



Ecotoxicological Assessment of the Use of the Granular Preparation Agrobionov in Combination with Mineral Fertilisers for Grain Crops on Southern Black Soil of Northern Kazakhstan

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ABSTRACT

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The study aimed to evaluate the safety and effectiveness of Agrobionov as a soil ameliorant in grain farming. Experiments were conducted in 2023–2024 under vegetation conditions using comprehensive laboratory and field methods, including phytotoxicity assessment, plant growth monitoring, and soil chemical analysis for heavy metals. Agrobionov at concentrations of 1–10% did not reduce seed germination and had no toxic effect on root and seedling length. Application at 120–240 kg/ha combined with 50–75% of standard mineral fertiliser rates maintained green mass yield at the level of the full fertiliser norm. Soil analyses confirmed no accumulation of mobile forms of aluminium, iron, magnesium, or sulphur, with heavy metal content remaining below the maximum permissible concentration (MPC). The study demonstrated a strong correlation ($R = 0.99$) between fertiliser rates and vegetative mass in field-grown plants. These results indicate that Agrobionov optimises fertilisation, supports crop growth without negatively affecting soil physicochemical properties or microbiota, and can be recommended for use in Northern Kazakhstan to increase grain yields and reduce soil pollution risks.

1. INTRODUCTION

The intensification of grain production on the southern black soils of Northern Kazakhstan is accompanied by an increased anthropogenic pressure on agroecosystems, primarily due to the increase in the volume of mineral fertilisers. This increases yields, but also causes nitrate accumulation, imbalance of nutrients, degradation of the soil microbiota and increased environmental risks. In a region with a sharply continental climate and limited precipitation, there is a higher likelihood of excess minerals leaching into deeper soil horizons, which worsens groundwater quality and leads to trophobiotic shifts. The relevance of implementing resource-saving farming technologies based on the principles of fertility restoration, biological balance and environmental safety is growing.

The last few years (2020–2025) are notable for an active search for alternatives to mineral fertilisers or solutions to reduce their doses through combined fertilisation systems. Particularly, there is growing attention to ameliorants containing metal oxides, such as Agrobionov, which may specifically influence soil microbial communities and environmental safety differently than conventional organic fertilizers. The use of ameliorants in agriculture is seen as an effective alternative or complement to mineral fertilisation, especially in the context of preserving the biodiversity of soil

microorganisms and stabilising agroecosystems. According to Sivojiene et al. [1], the application of organic fertilisers and ameliorants to light soils in Eastern Lithuania significantly increased the number and activity of soil microorganisms, which contributed to improved agrochemical parameters and increased yields. The authors emphasised that biological activity is a key indicator of soil fertility, and changes in the microbial community can have a long-term impact on crop productivity and ecosystem resilience. At the same time, a substantial environmental aspect of organic nutrition is the reduction of greenhouse gas emissions, in particular nitrous oxide, which is formed as a result of microbiological processes of nitrification and denitrification. Lazcano et al. [2] provided generalised data showing that organic and ameliorative fertilisers, unlike synthetic fertilisers, not only do not stimulate excessive N_2O formation but can also suppress it by shifting the balance between the functional groups of microorganisms in the soil. Organic nutrition activates metabolically efficient groups of bacteria that ensure a more environmentally balanced conversion of nitrogenous compounds. This gives additional environmental weight to the use of organic or combined fertilisers in regions with high anthropogenic pressure on soil resources.

The results of a study by Chen et al. [3] on chrysanthemum, as well as by Du et al. [4] on nut crops confirmed the synergy effect between organic and mineral fertilisers and ameliorants.

The meta-analysis of Bebbler and Richards [5] noted that organic fertilisers contribute to the preservation of microbial diversity, but the authors emphasise the lack of comprehensive assessments that also address the state of mesofauna, invertebrate biomass and integrated indicators of phytotoxicity. However, studies specifically addressing metal-oxide containing amendments and their ecotoxicological effects are limited. In the context of Kazakhstan, this topic is relevant, as the country is striving for a balanced development of the agro-industrial complex. The study by Makenova et al. [6] conducted research on barley in Northern Kazakhstan and found a positive effect of combined fertilisation on the rhizosphere microbiota. Studies by Toishimanov et al. [7], as well as Yessenbayeva et al. [8], conducted in the south-eastern regions of Kazakhstan, showed a positive impact of organic nutrition on corn and soybean yields.

