiliser distribution improves the mechanical properties of stems by increasing the light exposure of the plant cover. This promotes the synthesis and accumulation of lignin in the stems and reduces wheat lodging. The use of precision farming and GPS positioning technologies significantly improves the uniformity of fertiliser distribution, which reduces fertilszer costs and increases their efficiency. Optimising fertiliser rates and application times significantly improves nutrient use efficiency.

The aim of the study was to assess the effect of artificially created heterogeneity in fertiliser application at ±10-25% of the standard DAFK rate (300 kg/ha), which occurs due to different granule sizes when spread by spreaders, on the intensity of above-ground mass and root system growth, the yield and quality of winter wheat.

Materials and Methods

The research was conducted in a field experiment by the Department of Agrochemistry and Plant Product Quality named after O.I. Dushechkin of the National University of Life and Environmental Sciences of Ukraine on the land of Biotech LTD (Boryspil district, Kyiv region) during 2023-2024. according to the developed experimental design with four replicates (Table 1; Fig. 1). The control was set at a rate of 300 kg/ha of diammonium phosphate (DAFK 10-26-26), which is widely used by agricultural producers. The heterogeneity of fertiliser distribution was created artificially using a 10*10 cm grid, and the fertiliser was applied manually to each cell according to the research variant.

Table 1. *Experimental design for determining the effect of uneven fertiliser application on winter wheat productivity*

No.	Fertilisation option	Percentage of uniformity of fertiliser distribution, %
1	$N_{30}P_{78}K_{78}$	100 % – control
2	$N_{27}P_{70}K_{70}$	90
3	$N_{34}P_{86}K_{86}$	110
4	$N_{26}P_{66}K_{66}$	85
5	$N_{35}P_{90}K_{90}$	115
6	$N_{24}P_{62}K_{62}$	80
7	$N_{36}P_{94}K_{94}$	120
8	$N_{23}P_{59}K_{59}$	75
9	$N_{38}P_{98}K_{98}$	125

Source: compiled by the authors

The area of the experimental plot was 250 m^2, and the area of the control plot was 180 m^2. The experiment was repeated four times, and the plots were arranged systematically. The experiments were set up and conducted in accordance with generally accepted methods (Ehrmantraut *et al.*, 2018). The study was conducted in accordance with the Convention on Biological Diversity (1992). The experimental field soil is dark grey podzolised light loam, formed on loess-like loam. The humus content is low – 2.12 ± 0.08%, the soil solution reaction is slightly acidic – pH 6.1±0.15, the level of mobile phosphorus compounds is average (167 mg/kg), and potassium (224 mg/kg) high, increased mobile magnesium (2.64 mg-eq/100 g), calcium (7.93 mg-eq/100 g) average, mobile sulphur (3.64 mg/kg) and mineral nitrogen (14.5 mg/kg) low. The Yulia winter wheat variety was selected for the study.

Figure 1. *Photos of the experimental plots*

Source: compiled by the authors

Soil preparation in the pre-sowing period was aimed at maximising moisture retention and accumulation in the soil and destroying weeds. The cultivation technology was generally accepted for the Kyiv region and included the following operations: application of mineral fertilisers in accordance with the research scheme, manually placing granules in cells; primary soil cultivation was performed with a HORSCH Tiger MT (Germany) deep loosener to a depth of 25-30 cm; sowing with the Amazone D9 6000 (USA) – TC sowing complex to a depth of 5 cm; nitrogen fertilisation during the tillering phase (CAS 150 kg/ha) and heading phase (CAS 100 kg/ha); to combat fungal diseases of the leaves during the tillering phase, the systemic fungicide Tebuconazole (250 g/l) was applied using a Tecnoma Lazar sprayer (France).

According to data from the Boryspil meteorological station, the average annual air temperature in 2023 was 0.9°C higher than the long-term average and amounted to 10.8°C. The temperature increase was 2.7°C in January, 2.1°C in February, 2.2°C in March, 4.9°C in September, 2.9°C in October, 1.5°C in November, and 2.7°C in December. Precipitation in 2023 was 15 mm higher than the long-term average and amounted to 636 mm. Precipitation distribution was uneven, with a maximum in June. The average annual air temperature in 2024 was 2.5°C higher than the long-term average and amounted to 11.4°C. The largest increase in temperature was observed in February (5.2°C) and September (6.4°C). In 2024, precipitation in Kyiv amounted to 642 mm, which is 4% higher than the climatic norm. The distribution of precipitation was uneven: in April and June, almost two months' worth of precipitation fell, while in May and September, precipitation amounted to only 23% and 36% of the long-term average, respectively.

