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Efficiency of the compensatory scheme of using Organic Acid Nano-Complex microfertilizers in spring wheat cultivation technologys

Abstract. In recent years, significant advances in nanotechnology have increased the ability to produce nanoparticles of physiologically important metals on a large scale, which are now used to improve fertilizer formulations to increase uptake by plant cells and minimize nutrient losses. Fertilizers with nanostructure can increase the efficiency of nutrient use through mechanisms such as targeted delivery, slow or controlled release. The aim of the research is to substantiate a

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compensatory scheme for the use of biodynamic nanofertilizers (nanocomplex micronutrient fertilizers with organic acids) by partially replacing the main macrofertilizers in the spring wheat fertilization system. The research was conducted on the basis of the educational and scientific laboratory Department of Plant Industry of the National University of Life and Environmental Sciences of Ukraine. In research, there were used the methods of field experiments of A.O. Rozhkov, notching method and scanning method for determination of leaf surface area. The studies showed that it is possible to replace within 30-40% of the recommended amount of mineral fertilizers with biodynamic nanofertilizers in the spring wheat fertilization system. In general, the use of nanofertilizers increased wheat growth and improved yield and yield components. Substitution of mineral fertilizers, Innoparmis Agroscience Biodynamic fertilizers, provides a more favourable 86-88% survival rate of spring wheat plants during the growing season. By replacing 34% of the recommended rate of mineral fertilizers, the content of photosynthetic pigments in wheat leaves increases by 5% and the leaf surface area increases by 7%. The created compensatory schemes for the use of biodynamic nanofertilizers by partial (34% in the wheat fertilization system) replacement of the main macronutrients can increase the yield of spring wheat by 9.9%. The proven possibility of replacing mineral fertilizers with biodynamic nanofertilizers in the fertilization system of agricultural crops will reduce environmental pollution and the economic dependency of using mineral fertilizers against the background of their rapid increase in price in recent years

Keywords: *Triticum aestivum* L.; biodynamic nanofertilizers; crop photosynthetic activity; yield; yield structure; quality of the products

INTRODUCTION

Fertilizers have a key role in increasing crop yields and the ecosystem surrounding agriculture. Excessive use of fertilizers irreversibly changes the soil ecology, reducing the area available for crop production. Sustainable agriculture involves the balanced use of agrochemicals, which over time can protect the environment and save certain species from extinction. The creation and implementation of new environmentally safe and technological preparations designed to increase the efficiency of plant nutrient use of mineral fertilizers and soil is relevant for Ukrainian agriculture. One of the ways to achieve this may be the development of innovative technologies for growing plants in crops. There are many solutions proposed on the market today that deliver mixed results from a crop efficiency and environmental impact perspective. Examples of these new products are: nanofertilizers, growth-stimulating complexes, biodynamic nanofertilizers etc.

S.K. Kumar *et al.* (2022) point out that rapid urbanization with shrinking agricultural land, dramatic climate change and the widespread use of agrochemicals in agricultural practices are causing environmental disturbances and threats to public health, affecting food security and agricultural sustainability. Besides this, agriculture soils are continuously losing their quality and physical properties as well as their chemical (imbalance of nutrients) and biological health due to indiscriminate use of agrochemicals. Therefore, the creation and implementation of new environmentally safe and technological preparations aimed at increasing the efficiency of plant nutrient use of mineral fertilizers and soil is relevant for the global agricultural sector, according to L. Batsmanova *et al.* (2020).

According to D.M. Mahapatra *et al.* (2022) the development of innovative technologies for growing plants in crops, such as nanofertilizers, growth-stimulating complexes, etc., are starting to play an important role in increasing the efficiencies and quality of crops. The same opinion is shared by C.F. Okey-Onyesolu *et al.* (2021), who believe that the development of new nanofertilizers offers a promising opportunity to improve plant mineral nutrition. R.K. Krishnasree *et al.* (2021) also find that through the use of nanostructured fertilizers, the long-term availability of all the supplemented nutrients to the plant throughout the growing season is crucial to promote germination, growth, flowering and fruiting. M.R. Rehana *et al.* (2022) also point out that the use of controlled release fertilizers (CRFs) is beginning to emerge as a promising area, offering excellent means to improve nutrient management and thus significantly reduce environmental threats while maintaining high yields of good quality crops. Controlled-release fertilizers allow for a better alignment of nutrient release with the plant life cycle. A. Gorczyca *et al.* (2021) and A. Padmakumar *et al.* (2023) concluded that the undoubted prospects for the development and widespread use of nanotechnology lie in the fact that nanoparticles of biogenic metals have extremely high activity and sizes corresponding to the size of living cells, contribute to an increase in yields, gross yields of crops and product quality; increase the efficiency of nutrient use and their intended use, and have a positive effect on reducing the toxicological burden on the environment due to a significant reduction in the gross volume of fertilizer and pesticide application. In addition, according to T. El-Saadony *et al.* (2021), nanoparticles in fertilizers are more reactive, able to penetrate the epidermis, providing gradual release and targeted distribution, and therefore reducing excess nutrients, increasing their use efficiency, are crucial in reducing abiotic stress and heavy metal toxicity. In general, the use of nanoparticles in nanofertilizers and nanopesticides, the use of nanoparticles in agriculture and their role in enhancing the function of biological factors is an important and interesting area of research.