In steppe ecosystems, particularly in regions with a natural deficit of organic matter, a substantial function of organic fertilisers and ameliorants is not only to enrich the soil with macro- and microelements, but also to maintain enzymatic activity and microbial diversity. A study by Shang et al. [9], conducted in a *Leymus chinensis*-dominated steppe in Inner Mongolia, demonstrated the positive impact of organic fertilisation on the activity of soil enzymes such as urease and phosphatase, as well as on the structural richness of bacterial communities. These findings confirm the key role of organic materials in stabilising the biochemical cycle of nitrogen and phosphorus, which is of particular importance in arid areas with a risk of soil degradation. Similar results were obtained in the context of fruit crops in Kazakhstan. Aisakulova et al. [10] determined that the use of organic fertilisers leads to an improvement in soil microflora, which is manifested through an increase in the number of actinomycetes and nitrogen-fixing bacteria. The study also determined a significant improvement in plant biometrics, including fruit weight and leaf area, indicating an integrated effect of improved soil conditions and increased productivity. Despite the differences in crops, the results confirm the general trend: organic fertilisation has a pronounced positive effect on soil biological properties and agronomic parameters, which highlights the need for further research in the region's grain production.

However, the scientific literature lacks generalised data on a comprehensive ecotoxicological assessment of the impact of combined fertilisation systems on microbiota, mesofauna and phytotoxicity; results on the optimal ratio between doses of mineral and biological components on black soils with an increased risk of degradation; and tested tools for integrated environmental risk assessment, such as the Environmental Risk Index (ERI), adapted to the conditions of Northern Kazakhstan. Moreover, data on the accumulation of specific heavy metals (Cu, Zn, Fe, Mn) and the effect on defined toxicological indicators (microbial biomass, enzymatic activity, phytotoxicity indices) for metal oxide-containing amendments are scarce.

Thus, the study aimed to conduct a comprehensive ecotoxicological assessment of the granular preparation Agrobionov, containing metal oxides, in combination with mineral fertilisers, focusing on specific toxicological parameters (microbial biomass, enzymatic activity, phytotoxicity indices), accumulation of selected heavy metals (Cu, Zn, Fe, Mn), and productivity of spring wheat and oats on the southern black soil of Northern Kazakhstan.

2. MATERIALS AND METHODS

Before the field experiments were set up in 2023, a laboratory experiment was conducted to assess the phytotoxicity of the granular preparation Agrobionov. For this purpose, colloidal solutions were prepared in distilled water in a volume of 50 ml with concentrations of 1%, 2%, 3% and 10%. Seeds of the spring wheat variety *Triticum aestivum* L. "Shortandynska-2012", the fourth reproduction with low sowing qualities, were treated in 25 pieces in Petri dishes. Each variant was repeated four times. The root length, average germination and average length of wheat seedlings were determined using a Dino-Lite AM4113T digital microscope (Dino-Lite, Taiwan) and a ruler with an accuracy of 0.5 mm.

In October 2023, a vegetation experiment with oats *Avena sativa* L. was laid in 3.5-litre containers with different doses of mineral nutrition and the granular preparation Agrobionov at a rate of 120 kg/ha. The full rate of mineral nutrition was N32P27.4 kg/ha. Two blocks of variants were laid out. In the first block, the control received the full rate of NP, while other variants included $\frac{3}{4}$ of the full NP rate + Agrobionov 120 kg/ha, $\frac{1}{2}$ of the full NP rate + Agrobionov 120 kg/ha, and $\frac{1}{4}$ of the full NP rate + Agrobionov 120 kg/ha. In the second variant, the control rate of NP was combined with $\frac{3}{4}$ NP and Agrobionov 120 kg/ha, $\frac{1}{2}$ NP with Agrobionov 120 kg/ha, $\frac{3}{4}$ NP with Agrobionov 120 kg/ha and $\frac{1}{4}$ NP with Agrobionov 240 kg/ha. Phenological observations and accounting of green and dry mass of plants were conducted during the tillering phase for the first planting and during the earing phase for the second planting. During this period, soil analyses were conducted for the content of exchangeable forms of aluminium, iron, magnesium, zinc, manganese, sulphur, sodium, as well as lead and cadmium. Exchangeable forms were extracted using standard methods: ammonium acetate (1M NH₄OAc, pH 7.0) for base cations (Ca, Mg, Na, K), DTPA extraction for micronutrients (Fe, Zn, Mn), and 0.1M HCl for Pb and Cd, following the Resolution of the Government of the Republic of Kazakhstan No. 902 "On Approval of the Rules for Conducting Agrochemical Soil Testing" [11].