Soil samples were selected and prepared in accordance with standard requirements for sample preparation and storage in laboratory conditions, in accordance with DSTU 4287:2004 (2004). Soil samples were examined in four replicates. The biometric indicators of winter wheat were determined by the weight method during the tillering, stem elongation and heading phases. The ratio of the root and above-ground parts was calculated as the ratio of the dry weight of the root system to the dry weight of the above-ground part of the plant at each stage of development. This indicator was determined to assess the balance of plant development under different nutritional conditions. The weight of wheat plant roots was determined by weighing after washing in tap water and drying at 100°C in a drying oven. Grain samples for quality analysis were pre-ground to a particle size of 1 mm using a laboratory mill. The quality indicators of winter wheat grain were determined in accordance with DSTU 4117:2007 (2007). Yield was determined for each research variant using the 1 m^2 test plot method, and threshing was carried out manually. Grain yield results were adjusted to standard moisture content in accordance with DSTU 3768:2019 (2019). Quality indicators were determined by infrared spectroscopy using an Infratec 1241 FOSS express analyser (Labimpex Ltd., Ukraine). Statistical processing of the results was carried out using standard methods with computer data processing via MS Excel and Statistica 8.0. To assess the reliability of the experimental data presented in the work, parametric criteria of normal distribution were used, calculating the arithmetic mean (Xavg.) and standard deviation (SXavg.) at a significance level of < 0.05.

Results and Discussion

The main indicator affecting the yield of vegetative mass is the height of the plant stem, which is a genetic trait of the variety and depends on the fertiliser rate (Gangur *et al.*, 2020). This was confirmed by the results of this study (Fig. 2). Under the conditions of the experiment, fairly high growth rates of winter wheat plants were established, and in the spring tillering phase, their height reached 34.1-38.0 cm, stem elongation 62.0-65.8 cm, and heading 99.1-109.0 cm.

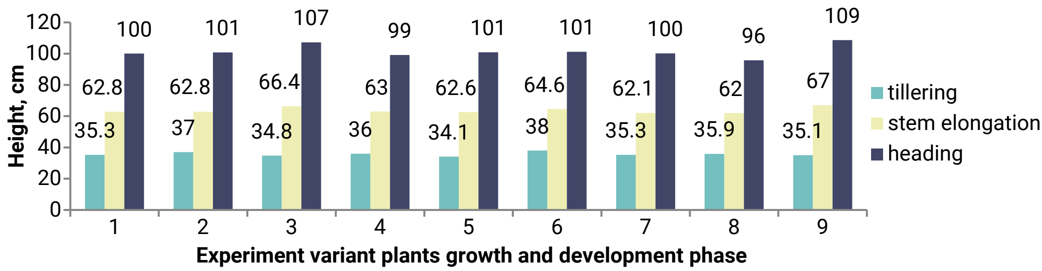

Figure 2. Dependence of winter wheat plant height on the uniformity of fertiliser distribution in pre-sowing application, average for 2023-2024

Note: 1. $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution)
Source: compiled by the authors

Analysis of the data obtained shows that growth processes in plants reflect the influence of external and internal conditions, including nutrition, with plant height being one of the key indicators characterising the intensity of these processes. An increase in the uniformity of fertiliser distribution (by 25%) led to an increase in this indicator during the stem elongation phase (by 6.6%) and heading phase (by 8.7%). Also, in the heading phase, a positive effect on plant height of 7% was noted from a 10% increase in the fertiliser rate due to its uneven distribution. Research by V.V. Gamayunova (2015) showed that winter wheat varieties differed in plant height, which is determined by their genetic basis, high heritability and sowing dates. The highest height was achieved by plants of the Kolchuga and Natalka varieties – 83.2 cm and 76.7 cm, respectively. Plants of the "Podolyanka" and "Blagodarka Odeska" varieties were slightly shorter – 74.5

and 71.4 cm, respectively, and the shortest were plants of the Kosovitsa variety – 66.6 cm. The height and growth of the above-ground part of plants are interrelated.