The purpose of the study performed is to develop and substantiate a compensatory scheme for the use of organic acid complex fertilizers containing nano-particles by partially replacing the main macrofertilizers in crop cultivation technologies.

MATERIALS AND METHODS

Field studies were conducted in 2021-2022 in the educational and scientific laboratory "Demonstration collection field of crops" of the Department of Plant Industry of the National University of Life and Environmental Sciences of Ukraine (Kyiv) on the territory of the Botanical Garden of National University of Life and Environmental Sciences of Ukraine (NULES of Ukraine). Laboratory research was conducted in the laboratories of the Department of Plant Industry of the National University of Life and Environmental Sciences of Ukraine "Quality of seeds and planting material" and "Analytical research in plant production".

The soils of the Demonstration Collection Field of Crops of the Department of Plant Production are predominantly grey forest soils. On the elevated areas of the Kyiv plateau and in the upper parts of the slopes of the beams, grey forest and light grey forest soils prevail on loess deposits under the canopy of oak-hornbeam forests. The territory borders on Holosiivskyi Park.

The soil of the experimental plot is grey forest coarse-loamy – light loamy in terms of granulometric composition. The following horizons are distinguished in the profile of grey forest soils: No – forest floor (only in soils under forest); H – humus with a thickness of 12-30 cm, grey in colour; NE – humus-eluvial, with whitish SiO_2; I – illuvial with a nutty or nutty-prismatic structure (humus films are present on structural parts), grey-brown in colour; C – parent rock.

The physical and chemical parameters of the grey forest soil of the experimental plot are given in Table 1.

Table 1. Physical and chemical properties of the soils of the experimental site

Type of soil	Layer, cm	Humus content, %.	pH of the salt hood	Sum of absorbed bases, mg-eq/100 g of soil	Amount of absorbed cations, mg-eq/100 g of soil			Content of mobile forms of nutrients, mg/100 g of soil		
					Ca^{2+}	Mg^{2+}	H^+	N	P_2O_5	K_2O
Grey forest coarse-dusty-light loamy	0-10	3.0	5.8	10	9.1	1.9	3.1	8.3	12.0	10.1
	20-30	2.1	6.1	15	12.5	2.3	2.2	6.2	7.5	4.2

Source: the results were obtained from the Ukrainian Laboratory of Quality and Safety of Agricultural Products

The humus-eluvial horizon of these soils is 50-60 cm, with carbonates occurring at a depth of 110-150 cm. They are medium loamy in terms of particle size distribution. The humus content in the topsoil is 2.1-3.0%, the amount of absorbed bases is 10-15 mg-eq/100 g of soil, the degree of saturation with bases is 82-88%, and the reaction of the soil solution is slightly acidic (pH = 5.8 - 6.1). Groundwater is located at a depth of 2-4 metres. The soil density in the equilibrium state is 1.1-1.2 g/cm, the moisture content of stable wilting is 10.2%. The total moisture capacity of the soil is 39-40%, the field moisture capacity of this soil is 27.2%, the capillary break moisture is 19.4%, the maximum hygroscopicity is 7.3%, and the moisture inaccessible to plants is 10%.

The soil is characterized by a high content of gross and mobile forms of nutrients. As a result of the regradation process, the carbonate line has risen in these soils, the illuvial horizon has become looser, the humus content has increased, and the saturation with bases has increased compared to dark grey and podzolic chernozems. From the above data, it can be said that the soil is quite favourable for growing many crops, as it has favourable water and physical and chemical soil properties. With a sound soil cultivation system and rational fertilization, the decline in its economic properties can be prevented.

The contrast of temperature regime and uneven precipitation during the season, individual months and even decades observed during the months of vegetation of the studied crops in the years of research created extreme conditions for the formation of plant productivity in some periods, the degree of negative impact of which on the level of crop yield was determined by time (developmental phase, stage of organogenesis) and duration of their action.

The weather conditions in 2021 also differed significantly from the long-term average in terms of monthly average air temperature, the sum of active temperatures and precipitation. The average daily temperature in April and May 2021 was lower than the long-term average, which led to a shift in the sowing of crops to later dates. The total precipitation in May was 77 mm, which is 29 mm above the long-term average, and due to the lower temperature, the moisture regime in this month corresponded to the excessive one, as the calculated HCC was 1.7. The air temperature in June increased significantly and reached 21.3°C, which is 2.8°C above the long-term average, and lower precipitation (24 mm) resulted in a moisture regime that corresponded to dry conditions, and the negative impact was partially avoided due to waterlogging in the previous month.

The total precipitation for July was 61 mm, which is only 22 mm less than normal, but the average monthly temperature was 24.6°C, which is 5°C higher than the long-term average. In such extreme conditions, even with sufficient precipitation, the HTC (hydrothermal coefficient) dropped to 0.8, indicating dry conditions. In August, the temperature regime stabilized, and the excess of the long-term average was only 0.9°C. At the same time, the amount of precipitation was 55 mm, which, combined with the heat input, corresponded to the HTC of 0.8, i.e. slightly dry conditions close to normal. The average monthly temperature in September was 0.8°C below the long-term average, and the amount of precipitation was 23 mm, which was generally favourable for soybean maturation.