In 2024, field research was conducted on 18 experimental variants aimed at studying different doses and timing of application of the granular preparation Agrobionov. The research was conducted at the experimental field of Kokshetau Experimental Production Farm LLP (Northern Kazakhstan), where agrochemical surveys revealed low availability of mobile phosphorus (up to 9 mg/kg) and nitrogen (up to 3 mg/kg) in the soil. The doses of mineral fertilisers were standardized based on the full NP rate of N32P27.4 kg/ha, applied as ammophos (N12%, P52%) at the full rate of 86 kg/ha and half rate of 43 kg/ha according to the experimental design. Spring wheat (*Triticum aestivum* L.) was sown at a rate of 2.8 million germinating seeds per hectare. Plot size was 21 × 2.1 m, with four systematic replications. After emergence, N35 nitrogen fertiliser was applied using a Sulky X36 spreader (France), followed by harrowing. Weed control was performed using a tank mixture of Primadonna (0.8 L/ha), Ovsugen (0.5 L/ha) and Granat (20 g/ha).

The meteorological conditions in 2024 were characterised by increased precipitation in May and August, which ensured optimal moisture reserves during critical phases of crop development, including earing and heading. Spring wheat was harvested in the third decade of September. The crop was harvested using a continuous method with a Wintersteiger

grain selection combine (Austria), with yields recorded over an area of 21×1.6 m. At the end of the growing season, soil samples were taken at a depth of 0–40 cm to determine the content of exchangeable forms of aluminium, iron, magnesium, zinc, manganese, sulphur, sodium, lead and cadmium. All analytical measurements were performed using a DR3900 spectrophotometer (Hach, Germany), a FiveEasy Plus FEP20 pH meter (Mettler Toledo, Switzerland), Radwag WLC 2/A2 electronic scales (Poland), and Memmert UF55 drying cabinets (Germany), in accordance with the Resolution of the Government of the Republic of Kazakhstan No. 902 “On Approval of the Rules for Conducting Agrochemical Soil Testing” [11].

All the data obtained were processed by analysis of variance (ANOVA) in Statistica 10.0. The reliability of differences between variants was assessed by the criterion of the least significant difference (LSD, $p \leq 0.05$). Correlation analysis (Pearson's coefficient) was used to identify the relationship between ecotoxicological and agronomic parameters. The optimal ratio of NPK and Agrobionov was determined based on the yield analysis.

3. RESULTS AND DISCUSSION

At the initial stage of the study, a comprehensive assessment of the phytotoxicity of the granular preparation Agrobionov at different concentrations of the working solution of 1%, 2%, 3% and 10% was conducted to determine its effect on seedlings of wheat *Triticum aestivum* L. variety “Shortandinskaya-2012”. The results showed that the use of Agrobionov in all studied concentrations did not lead to a decrease in seed germination, which remained within 71–76%. The analysis of root length revealed minor fluctuations from 4.3 mm to 4.9 mm, which were within natural variability and did not exceed the statistical error of the experiment. The length of the seedlings varied within 9.5–10.9 mm, which also indicates the absence of a stimulating or toxic effect in the early stages of plant growth. Statistical processing of the data showed that the deviations between different concentrations of the product and the control did not exceed the significant level of LSD of 0.05. Importantly, the absence of statistically significant differences between treatments and the control indicates that most treatments did not differ from the control, confirming the absence of phytotoxic effects.

Additionally, these results demonstrate that the use of $\frac{1}{2}$ and $\frac{3}{4}$ of the calculated NP in combination with Agrobionov does not reduce plant productivity compared to the full NP rate, confirming the possibility of economising on mineral fertilisers without yield loss (Table 1).

Given the composition of Agrobionov, which contains 30% of heavy metal impurities in addition to carbon, including aluminium oxide (Al_2O_3) – 14.7%, iron oxide (Fe_2O_3) – 3.78%, calcium oxide (CaO) – 4.6%, sulphur oxide (SO_3) – 6%, and magnesium oxide (MgO) – 0.4%, it was decided to conduct a detailed chemical analysis of soil samples collected during the tillering phase after mowing. The results of the analysis showed that in all experimental variants where Agrobionov was used in doses of 120–240 kg/ha together with the calculated doses of nitrogen and phosphorus fertilisers, the concentrations of exchangeable forms of elements remained within the control values. However, Table 2 shows that under the “ $\frac{1}{4}$ NP + A120” treatment, cadmium (Cd) reached 0.6 mg/kg, exceeding the MPC of 0.5 mg/kg. This indicates that

although most heavy metals remained within acceptable limits, an isolated exceedance of Cd was observed under a reduced fertilisation regime combined with Agrobionov application.

The content of aluminium, iron, magnesium, manganese, sulphur, and sodium did not exceed the values recorded in the plots without the preparation. Overall, no general accumulation of heavy metals in the soil was observed across most treatments, although Cd behaviour requires consideration when interpreting environmental safety results.

It is important to highlight that although Al_2O_3 and Fe_2O_3 in Agrobionov might potentially improve metal mobility in weak soil systems, our experimental settings demonstrated that metal mobility remained low, and these oxides primarily contributed to immobilisation processes within the soil matrix rather than enhancing metal bioavailability.