The above-ground mass of plants is one of the main components of the crop, on which the productivity of the crop largely depends. It reflects the impact of weather conditions, the level of agricultural technology, etc. on plants. It has been established that the doses of mineral fertilisers and winter wheat varieties significantly affected plant height and above-ground mass growth in all phases of plant development. Fertilisers increased plant height depending on the application rate and variety. This study found that different uniformity of mineral fertiliser distribution significantly affected the growth of above-ground plant biomass (Fig. 3).

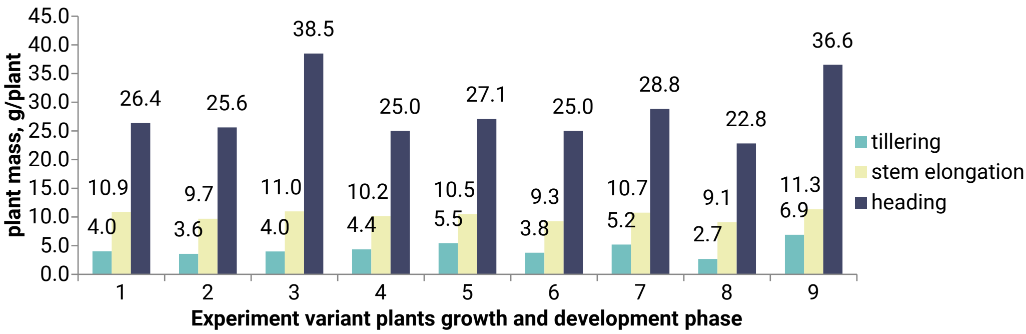

Figure 3. Dependence of the mass of the above-ground part of winter wheat plants on the uniformity of fertiliser distribution in pre-sowing application, average for 2023-2024, g/plant

Note: $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution). LSD 0.95 in the tillering phase 0.21 g/plant; stem elongation 0.29; heading 0.89 g/plant

Source: compiled by the authors

Thus, during the spring tillering phase, the plant mass was 2.7-6.9 g/plant, the stem elongation phase was 9.3-11.3 g/plant, and the heading phase was 22.8-38.5 g/plant. The highest rates of above-ground biomass growth with varying fertiliser distribution were obtained during the spring tillering phase. Thus, a 10-25% reduction in fertiliser rates resulted in a 10-46% decrease in plant growth rates, while a 25% increase resulted in more intensive biomass growth (72% compared to the control). In the booting phase, a significant difference between the variants was obtained with a reduction in the rate by 15-25%. The above-mentioned intensity was also characteristic of the heading phase. Increasing the fertiliser rate by 10-25% increased the growth rate of the above-ground part of plants by 38-46%. The most intensive growth of the raw above-ground mass of winter wheat plants occurs from the tillering phase to the heading phase. In the tillering phase, the increase occurred in variants 5, 7 and 9 with 115-125% heterogeneity. In the heading phase, the highest biomass growth was obtained using $N_{34}P_{86}K_{86}$ with 110% heterogeneity and amounted to 38.5 g/plant. Studies by V.V. Gamayunova *et al.* (2021) show that there is a close positive correlation between the amount of above-ground mass and wheat grain yield: the higher the yield of vegetative mass, the higher the grain yield should be, as a rule.

Starting from the first stages of development, the accumulation of significant vegetative mass of plants is an important condition for the formation of a high yield. The above-ground mass of plants plays a particularly important role in southern Ukraine, where a significant part of the leaf apparatus dies off before the wheat grain filling period. Over the years of research, in the control of raw biomass, plants of the Zamozhnist variety accumulated 1,595 g/m^2 in the stem elongation phase, 2,083 g/m^2 in the heading phase, and 2,276 g/m^2 during the milk ripeness phase, which is 84-107 g/m^2 or 3.8-5.3% more than the raw mass formed by plants of the Kolchuga variety. The same trend was observed in other variants of the experiment. In the work of M. Kazlauskas *et al.* (2022), results similar to this study were obtained and it was shown that the use of precision farming technologies on more productive land plots led to an increase in wheat biomass growth (up to 6.74%), grain yield (up to 14.5%), number of grains per ear (up to 6.2%) and protein content in grain (up to 12.56%), as well as a lower (up to 8.61%) average weight of 1,000 grains than with conventional fixed fertilisation. There was a direct relationship between the intensity of above-ground mass formation, the development of the root system of field crops and their productivity. Therefore, this should be given sufficient attention, as an increase in the proportion of the root system has the potential to increase yield (Fig. 4).