The research in 2019-2022 was aimed at proving the possibility of partial replacement of basic macrofertilizers with *organic acid nano-complex* (OAC) micronutrient fertilizers and developing compensatory schemes for their application. In the research, the organic acid complex micronutrient fertilizers manufactured by UAB Innoparmis Agrocience (Republic of Lithuania) supplied by *Natural Fertilizers* Limited (Ireland), ("*Innoparmis Agroscience*" ™) were used.

The research was conducted on spring wheat crops of the Elegia Myronivska variety and soybean variety Khorol. The reaction of plants to the application of macro-microfertilisers was determined by assessing the dynamics of formation and functioning of the photosynthetic (pigment content in leaves) and symbiotic (number and weight of nodules) systems, yield, and quality of the products obtained.

Spring soft wheat – Elegia Myronivska variety, seeding rate of spring wheat seeds – 5 million germinating seeds per hectare, row spacing – 15 cm. Fertilization background: $N_{20}P_{60}K_{60}$ – in pre-sowing cultivation + N_{20} – the beginning of the tube (BBCH 30-32) + N_{20} – the beginning or full earing (BBCH 51-59). Scheme of field experiments of the second block of research: 1) Control $N_{60}P_{60}K_{60}$, 2) $N_{50}P_{50}K_{50}$+OAC, 3) $N_{50}P_{40}K_{30}$+OAC, 4) $N_{40}P_{40}K_{30}$+OAC, 5) $N_{40}P_{30}K_{30}$+OAC, 6) $N_{30}P_{30}K_{30}$+OAC.

It was registered for cultivation in the Forest-Steppe and Polissya regions back in 2004. It belongs to high-yielding wheat of a strong type. It is suitable for early sowing and produces yields of up to 6.5 tonnes per hectare. Plant height is 90-100 cm. Variety type: low-growing, semi-intensive. Grain quality: weight of 1000 grains is 46.7 g, grain weight is 740 g/l, crude gluten content is 28%, protein is 15.7%, flour strength is 320 o.a.

The research was conducted in accordance with the methods of field experiments of A.O. Rozhkov *et al.* (2016). The location of the plots was systematic. Field research was conducted using the small plot method. The area of the accounting plot is 5 m^2, with six replications.

Leaf surface area was determined by the Nichiporovich notching method and scanning method. The content of chlorophyll *a* and *b in* the leaves was determined by biochemical analysis using a spectrophotometer, with subsequent calculation of pigment concentration according to the equation of Wetstein and Holm (Gritsayenko *et al.*, 2003). Stages and microstages of crop growth and development were determined according to the BBSH (Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und der CHemischen Industrie) scale.

Yields of the main and by-products were determined in plots by the method of continuous accounting using a Minibatt (France) hand combine harvester. The resulting weight of spring wheat grain was converted to the yield per 1 hectare, taking into account weediness and moisture content by 14% (DSTU 3768:2010..., 2010). Before threshing, a "trial sheaf" of each variant was taken from 1 metre running length to determine the structure of the crop. The study was conducted per the requirements of the International Convention on Biological Diversity (1992).

The quality of grain was determined in the laboratory "Analytical Research in Plant Production" using the method of infrared spectrometry on the device "Infratec 1241 FOSS" (Denmark). Statistical analysis of the data was performed using the Serial Attached SCSI (SAS) 9.4 software package.

RESULTS AND DISCUSSION

The grain yield of the wheat variety Elegia Myronivska in the 2021/2022 growing season was somewhat low, due to extremely dry conditions throughout the growing season. At the same time, partial (up to 35%) compensation of the mineral fertilizer application rate with Organic Acid Complex micronutrient fertilizers allowed the crop to generate higher yields. According to A.K. Márquez-Rrieto *et al.* (2022), the absorption efficiency of macronutrients is 19% higher when applying nanofertilizers compared to conventional fertilizers, it is logical that crop yields are higher. In research, the average yield varied from 4.63 t/ha in the control variant ($N_{60}P_{60}K_{60}$) to 5.09 t/ha (9.9% higher than the control) in the variant of substitution $N_{50}P_{50}K_{50}$+OAC (compensation scheme 16:16:16%) (Table 2, Fig. 1).