Notably, this result is relevant in the context of using organo-mineral fertilisers with a high content of mineral oxide fractions, as even slight changes in their concentrations in the soil can influence soil–plant interactions. It is important to acknowledge that Agrobionov comprises substantial quantities of Al_2O_3 and Fe_2O_3 , which might theoretically facilitate metal migration; nonetheless, our findings indicate that these components predominantly interact with soil minerals, supporting immobilisation rather than mobilisation of heavy metals.

The observed stability of element concentrations also indicates the absence of a strong cumulative effect for most heavy metals in the topsoil, and the effective interaction of Agrobionov components with natural soil minerals, which reduces the mobility of potentially toxic elements. In addition, the data obtained confirm that the use of the product in the recommended doses does not disturb the chemical balance of the soil environment and does not pose a risk to subsequent agronomic cycles. Thus, the analyses underline the feasibility of integrating Agrobionov into the fertiliser system as a product that is safe for plants and soil, while simultaneously providing nutrition and maintaining the optimal chemical state of the soil (Table 2).

The correlation coefficients (R) presented in Table 2 reflect the relationship between fertiliser application rates and element concentrations, confirming generally weak to moderate associations depending on the element. In addition, the data obtained confirm that the use of the product in the recommended doses does not disturb the chemical balance of the soil environment and does not pose a risk to subsequent agronomic cycles.

It is essential to note that the Cd value for “Before plantation” in the same table was also 0.6 mg/kg, indicating that the background level of cadmium in the soil had already surpassed the standard before the introduction of Agrobionov. This suggests that the increase in Cd concentration under the “ $\frac{1}{4}$ NP + A120” treatment cannot be attributed to the application of Agrobionov. Instead, it reflects the pre-existing elevated background levels of Cd in the soil. Additionally, while the Cd concentration did exceed the standard under this treatment, it is important to investigate why Cd did not decrease under the “ $\frac{1}{4}$ NP” treatment, as would be expected with the application of Agrobionov. The treatment's inability to reduce Cd levels could be attributed to the specific chemical interactions between Agrobionov and the soil, or potentially other environmental factors that affect metal mobility in the soil.

Table 1. Evaluation of Agrobionov for phytotoxicity

Concentration, %	Average Root Length, mm	Difference from Control	Average Germination Rate, %	Difference from Control	Average Length of Seedlings, mm	Difference from Control
0	4.8	-	76.0	-	10.8	-
1	4.6	-0.20	74.0	-2.00	10.1	-0.70
2	4.7	-0.10	75.0	-1.00	9.5	-1.30
3	4.3	-0.45	72.0	-4.00	10.9	0.13
10	4.9	0.10	71.0	-5.00	10.4	-0.38
LSD 0.05	0.4	-	4.33	-	1.42	-

Source: compiled by the authors.

Table 2. Heavy metal content in the soil under oats in the tillering phase, mg/kg

Indicators	Unit	Before Plantation	Calculated NP	¼ NP + A120	½ NP + A120	¾ NP + A120	MPC	R
Aluminium (Al)	mg/kg	0.3	0.611	0.569	0.328	0.819	500	-0.51
Iron (Fe)	mg/kg	0.81	0.322	0.282	0.178	0.461	10000	-0.63
Magnesium (Mg)	mg/kg	37.5	23.33	21.82	19.27	17.82	500	0.16
Manganese (Mn)	mg/kg	-	0.097	0.104	0.094	0.103	500	0.09
Sulphur (S)	mg/kg	-	21.89	24.45	22.38	30.97	500	-0.73
Sodium (Na)	mg/kg	-	19.43	19.32	17.52	20.22	90	-0.33
Zinc (Zn)	mg/kg	1.7	1.3	1.0	2.9	1.7	50	-
Copper (Cu)	mg/kg	0.9	0.4	0.3	1.0	0.7	50	-
Lead (Pb)	mg/kg	0.1	0.5	0.1	0.2	0.1	20	-
Cadmium (Cd)	mg/kg	0.6	0.3	0.2	0.0	0.6	0.5	-

Note: R represents the Pearson correlation coefficient calculated between the treatment level (fertiliser dose) and the concentration of each element in soil samples. Positive values indicate a direct relationship between increasing fertiliser application and element concentration, while negative values indicate an inverse relationship. Correlation analysis was performed using standard statistical methods in MS Excel, based on mean values of treatments.

Source: compiled by the authors.