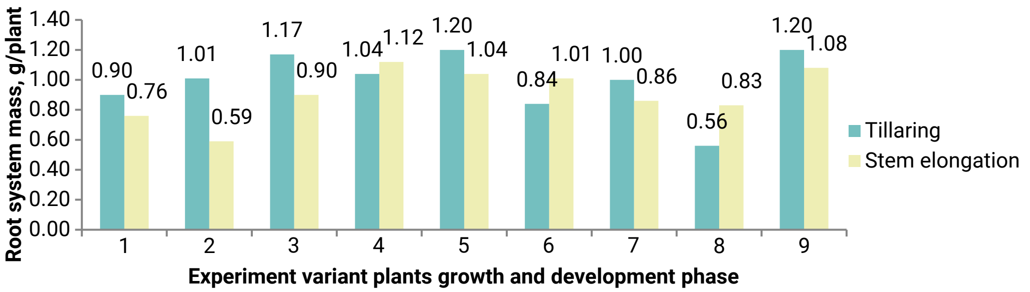

Figure 4. Dependence of the root system mass of winter wheat plants on the uniformity of fertiliser distribution in pre-sowing application (average for 2023-2024)

Note: 1. $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution)

Source: compiled by the authors

It was established that during the tillering phase, the root system weight was 0.9-1.2 g/plant, and the stem weight was 0.59-1.12 g/plant (Fig. 4). Deviations from the norm of fertilisers in the direction of an increase of 20 and 28 kg/ha of phosphorus and potassium caused an intensification of the growth of the root system of plants in the tillering phase by 33%, and, accordingly, a decrease of 28 kg/ha inhibited it (by 60%). In the stem elongation phase, the dependence on fertiliser unevenness was less pronounced (growth of the root system and central root). Only in variant 9 (125% uniformity of fertiliser distribution) did the root system weight increase by 45% compared to the control. Thus, uneven fertiliser distribution, with increases and decreases of 20 and 28 kg/ha of phosphorus and potassium, significantly affected the development of the root system of winter wheat.

An important condition for obtaining high yields of winter wheat is the good development of embryonic and nodal roots in plants. Studies by Yu. Tkalich (2015) show that the root system of wheat develops most intensively from the autumn vegetation period (2.4 cm/day) and in spring until the heading phase (1.1-1.4 cm). The central root, or taproot, plays an important role in the development of wheat, especially in the early stages. It is the first root to sprout from the seed and provides the initial anchoring of the plant in the soil and the absorption of water and nutrients. Although wheat has a fibrous root system (without a clearly defined main root), the central root still plays an important role in the formation of young plants (Kalenska, 2020). According to the data of this study, the length of the central root increased with an increase in the fertiliser rate (Fig. 5).

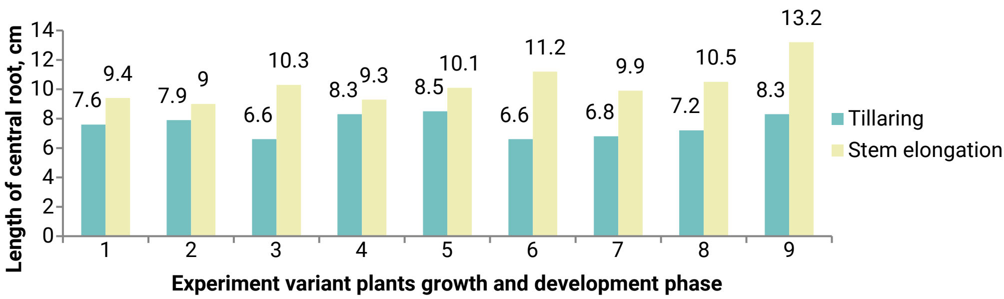

Figure 5. Dependence of the length of the central root of winter wheat plants on the uniformity of fertiliser distribution, average for 2023-2024