Table 2. Spring wheat yield depending on the compensatory fertilizer substitution scheme, t/ha

Fertilizers	% compensation	2021	2022	Average	Increase	
					t/ha	%
Control $N_{60}P_{60}K_{60}$	—	4.14 **a**	5.11 **b**	4.63 **b**	—	—
$N_{50}P_{50}K_{50}$+OAC	16:16:16	4.44 **b**	5.74 **a**	5.09 **a**	+0.46	+ 9.9
$N_{50}P_{40}K_{30}$+OAC	16:34:50	4.40 **b**	5.65 **a**	5.02 **a**	+0.39	+ 8.4
$N_{40}P_{40}K_{30}$+OAC	34:34:34	4.32	5.50	4.91	+0.28	+ 6.0
$N_{40}P_{30}K_{30}$+OAC	34:50:50	4.14 **a**	5.26	4.70	+0.07	+ 1.5
$N_{30}P_{30}K_{30}$+OAC	50:50:50	4.07 **a**	5.15 **b**	4.61 **b**	-0.02	-0.5

Note: the same letters in a column indicate no significant difference between the variants, no letters – the variant has a significant difference in NIR05 (the least significant difference) with the rest (Analysis of variance (ANOVA) was performed to test the effect of substitution of mineral fertilizers with nanofertilizers. The analysis was performed using the Tukey's HSD test. Statistically significant differences do not have letters (two-factor analysis of variance, Tukey's test, $p < 0.01$)

Source: developed by the authors

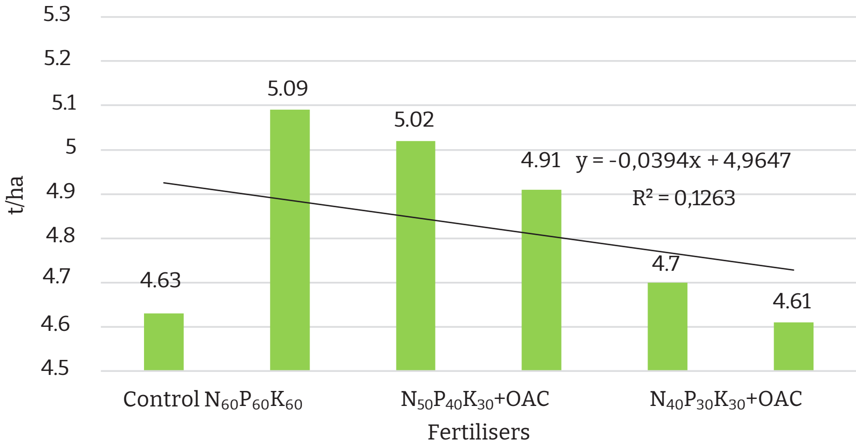

Figure 1. Average yield of spring wheat, t/ha (2021-2022)

Source: developed by the authors

With a further increase in the percentage of compensation of mineral fertilizers with Organic Acid Complex micronutrient fertilizers, the yield gradually decreased and, under the condition of 50% replacement, was the lowest – 4.61%, below the control by 0.5%. Replacement of 34% of fertilizers with Organic Acid Complex fertilizers increased wheat yield by only 6.0%. The yields of the fertilizer substitution variants $N_{50}P_{50}K_{50}$+OAC and $N_{50}P_{40}K_{30}$+OAC – 4.91 and 4.85 t/ha – did not differ significantly from each other according to the analysis of variance.

The reasons for the increase in yields under the influence of organic acid complex fertilizers are related to the optimization of plant nutrition through microelements and the overall improvement of physiological processes in the plant. Another possible reason for the increase in yields is the minimization of external negative factors, in particular, air drought on some days in May and June 2021. Fertilizing spring wheat crops with Organic Acid Complex micronutrient fertilizers in the tillering – earing phase allows us to maintain plants in good condition during the dangerous period of summer droughts, which leads to a significant increase in yield.

The compensatory scheme of replacing 50% of the norm of applied mineral fertilizers ($N_{30}P_{30}K_{30}$+OAC) did not work to increase spring wheat yield due to a decrease in other elements of the spring wheat yield structure, in particular, crop density and leaf area. In contrast to results, B. Hasan & T. Saad (2020), who conducted similar studies on the partial replacement (0.25, 0.5 and 0.75%) of mineral NPK fertilizers with nanofertilizers, showed a significant increase in grain yield for all years of research in the variant with 50% replacement of NPK fertilizers. K. Al-Saidan *et al.* (2019), who also studied the interaction between mineral and nano-organic fertilizers and their impact on durum wheat, found that various combinations of organic and biological fertilizers with nanoparticles provide higher yields than 50 and even 100% of the recommended rate of mineral fertilizer application.

The advantage of replacing NPK with nanofertilizers is firstly in their complex composition and secondly in their foliar application, which contributes to the rapid absorption of the minerals and their incorporation into the plant's metabolic processes without loss and environmental pollution. A review article by A. Alhasan *et al.* (2022) indicates that foliar application of nanofertilizers directly leads to a reduction in the time delay between application and plant uptake during the rapid growth phase, and can improve the efficiency and rate of immediate utilization of the nutrient. required by the plant for maximum growth and yield. The application of nanobiological fertilizer increased the spike length, number of spikes, number of seeds, number of seeds per spike, seed weight and number of days to physiological maturity. In general, the use of nanobiological fertilizers has a positive effect on the growth and development of crops, in particular, nano-iron had a significant effect on yield, plasma membrane stability and chlorophyll content (Delfani *et al.*, 2014), nanozinc had a positive effect on seed yield, lipid peroxidation and various antioxidant biomarkers in soybean (Yusefi-Tanha *et al.*, 2020).