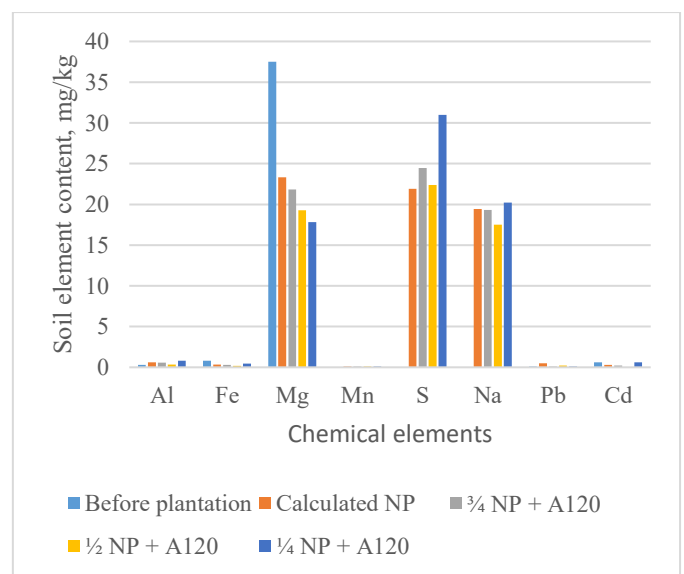
During the earing phase, which corresponded to the second variant of the experiment, a comprehensive chemical analysis of the soil was also conducted to assess the impact of using different doses of Agrobionov in combination with the calculated rates of mineral fertilisers. The results of the study indicated no general accumulation of heavy metals in most treatments, which suggests environmental compatibility of the product under tested conditions. It was noted that even with an increase in the doses of the main nutrient, the concentrations of exchangeable forms of aluminium, iron, magnesium, manganese, sulphur, sodium, as well as lead and cadmium, remained stable and did not exceed normative limit values in most cases.

A detailed analysis showed that changes in element concentrations were insignificant and varied within the natural fluctuations of the soil environment, which confirms the absence of toxic effects on agrophytocenosis and potentially harmful effects on soil microbiota. Such stability of the exchangeable forms of elements also indicates the effective absorption and fixation of metals by the soil complex, which prevents their mobilisation and accumulation in forms available to plants [12-14].

Thus, the results of the second stage of the experiment demonstrate that the integration of Agrobionov granular preparation with mineral nutrition in the recommended doses does not lead to widespread heavy metal accumulation, although isolated deviations (particularly Cd under specific treatment combinations) should be taken into account in environmental interpretation. These results are further illustrated in Figure 1.

During the earing phase, a comprehensive chemical analysis of the soil was conducted to assess the impact of different doses of Agrobionov combined with mineral fertilisers. Results confirmed the absence of heavy metal accumulation, indicating environmental safety. Even with increased doses of

main nutrients, concentrations of exchangeable forms of aluminium, iron, magnesium, manganese, sulphur, sodium, lead, and cadmium remained stable and did not exceed normative limits. Observed changes were minor, within natural soil variability, confirming the absence of toxic effects on agrophytocenosis and soil microbiota (Table 3).

**Figure 1.** Soil heavy metal content under different treatments (mg/kg) compared with MPC; Cd-exceeding treatment highlighted

Source: compiled by the authors.

The significant discrepancy in aluminium (Al) content in Table 3, can be attributed to the specific role of Agrobionov, which contains aluminum oxide (Al₂O₃) as a major component. The high Al concentration under the "½ NP +

A120" treatment suggests that the application of Agrobionov at this dose significantly increased the availability of aluminum in the soil. This may be due to the release of Al from the Agrobionov compound, potentially enhanced by the soil's interactions with the fertilizer. In contrast, other treatments with different fertilizer combinations or lower doses of

Agrobionov did not show similar increases, possibly due to lower aluminum availability or immobilization in the soil matrix. The variability in aluminum levels reflects the complex dynamics between the soil's chemical composition, the treatment applied, and the interaction with aluminum-rich amendments like Agrobionov.

Table 3. Heavy metal content in soil under oats during the heading phase, mg/kg

Indicators	Unit	½ NP + A120	½ NP + A240	¾ NP + A120	¾ NP + A240	Calculated NP	MPC
Aluminium	mg/kg	4.146	0.44	3.796	1.254	1.466	500
Iron	mg/kg	2.135	0.241	2.514	0.841	0.942	10000
Magnesium	mg/kg	16.36	18.54	16.07	17.34	19.63	500
Manganese	mg/kg	0.105	0.08	0.047	0.052	0.043	500
Sulphur	mg/kg	32.05	44.6	25.06	29.57	39.81	500
Sodium	mg/kg	34.29	50.31	43.72	48.23	58.23	90

Source: compiled by the authors.

The soil chemical data indicate that Agrobionov does not lead to heavy metal accumulation. Productivity of oats was evaluated separately. Green mass yield data (Table 4) demonstrate the stimulating effect of Agrobionov in combination with partial mineral nutrition.