Note: 1. $N_{30}P_{78}K_{78}$ (DAFK 10-26-26) (100% uniformity of fertiliser distribution) – control; 2. $N_{27}P_{70}K_{70}$ (DAFK 10-26-26) (90% uniformity of fertiliser distribution); 3. $N_{34}P_{86}K_{86}$ (DAFK 10-26-26) (110% uniformity of fertiliser distribution); 4. $N_{26}P_{66}K_{66}$ (DAFK 10-26-26) (85% uniformity of fertiliser distribution); 5. $N_{35}P_{90}K_{90}$ (DAFK 10-26-26) (115% uniformity of fertiliser distribution); 6. $N_{24}P_{62}K_{62}$ (DAFK 10-26-26) (80% uniformity of fertiliser distribution); 7. $N_{36}P_{94}K_{94}$ (DAFK 10-26-26) (120% uniformity of fertiliser distribution); 8. $N_{23}P_{59}K_{59}$ (DAFK 10-26-26) (75% uniformity of fertiliser distribution); 9. $N_{38}P_{98}K_{98}$ (DAFK 10-26-26) (125% uniformity of fertiliser distribution)

Source: compiled by the authors

A 10% reduction in fertiliser rates compared to the control did not result in a significant difference compared to the control, while an increase in these rates during the tillering phase reduced the central root by 14% and increased it by 9.6% during the stem elongation phase. Accordingly, ±15% unevenness increased the indicator in the tillering phase by 9.6-12%, in the stem elongation phase by 7%, ±20% unevenness decreased in the tillering phase by 13.6-14%, increased in the stem elongation phase by 19%. The longest central root was obtained in variant 9 using $N_{38}P_{98}K_{98}$, which was 8.3 cm in the tillering phase and 7.6% longer than the control, and 13.2 cm in the stem elongation phase and 44% longer. The work of M. Hashimoto *et al.* (2024) shows that the growth of wheat shoots depends on the phosphorus content and its distribution in the soil. Among the root types, only the intensity of lateral roots increased significantly in areas with high phosphorus content and was lower in phosphorus-deficient soils, despite the absence of differences in the total root intensity per plant. The reaction of lateral roots after emergence was strongly dependent on the available phosphorus content in the soil.

The biometric indicators of winter wheat plants in the spring period until the onset of heading determine the rate of formation of the structural elements of its yield. However, according to G.M. Gospodarenko *et al.* (2020), only in the stem elongation and heading phases was there a strong ($R = 0.77$) and very strong ($R = 0.97$) correlation between phytomass and winter wheat yield. The unevenness of processes and different timing of plants entering individual phases cause a decrease in crop productivity as a whole. Under the conditions of the experiment, it was found that a significant increase in yield was characteristic only for variants with a 25% increase in dose. Its value reached 10.4 t/ha with an increase of 0.62 t/ha (Table 2).

Table 2. *Winter wheat productivity with varying unevenness of fertiliser distribution in pre-sowing application on dark grey podzolised soil, average for 2023-2024*

Experiment variant	Yield, t/ha	Yield increase		Grain content, %	
		t/ha	%	raw gluten	protein
$N_{30}P_{78}K_{78}$ (100 % uniformity of fertiliser distribution) - control	9.56	-	-	24.1	13.3
$N_{27}P_{70}K_{70}$ (90 % uniformity of fertiliser distribution)	9.19	-	-	22.4	12.3
$N_{26}P_{66}K_{66}$ (85 % uniformity of fertiliser distribution)	8.98	-0.58	-6.1	25.4	12.4
$N_{24}P_{62}K_{62}$ (80 % uniformity of fertiliser distribution)	9.60	+0.04	+0.4	22.3	12.8
$N_{23}P_{59}K_{59}$ (75 % uniformity of fertiliser distribution)	8.92	-0.64	-6.7	22.3	12.5
$N_{34}P_{86}K_{86}$ (110 % uniformity of fertiliser distribution)	9.31	-	-	25.4	13.7
$N_{35}P_{90}K_{90}$ (115 % uniformity of fertiliser distribution)	9.69	+0.13	+1.4	22.9	14.0
$N_{36}P_{94}K_{94}$ (120 % uniformity of fertiliser distribution)	9.39	-	-	24.5	13.6
$N_{38}P_{98}K_{98}$ (125 % uniformity of fertiliser distribution)	10.4	+0.84	+8.8	24.7	13.2
LSD 0.95	0.41	-	-	0.48	0.26