Field germination of seeds in all compensatory schemes of Organic Acid Complex micronutrient fertilizers application was quite high – 84-86%, while field germination in the control variant ($N_{60}P_{60}K_{60}$) was 85% (Table 3). Substitution of 50% of mineral NPK fertilizers reduced the field germination of spring wheat. During the growing season, the difference between the variants in terms of intensity of metamer development and reduction increased. In the control variant, only 81% of plants survived to the full ripeness stage. Under different combinations of substitution of 16 and 34% NPK, plant survival was the highest – 88 and 86%, respectively. Substitution of half of the recommended rate of PK with nanofertilizers provided less favourable survival of spring wheat plants during the growing season – 82%.

Table 3. Structure of spring wheat agrocenosis depending on the compensatory fertilizer replacement scheme, average for 2021-2022

Fertilizers	% compensation	Stairs, *VVSN 10*		Full ripeness, *VVSN*		
		field similarity seed	CR*	survival plants	PDA	CPS
		%	pcs/m²	%		pcs/m²
Control $N_{60}P_{60}K_{60}$	—	85	425	81	1.30	447
$N_{50}P_{50}K_{50}$+OAC	16:16:16	86	430	88	1.38	522
$N_{50}P_{40}K_{30}$+OAC	16:34:50	86	430	88	1.34	507
$N_{40}P_{40}K_{30}$+OAC	34:34:34	86	426	86	1.32	483
$N_{40}P_{30}K_{30}$+OAC	34:50:50	84	420	84	1.32	465
$N_{30}P_{30}K_{30}$+OAC	50:50:50	84	420	82	1.31	451

Note: NP – number of plants; CPC – coefficient of productive tillering; CPS – number of productive stems
Source: developed by the authors

An important structural component of yield is the number of productive stems per unit area at full maturity. The range of changes in the number of productive stems in field experiments reached 507-522 pieces/m² with no more than 34% of the recommended rate of mineral fertilizer application. The lowest number of productive stems was formed in the control variant, in which plants were grown without additional nutrients, which led to the lowest coefficient of productive tillering – 1.30 and the formation of 447 productive stems/m². Substitution of half ($N_{30}P_{30}K_{30}$+OAC) of the recommended rate of mineral fertilizers did not contribute to the formation of a high productive stem (451 productive stems/m²), the coefficient of productive tillering was also low – 1.31.

The photosynthetic activity of crop plants is the basis of their productivity and largely depends on the pigment content of the plants. Of particular importance are green pigments, chlorophylls *a* and *b, which are* sensitive indicators of the physiological state of plants. The amount and functional activity of these pigments is an indicator of the potential ability of plants to form a biological yield. These pigments are directly involved in the formation of the structure of the photosynthetic apparatus, play an important role in photosynthetic and photochemical reactions associated with the absorption and transformation of energy used in the synthesis of substances necessary for plant growth and development (Long *et al.*, 2006; Bramley, 2013).

The most important photosynthetic pigments are chlorophylls, and therefore a positive correlation between their content in leaves and photosynthesis leads to an increase in plant productivity. The maximum level of photosynthetic pigments in the leaves of durum spring wheat plants, on average, was reached during the earing phase. The decrease in the amount of photosynthetic pigments in spring wheat plants, starting from the flowering phase, is a natural process, since the chloroplast stroma loses water, they break down into granules, resulting in the destruction of chloroplasts.

It has been shown that the higher the percentage of mineral fertilizer substitution by Organic Acid Complex micronutrient fertilizers in the fertilization system, the higher the pigment content in wheat leaves, with a direct and close correlation of r = 0.96. The positive effect of partial fertilizer substitution on the content of chlorophyll *a* and *b* compared to this indicator in the control was found in all experimental variants. The difference in the amount of chlorophyll *a* in the leaves of plants between the least effective variant of substitution $N_{50}P_{50}K_{50}$+OAC and the control averaged 0.31 mg/g in the earing phase (Fig. 2).

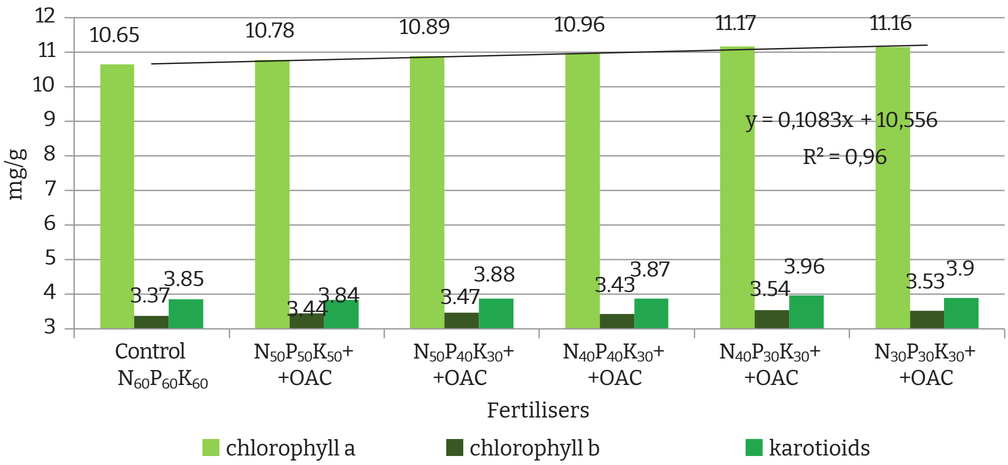

Figure 2. Content of photosynthetic pigments in spring wheat leaves in the earing phase, mg/g
Source: developed by the authors