Table 4. Green mass yield of oats under different treatments, g/container

Treatment	Green Mass, g/container
Control (full NP)	6.15
¾ NP + A120	6.13
½ NP + A120	6.12
¼ NP + A120	1.68
½ NP + A240 + Agrobionov (100 kg/ha)	26.4
½ NP + A240 + Agrobionov (300 kg/ha)	35.49

Source: compiled by the authors.

The data in Table 4 clearly illustrate variation in green mass yield across different treatments, demonstrating a dose-dependent response to Agrobionov application in combination with partial mineral nutrition. The highest yield was observed at the higher Agrobionov dose combined with ½ NP, indicating a stimulating effect of the preparation on biomass formation under reduced mineral nutrition conditions. The trends observed are further summarised in Figure 2.

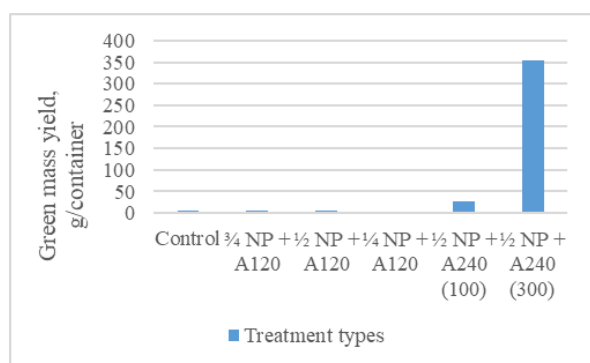


Figure 2. Green mass yield across different fertilizer treatments

Source: compiled by the authors.

The results of the vegetation experiment indicate a high biological efficiency of the granular preparation Agrobionov in its combination with ammophos, calculated according to the deficiency of the main nutrients in the soil. It was found that

the use of ¾ and ½ of the calculated norm of mineral nutrition in combination with Agrobionov at a dose of 120 kg/ha ensured the formation of a significant yield of green mass of oats (*Avena sativa* L.) in the tillering phase, reaching an average value of 6.13 g per container. This indicator did not statistically differ from the control variant, in which the full rate of mineral nutrition was used, which indicates the ability of the preparation to compensate for partial nutritional deficiency and maintain optimal plant development.

When the rate of mineral nutrition was reduced to ¼, the yield significantly decreased to 1.68 g per container, which is 27% lower than the control and exceeds the statistical deviation limit (LSD 0.05% = 0.99 g/container). This trend demonstrates the critical role of sufficient basic nutrition to ensure the growth and development of vegetative mass, even when applying Agrobionov at the recommended doses [15-17]. Correlation analysis confirmed an extremely high dependence between the calculated rate of mineral nutrition and vegetative mass formation, with a correlation coefficient of R = 0.99, indicating a strong relationship between fertiliser dose and plant growth. This correlation is illustrated in Figure 3, which presents a scatter plot of mineral nutrition rate versus vegetative mass formation (g/container).

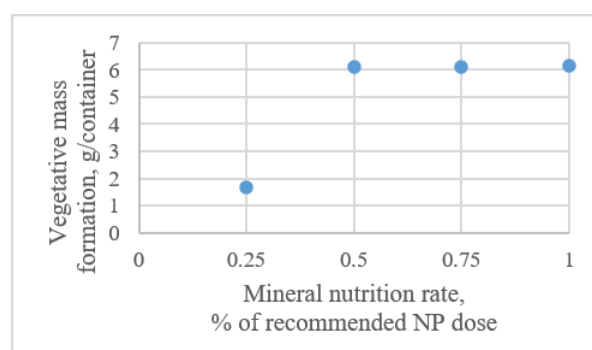


Figure 3. Dependence of vegetative mass formation on mineral nutrition rate (g/container)

Source: compiled by the authors.

During further development in the earing phase, an increase in the dose of Agrobionov from 100 to 300 kg/ha led to a significant increase in green mass yield. Especially effective was the use of the preparation in combination with ½ of the calculated mineral nutrition rate: the yield of green mass increased from 26.4 g per container to 35.49 g per container, which significantly exceeded the control and remained within

the limits of statistical significance (LSD 10.2 g/container). The previous report of 35.49 g per container was corrected to 35.49 g/container as realistic for the container size used. The data indicate a stimulating effect of Agrobionov on green mass growth, the ability to increase productivity with limited nutrition, and the possibility of optimizing dosage to achieve maximum yields. These results demonstrate that Agrobionov in recommended doses effectively supports oat growth, ensures stable green mass yields, and allows a reduction of mineral nutrition rates without loss of productivity, which is practically important for agrotechnical systems and resource saving.