Source: compiled by the authors

It should be noted that, thanks to the high level of technological support for both winter wheat and its predecessor (table potatoes), high yields (8.92-10.4 t/ha) were achieved in the experiment. The uniformity of fertiliser distribution at 90%, 110% and 120% did not lead to a significant decrease or increase in wheat yield. Accordingly, 85 and 75% of fertilisers from the norm of 300 kg/ha of diammonium phosphate reduced the yield of winter wheat by 6.1-6.7%, while an increase of 15 and 25% increased the yield by 0.13-0.84 t/ha and 1.4-8.8%.

Similar results regarding the positive effect of fertilisers on winter wheat yield were obtained in studies by D. Litvinov *et al.* (2024). The work of Y. Chen *et al.* (2020) showed that nitrogen application significantly increased grain yield and protein concentration in grain due to an increase in residual nitrates in the soil during both growing seasons, at three phosphorus application rates. Phosphorus application alone did not affect these parameters. Significant interaction between nitrogen and phosphorus fertilisers was found for most of the parameters tested. The highest grain yield, nitrogen content and nitrate content in the soil, as well as the lowest residual nitrate content in the soil, were observed with N1P1 treatment. The recommended fertiliser rate was N 240 kg/ha^{-1} and P 150 kg/ha^{-1} as the optimal nitrogen-phosphorus regime in the North China Plain.

Uneven fertiliser application can lead to excess or deficiency of nutrients and reduce their efficiency. For example, under dry conditions during the growing season, the application of 70 and 90 kg/ha of nitrogen had the same effect on yield, which varied depending on the amount and distribution of precipitation (Basso *et al.*, 2013). Research by Z. Li *et al.* (2022) has shown that irrigation and nitrogen use increased the average yield of winter wheat by 40% and 15%, respectively, compared to control variants without irrigation or fertiliser application. The state of nutrients in the soil and the organic carbon content in the soil had a more significant impact on wheat yield than climatic factors (average annual temperature) or water and nitrogen management methods.

This could be the basis for offsetting the negative impact of uneven fertiliser distribution on this indicator. Regardless of the yield obtained (9-10 t/ha) and the probable possibility of a decrease in grain quality under the conditions of the experiment, regardless of the degree of uneven distribution of fertilisers, grain of class 2 was obtained in accordance with DSTU 3768:2019 (2019), with the exception of the variant where DAFK was applied at a reduced dose of 10-15% (protein content 12.3-12.4%). In all other variants, the protein content ranged from 12.5 to 14.0%. In terms of "raw" gluten content, all variants provided grain of at least grade 2. It should be noted that with an increase in the DAFK dose, the grain quality improved. A number of authors show that with an increase in the rate of fertiliser, the protein content increases and its content was higher when wheat was grown after a nitrogen-fixing crop (Ali *et al.*, 2019; Novak *et al.*, 2019). Research by A. Shuvar *et al.* (2024) has shown that the use of differentiated nitrogen fertiliser application when feeding winter wheat not only increases yield but also has a positive effect on the quality indicators of the grown crop. In the control variant of the experiment, a fourth (feed) class wheat grain yield was obtained, while in the experimental variant with differentiated nitrogen application using the Yara N-Sensor device, a third (food) class yield was obtained. Thus, the results of numerous studies indicate the importance of optimising the rates and methods of nitrogen fertiliser application, taking into account soil and climatic conditions and technological solutions, in order to achieve stable yields and high grain quality.