In the least effective variant of the same substitution, the content of chlorophyll *b* compared to the control in the indicated stages of development was 0.04, 0.08 and 0.07 mg/g higher than in NIR_{05} – 0.03, 0.07 and 0.03 mg/g, respectively. It should be noted that the use of low rates of mineral fertilizer replacement – from 16 to 34% ($N_{50}P_{50}K_{50}$+OAC, $N_{50}P_{40}K_{30}$+OAC, $N_{40}P_{40}K_{30}$+OAC) did not provide a significant increase in the amount of carotenoids in plant leaves. Indicators of carotenoids content in the leaves of plants of these variants and control belonged to one homogeneous group. The greatest influence on the amount of chlorophyll *a* and *b and the* amount of carotenoids in the leaves of spring wheat plants was recorded in the variants with the replacement of 50% of the norm of phosphorous and potassium fertilizers and 34% ($N_{40}P_{30}K_{30}$+OAC) of nitrogen fertilizers. Its further increase to 50% ($N_{30}P_{30}K_{30}$+OAC) did not provide a significant increase in the content of photosynthetic pigments in the leaf mass of plants. In the experiment, it was found a direct close relationship between wheat yield and leaf area index (r = 0.948). The studies also showed a tendency to reduce the leaf surface area with an increase in the proportion of Organic Acid Complex microfertilizers in the spring wheat fertilization system (Fig. 3).

Two-year studies of the compensatory scheme of using Organic Acid Complex microfertilizers in spring wheat cultivation technology convincingly proved the possibility of replacing from 16 to 34% of the recommended NPK rate with Organic Acid Complex microfertilizers (Table 4). An increase of 12% in the number of grains per ear and 17% in the weight of grains per ear was observed, and the weight of 1000 seeds increased by 7% under the compensatory scheme $N_{50}P_{50}K_{50}$+OAC. In the variant with NPK substitution by 34% ($N_{40}P_{40}K_{30}$+OAC), the number of grains per ear increased by 6%, the weight of grain per ear – by 5%, the weight of 1000 seeds – by 7% compared to the control.

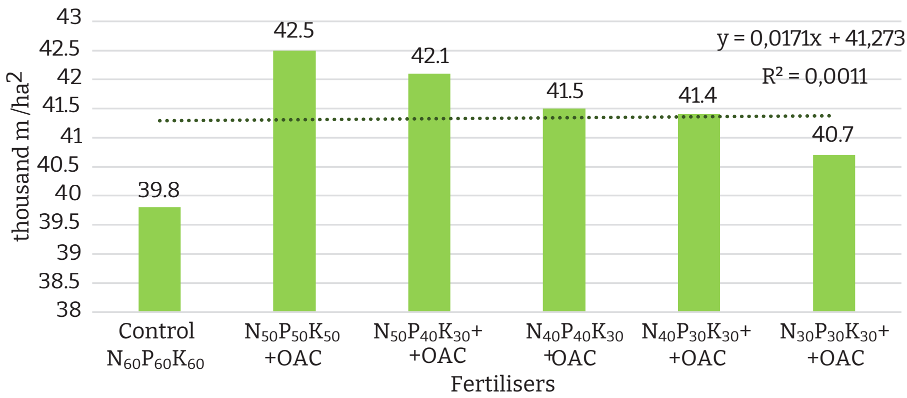

Figure 3. Leaf area of spring wheat in the earing phase, thousand m /ha^2

Source: developed by the authors

Table 4. Individual productivity of wheat plants depending on the compensatory fertilizer replacement scheme (average for 2021-2022)

	Fertilizers	Plant height, cm	Spike length, cm	Number of grains per ear, pcs	Grain weight per ear, g	Weight of 1000 seeds, g
1	Control $N_{60}P_{60}K_{60}$	85.7	11.4	44.6	1.20	41.6
2	$N_{50}P_{50}K_{50}$+OAC	85.2	11.8	50.1	1.40	45.7
3	$N_{50}P_{40}K_{30}$+OAC	83.3	11.8	51.2	1.38	44.4
4	$N_{40}P_{40}K_{30}$+OAC	86.5	11.4	47.4	1.26	43.6
5	$N_{40}P_{30}K_{30}$+OAC	84.8	11.4	44.0	1.28	43.3
6	$N_{30}P_{30}K_{30}$+OAC	86.7	11.5	43.6	1.22	42.9
	$NIR_{0.05}$	1.5	0.3	1.7	0.07	1.4

Source: developed by the authors

The effectiveness of the compensatory fertilizer replacement schemes developed by us for the formation of wheat grain quality has been demonstrated. The quality of wheat grain is determined by the whole range of technological factors, but the most important is the supply of nutrients to plants. Substitution of basic fertilizers for spring wheat with Organic Acid Complex microfertilizers contributed to an increase in protein synthesis in the grain – from 13,2 in the control variant to 13.8% in the variants $N_{40}P_{30}K_{30}$+OAC and $N_{30}P_{30}K_{30}$+OAC (Table 5). The protein content, in contrast to the yield indicator, increased with an increase in the proportion of replacement of mineral fertilizers with Organic Acid Complex microfertilizers. When substituting according to the schemes $N_{50}P_{50}K_{50}$+OAC – $N_{50}P_{40}K_{30}$+OAC, the trend towards an increase in protein content in grain was maintained, but the indicators were somewhat lower.