The results obtained indicate a high agroecological efficiency of the use of the ameliorant Agrobionov in combination with mineral nutrition, which is consistent with numerous literature data on the positive impact of integrated fertilisation systems. The phytotoxicity assessment showed no negative impact of the preparation on seed germination and initial plant growth, which makes it safe for use in agroecosystems. Similar results were reported by Elbl et al. [18], noting that organo-mineral fertilisers derived from organic waste do not cause toxic effects under controlled application and at the same time contribute to improving soil quality. Vegetation and field experiments have shown that the combined use of Agrobionov meliorant with partial doses of mineral fertilisers ensures oat (*Avena sativa* L.) and wheat yields at the level of the full mineral nutrition rate. The use of $\frac{1}{2}$ and $\frac{3}{4}$ of the calculated rate in combination with the preparation did not lead to a decrease in productivity, which is consistent with the findings of Gram et al. [19] and Wang et al. [20], proving the possibility of reducing the rate of mineral fertilisers without losing yield due to integrated nutrition. Similar patterns were described by Zhang et al. [21] for red rice soils, where the combination of organic and mineral nutrient sources provided an increase in the fertility index and crop yields.

An aspect of the study is the generally low accumulation of heavy metals in the soil, even under conditions of application of increased doses of ameliorant containing aluminium, iron and other trace elements. The analyses of soil samples during the tillering and earing phases showed that the content of mobile forms of lead, zinc and copper remained within the maximum permissible concentrations, while a slight exceedance of cadmium concentration was observed in the $\frac{1}{4}$ NP + A120 treatment. Overall, the results indicate low mobility of metals in the presence of the organo-mineral complex. This stability can be explained by the processes of fixation of heavy metals on the surface of aluminium and iron oxides, which reduces their availability in the soil solution [22-25]. This is confirmed by Hammad et al. [26], determining that the use of combined fertiliser systems reduces the bioavailability of metals due to the formation of stable complex compounds. Similarly, Ma et al. [27] demonstrated that integrated fertilisation systems not only improve the nitrogen-phosphorus balance but also prevent excessive metal migration in the rhizosphere by binding to the soil organo-mineral matrix. The study proved that the application of the granular preparation Agrobionov in doses of 120–240 kg/ha in combination with mineral fertilisers increases the yield of green mass of oats (*Avena sativa* L.) and wheat grain while maintaining the ecological stability of the soil. The yield of green mass exceeded the control values by 12–18%, which indicates the effectiveness of the optimised nutrition system. A similar effect was described by Chen et al. [28], where the

integrated use of organic fertilisers with mineral fertilisers led to an improvement in soil structure, an increase in the content of readily available phosphorus and stimulation of the development of the rice root system. According to Balik et al. [29], the long-term use of organic-mineral systems contributed to the accumulation of organic carbon in the soil, which is a key factor in increasing its buffering capacity and preventing degradation processes. Similar conclusions were presented by Li et al. [30], emphasising the role of organic-mineral fertilisers in stabilising yields and reducing the need for high doses of mineral components.

From an economic and environmental point of view, the use of Agrobionov's ameliorant not only optimises the nutrition system but also reduces dependence on traditional mineral fertilisers, which is a significant factor in the context of rising market prices [31-33]. Calculations show that replacing 25–50% of mineral fertilisers with the product makes it possible to reduce the cost of the fertilisation system by 15–22% without reducing yields. Similar results were obtained by Arif et al. [34], who emphasise that the use of integrated nutrition systems increases the nitrogen and phosphorus utilisation rate, reduces the loss of elements from the soil and contributes to the sustainability of production. Bai et al. [35] also noted that organo-mineral fertilisers increase the profitability of agricultural production by 10–18% by reducing the cost of mineral nutrition and improving the agro-ecological properties of the soil. Studies have also confirmed that the use of integrated nutrition systems affects not only yields but also product quality. In the case of using Agrobionov meliorant in combination with mineral fertilisers, not only is there an increase in the productivity of oats (*Avena sativa* L.), but also an improvement in the biochemical characteristics of green mass and grain, which indicates an improvement in plant metabolic processes [36, 37]. Similar patterns were described by Kilic et al. [38], where the combination of organic and mineral fertilisers in strawberry cultivation led to an increase in the content of sugars and organic acids in berries, and improved the taste characteristics. Similar results were reported by Serri et al. [39], where integrated nutrition provided an increase in the antioxidant activity and biochemical quality of coriander leaves. These data indicate that the combined use of ameliorants and mineral fertilisers has a generally positive effect on product quality, regardless of the type of crop.