Conclusions

Critical limits of uneven fertiliser distribution for winter wheat on dark grey podzolised soil have been established, at which significant changes in crop productivity occur. The possibility of compensating for the negative impact of uneven fertiliser application has been proven, provided that high technological support for cultivation is available. Artificially created heterogeneity of fertiliser application at ±10-25% of the standard DAFK rate (300 kg/ha) for winter wheat cultivation on dark grey podzolised soil showed a significant effect on plant height, above-ground mass and root system growth, yield and quality of the crop under study. The difference in plant height during the tillering and stem elongation phases of wheat did not exceed 5%. In the heading phase, the highest indicators were obtained with the application of $N_{34}P_{86}K_{86}$ and $N_{38}P_{98}K_{98}$ (variants 3 and 9) and amounted to 107 and 109 cm, which is 7 and 9% more than the control variant. Also, in these variants, with an increase in the fertiliser rate by 10 and 25%, the highest mass of the aboveground part of winter wheat plants was obtained in the ear emergence phase. The indicators were 46% (110% fertiliser unevenness) and 38% (125% fertiliser unevenness) higher than the control variant. Moreover, the difference in the last variant (9) is evident from the tillering phase, when the excess of the indicators compared to the control was 73%. A 10-25% higher fertiliser rate contributed to the intensification of wheat root system growth in the tillering phase by 30-33% and tillering by 29-32%.

When the dose was reduced (by 10-25%), the ratio between the root system of plants and their aboveground part was not significantly affected (during the tillering phase, it ranged from 0.016 to 0.029, and during the stem elongation phase, from 0.009 to 0.018) . When the dose was increased (by 10-25%), this indicator was significantly optimised (during the tillering phase, it ranged from 0.028 to 0.036, and during the stem elongation phase, from 0.014 to 0.017). With high technological support for the cultivation of winter wheat and its predecessor (table potatoes), it is possible to offset the negative impact of uneven fertiliser distribution on yield, which reached 8.92-10.4 t/ha, and grain quality, which was classified as grade 2 (protein content within 12.5-14.0%, and "raw" gluten – 22.3-24.7%). Further research prospects include studying the artificially created heterogeneity of fertiliser application on the yield and quality of winter wheat after other predecessors (peas, silage corn, etc.), studying heterogeneity that is ±20-35% greater than the standard DAFK rate (300 kg/ha).

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Conflict of Interest

None.

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Продуктивність пшениці озимої в умовах неоднорідного розподілу добрив при внесенні

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Анотація. Раціональне використання мінеральних добрив за умови їх нерівномірного розподілу є важливим чинником підвищення ефективності живлення рослин і формування високого врожаю озимих зернових. Метою дослідження було встановлення впливу неоднорідного розподілу гранул мінеральних добрив за передпосівного внесення на формування продуктивності пшениці озимої. Дослідження проводилися у польовому чотирикратному досліді на темно-сірому опідзоленому ґрунті з використанням 9 варіантів розподілу добрив, що включали контроль (100 %) та відхилення ±10-25 %. Встановлено, що норма фосфорних і калійних добрив, яка перевищувала на 10-15 % на темно-сірому опідзоленому ґрунті не має позитивного впливу на наростання надземної частини і кореневої системи пшениці озимої. Встановлено, що збільшення рівномірності розподілу добрив позитивно впливало на біометричні показники рослин, зокрема висоту, масу надземної та кореневої частини, що сприяло формуванню більшої врожайності та вищих якісних показників зерна. Максимальні темпи наростання надземної маси рослин були характерні для фази кущення. Відхилення норми добрив на 10-25 % від оптимальної обумовило у фазу кущення відхилення у показниках порівняно з контролем на 10-72 %, у фазу виходу в трубку – 6,4-25 %, колосіння, відповідно, на 38-46 %. Аналіз продуктивності показав, що тільки за зниження норми добрив на 15 % і 25 % встановлено достовірне зменшення урожайності пшениці озимої. Найбільшу урожайність (10,4 т/га) отримано за використання у передпосівне внесення $N_{38}P_{98}K_{98}$. Збільшення норми добрив до 110-120 % обумовило підвищення вмісту білку до рівня 13,6-14,0 %, що на 0,3-0,5 % більше порівняно з контролем. Результати з впливу нерівномірності добрив на формування врожаю культур можуть бути використані в точному землеробстві

Ключові слова: урожайність; посівні ділянки; надземна маса; коренева система; точне землеробство