Table 5. Wheat grain quality depending on the compensatory fertilizer replacement scheme (average for 2021-2022)

	Fertilizers	Content of 1, %.					
		Protein	gluten	ash	fat	fibre	starch
1	Control $N_{60}P_{60}K_{60}$	14.8	24.4	1.7	2.5	3.0	66.4
2	$N_{50}P_{50}K_{50}$+OAC	14.4	23.4	1.6	2.3	3.0	65.8
3	$N_{50}P_{40}K_{30}$+OAC	14.4	23.2	1.7	2.5	3.0	65.8
4	$N_{40}P_{40}K_{30}$+OAC	14.6	23.6	1.7	2.5	3.0	65.0

Table 5, Continued

Fertilizers		Content of 1, %.					
		Protein	gluten	ash	fat	fibre	starch
5	$N_{40}P_{30}K_{30}$+OAC	14.8	24.8	1.7	2.5	3.1	64.7
6	N30P30K30+OAC	14.8	24.6	1.7	2.6	3.0	64.6
NIR 0.05		1.5	0.3	1.7	0.07	0.1	1.4

Notes: the content of quality indicators is recalculated for standard wheat grain moisture content of 14%
Source: developed by the authors

The gluten content of grain is closely related to balanced nutrition, especially nitrogen. The lowest gluten content of 20.4% was in the grain formed in the control variant for the application of the recommended rate of mineral fertilizers, where nitrogen fertilizers were applied in the form of N_{20} kg/ha d.m. at the beginning of the tube and at full earing. The replacement of mineral nitrogen fertilizers with Organic Acid Complex fertilizers, which are characterized by higher solubility, more active penetration through the cuticle, which ensures targeted delivery and controlled release of elements, and rapid incorporation into plant metabolic processes, contributed to an increase in gluten in grain by 3-5% compared to the control. The fat content in the grain was 2.3 to 2.6% and varied slightly depending on the proportion of the Organic Acid Complex fertilizer substitution. Wheat grain is characterized by a low ash content of 1.7%, and the dynamics of change was practically absent in the variants of compensatory fertilization schemes. The starch content in the grain varied from 64.6 to 66.4% in an inverse correlation with the protein content.

The results obtained are consistent with the results of B. Hasan & T. Saad (2020), M. Mardalipour *et al.* (2014), who in their studies also showed the advantage of treating wheat crops with nanofertilizers over mineral fertilizers in terms of leaf area, number of ears, number of grains, weight of 1000 grains and grain yield. A. Joshi *et al.* (2022) generally noted a doubling of the number of grains in a wheat ear when seeds were treated with nanofertilizers before sowing. Results indicated that significant response was spraying of SMP Organic Acid Complex fertilizer followed by the spraying combined of tri (N+P+K), di (N+P), (N+K) and (P+K) Organic Acid Complex fertilizer compared to control and traditional (NPK+TE) fertilizer treatments respectively in all growth and yield parameters of wheat with an increment of the spray foliar (SMP) of 87.77 cm, 12.22 cm, 58.22 spad, 3.17%, 0.66% and 2.88% for plant height, length of spike, total chlorophyll, concentration of N, P and K respectively compared to control treatment (Al-Juthery *et al.*, 2018). However, in research A. Dapkekar *et al.* (2018), nanofertilizer application increased grain zinc content without affecting grain yield, protein content, spikelets per spike, thousand kernel weight, etc.

Literature data (Naderi & Abedi, 2012; Subbaiah *et al.*, 2016) confirms that foliar application of nanochelate microfertilizers helps to stimulate metabolic activity and increases leaf area, as it has a larger contact area, which increases physical and chemical activity.The leaf surface area of spring wheat under the replacement of 16% of the norm of NRC fertilizers ($N_{50}P_{50}K_{50}$+OAC) in the earing phase reached its maximum in the experiment – 42.5 thousand m^2/ha, exceeding the control $N_{60}P_{60}K_{60}$ by 7% or 2.7 thousand m^2/ha. However, the compensatory 50% rate of nanofertilizer application did not contribute to the formation of a sufficiently high leaf surface area – 40.7 thousand m^2/ha, which was higher than the control $N_{60}P_{60}K_{60}$ only by 2% or 0.9 thousand m^2/ha. The positive effect of nanofertilizers on the leaf area index of crops of different crops was also noted in B. Hasan & T. Saad (2020), N. Basavegowda & K.H. Baek (2021).