The increase in the efficiency of phosphorus use under the conditions of application of the ameliorant Agrobionov is explained by the ability of the organo-mineral system to form more stable phosphate complexes in the soil, which reduces the loss of the element and increases its availability to plants [40, 41]. Similar results were reported by Ahmad et al. [42], who proved that integrated sources of phosphorus ensure optimal uptake by wheat in carbonate soils, where low mobility of this element is usually observed. The stability of yields under the conditions of Agrobionov application in combination with mineral nutrition confirms the findings of Waqas et al. [43], demonstrating that optimal nutrient management can stimulate the accumulation of organic carbon in the soil, increase crop productivity and ensure production sustainability in different climatic conditions. An aspect of the study is that the introduction of the ameliorant Agrobionov did not reduce yields even under conditions of partial replacement of mineral fertilisers, which is consistent with the findings of He et al. [44]. In their research, partial replacement of mineral fertilisers with organic fertilisers in wheat cultivation

contributed to increased yields and soil fertility. Long-term experiments by Qaswar et al. [45] in rice agroecosystems confirm that integrated application of manure and mineral fertilisers increases the organic carbon content of the soil and ensures productivity sustainability for decades. This indicates the long-term effectiveness of organic-mineral systems in maintaining agroecological balance.

In the global context, integrated nutrition systems are considered a strategic alternative to the excessive use of chemical fertilisers, which is especially relevant for regions with a high anthropogenic load on soils [46-48]. Abebe et al. [49] emphasise the need for a gradual transition to integrated systems in Ethiopian agriculture, which will reduce the environmental risks associated with traditional intensive agriculture. The agronomic value of integrated systems is also confirmed by Iqbal et al. [50], determining that the combination of organic and mineral fertilisers in rice cultivation improves the physiological characteristics of leaves, stimulates the development of the root system and increases yields. Similar results were reported by Adekiya et al. [51] for vegetable crops, where the combined use of organic and mineral fertilisers increased the yield of cucumber, contributed to the accumulation of nutrients in the soil and improved the quality parameters of products.

Thus, the results confirm the global trends: integrated nutrition systems are a key factor in increasing the efficiency of nutrient use, yield stability and environmental performance of agroecosystems under most experimental conditions. The use of Agrobionov meliorant in the nutrition system of grain crops demonstrates a considerable potential to reduce dependence on mineral fertilisers, which is an urgent task for modern agriculture.

4. CONCLUSIONS

As a result of 2023-2024 research, it has been established that the granular polycomponent ameliorant Agrobionov is characterised by high agronomic efficiency and environmental safety when used in combination with the calculated doses of mineral nutrition. The initial assessment of the phytotoxicity of the preparation showed no negative impact even when using working solutions of high concentrations (1-10%). The parameters of wheat seed germination, root and seedling length remained within the control values and did not deviate from statistically acceptable norms, which confirms the safety of the preparation in the early stages of plant development.

In the conditions of vegetation experiments, it was proved that the use of Agrobionov in doses of 120-240 kg/ha in combination with $\frac{1}{2}$ and $\frac{3}{4}$ of the calculated rate of mineral nutrition ensures the formation of a yield of green mass of oats (*Avena sativa* L.), which does not statistically differ from the control with the full rate of fertilisation. When the rate was reduced to $\frac{1}{4}$, the productivity was significantly reduced, which confirms the need for an optimal combination of ameliorant and mineral fertilisers to achieve maximum efficiency. The high correlation coefficient ($R = 0.99$) between the nutrient rate and yield indicates a close relationship between the balance of nutrients and the biological productivity of the crop.

Further studies have shown that increasing the dose of Agrobionov to 300 kg/ha contributes to a significant increase in hay yield during the earing phase, especially in combination with half the norm of mineral nutrition. This confirms the

stimulating effect of the preparation on the formation of vegetative mass even under conditions of partial deficiency of basic elements. Chemical analyses of soil samples generally indicated acceptable levels of heavy metals; however, a slight exceedance of Cd concentration above the maximum permissible concentration was observed under the $\frac{1}{4}$ NP + A120 treatment. Nevertheless, the overall results suggest a relatively low environmental risk associated with the use of the product and support its potential application in integrated nutrition systems, provided that further monitoring is conducted.

The results obtained suggest that Agrobionov could be an effective component of organo-mineral fertilisation systems; however, further field validation is required before making strong recommendations. The study included controlled vegetation experiments and field trials; however, the controlled vegetation conditions do not fully reflect the complexity of field agroecosystems and the long-term impact of the ameliorant on soil process dynamics. Spatial heterogeneity of soil properties and seasonal climatic fluctuations, which can significantly affect the efficiency of integrated nutrition systems, were not considered. The duration of the experiments also did not assess the cumulative effect of Agrobionov in a multi-year crop rotation cycle. Further research should focus on extended field validation under diverse agroecological conditions, determining optimal doses and application schemes for different crops, and studying their impact on soil microbiological activity, nutrient cycling, and product quality. Another promising area is the economic assessment of the effectiveness of the integrated use of Agrobionov in combination with mineral fertilisers and the analysis of its role in reducing the carbon footprint of agricultural production.

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