The impact of nanofertilizers on product quality improvement was noted in A. Sabir *et al.* (2014). Similar results were also obtained by researchers T. Zhang *et al.* (2018), P. Sheoran *et al.* (2021), who observed the effect of foliar application of zinc nanofertilizers on wheat plant growth and found an increase of more than 20% in grain protein content and a significant increase in photosynthetic pigments compared to the usual foliar application of mineral zinc fertilizer. Also, a two-year experiment by F. Behboudi *et al*. (2018) showed an increase in grain protein content with all nanofertilizers compared to the control under both full irrigation and drought conditions. The increase was highest under water deficit conditions with nano-Zn and then nano-Si treatment, due to a decrease in yield under drought conditions, which leads to an increase in nitrogen content in grain.

CONCLUSIONS

The three season study has convincingly demonstrated the possibility of replacing no more than 30-40% of the recommended amount of traditional mineral fertilizers in the fertilization system for cereals (wheat) with Organic Acid Complex microfertilizers produced by UAB Innoparmis AgroScience. This will help reduce environmental pollution and reduce the economic costs of using mineral fertilizers against the backdrop of their extreme rise in price under martial law.

Organic Acid Complex microfertilizers are needed to reduce the use of inorganic fertilizers and their antagonistic effect on the environment. Organic Acid Complex fertilizers have a higher reactivity, can penetrate the epidermis, providing a gradual release and targeted distribution, thus reducing excess nutrients, increasing the efficiency of nutrient use. Also concluded that Organic Acid Complex microfertilizers are crucial for mitigating abiotic stress caused by drought.

Compensatory schemes for the use of biodynamic Organic Acid Complex fertilizers were created by partial (16 to 34%) replacement of the main macronutrients in the wheat fertilizer system – $N_{50}P_{50}K_{50}$+OAC – $N_{50}P_{40}K_{30}$+OAC, which can increase the yield of spring wheat by 9.9% due to more favourable (86-88%) survival of spring wheat plants during the growing season; increase of photosynthetic pigments content in wheat leaves by 5% and leaf surface area by 7%. Also, when replacing from 16 to 34% of the recommended NPK rate with biodynamic Organic Acid Complex fertilizers, an increase of 12% in the number of grains per ear and 17% in the weight of grains per ear was observed, and the weight of 1000 seeds increased by 7%.

Questions that may be the basis for future research are to determine the impact of these biodynamic Organic Acid Complex fertilizers on living organisms in the soil, as well as on humans and livestock, accumulation in cultivated products, especially at higher doses. It is also necessary to study the role of biodynamic Organic Acid Complex fertilizers in the conditions of climate change based on different scenarios and the expected adaptive behaviour of cultivated crops under such stresses.

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CONFLICT OF INTEREST

None.

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Ефективність компенсаційної схеми застосування нанокомплексних мікродобрив на основі органічних кислот у технології вирощування ярої пшениці

Анотація. В останні роки значні досягнення в галузі нанотехнологій збільшили можливості широкомасштабного виробництва наночастинок фізіологічно важливих металів, які зараз використовуються для поліпшення складу добрив, з метою збільшення поглинання рослинними клітинами та мінімізації втрат поживних речовин. Добрива з наноструктурою можуть підвищити ефективність використання поживних речовин за допомогою таких механізмів як цільова доставка, повільне або контрольоване вивільнення. Мета досліджень: обґрунтувати компенсаторну схему використання біодинамічних нанодобрив (нанокомплексні мікродобрива з органічними кислотами) шляхом часткового заміщення основних макродобрив в системі удобрення пшениці ярої. Дослідження проводились на базі навчально-наукової лабораторії кафедри рослинництва Національного університету біоресурсів і природокористування України. Було використано методи польових дослідів А.О. Рожкова, метод надрізу та метод сканування для визначення площі листкової поверхні. Проведені дослідження засвідчили можливість заміни в межах 30-40 % рекомендованої кількості мінеральних добрив біодинамічними нанодобривами в системі удобрення пшениці ярої. Загалом застосування нанодобрив збільшило ріст пшениці і покращило врожайність і компоненти врожайності. Заміщення мінеральних добрив нанодобривами забезпечує більш сприятливе – 86-88 % виживання рослин пшениці ярої упродовж вегетації. За рахунок заміщення 34 % рекомендованої норми внесення мінеральних добрив на 5 % підвищується уміст фотосинтетичних пігментів в листках пшениці, на 7 % зростає площа листкової поверхні. Створені компенсаторні схеми використання біодинамічних нанодобрив шляхом часткового (на 34 % в системі удобрення пшениці) заміщення основних макроелементів здатні підвищувати врожайність пшениці ярої на 9,9 %. Доведена можливість заміни в системі удобрення сільськогосподарських культур мінеральних добрив біодинамічними нанодобривами дозволить зменшити забруднення навколишнього середовища та знизить економічні витрати від використання мінеральних добрив на фоні надзвичайного їх здорожчання в умовах військового стану

Ключові слова: *Triticum aestivum* L.; біодинамічні нанодобрива; фотосинтетична діяльність посівів; урожайність; структура врожаю; якість отриманої продукції