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A biological additive in granulated mineral compound fertilizer improves productivity of spring wheat and sugar beet

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The use of biological additives often enhances plant fertilization efficiency and reduces the environmental impact of fertilizers; however, their effectiveness varies depending on the context. It is particularly important that such additives are compatible with mineral fertilizers and remain viable and effective during industrial production. The aim of this study was to develop bulk NPK compound fertilizers supplemented with the biological additive Fosfix, a commercial product from the Lithuanian company Bioenergy LT. This product contains bacteria that help absorb phosphorus from insoluble soil compounds. The study also aimed to evaluate their agronomic effectiveness under field conditions. The fertilizer formulations incorporating the biological additive were developed at Kaunas University of Technology, with the goal of adapting the additive for industrial fertilizer production. Laboratory tests demonstrated that optimal fertilizer characteristics – commercial fraction content of 64–78%, granule strength of 28–41 N per granule, and moisture content of 15–16.5% – were achieved using a raw material mixture containing up to 60% recycled product. These laboratory conditions were successfully applied at pilot scale in industry, and a pilot batch of the developed product was produced in a fertilizer manufacturing company. Agrochemical tests were conducted at the Rumokai Experimental Station, a branch of the Lithuanian Agricultural and Forestry Research Centre. Field tests showed that the biological additive improved the performance of sugar beet (*Beta vulgaris* L.) variety Severa KWS compared to spring wheat (*Triticum aestivum* L.) variety Triso: initial germination increased by 6%, root yield by 5.78 t·ha1, and basic sugar yield by 5.16 t·ha^{-1}. In conclusion, the newly developed fertilizer formulations promote plant physiological processes, support the expression of genetic potential, and ensure minimal nutrient loss.

KEYWORDS

bio-fertilizers, microorganisms, granulation technology, soil, agricultural efficiency, *Bacillus* sp.

1 Introduction

Considering current global challenges such as the growing world population, rising food demand, intensive agriculture, and climate change (Loiko and Islam, 2024), one of the most critical objectives in crop production is to achieve high yields of high-quality, environmentally friendly produce while optimizing input costs. Numerous long-term scientific studies indicate that approximately 30–35% of crop yield increases can be attributed to fertilizer effectiveness. However, fertilizer efficiency is affected by multiple factors, including physical and chemical properties of soil, fertilization levels, nutrient ratios, timing and method of application, and precision of application (Zaib et al., 2023). A global meta-analysis covering nearly 2,500 observations found that fertilizer application increased crop yields by an average of 30.9%, with variations depending on fertilizer type and crop species (Ishfaq et al., 2023). Long-term studies also highlight that excessive or imbalanced fertilizer application often leads to diminishing returns and reduced efficiency, emphasizing the importance of balanced nutrient management for maintaining both yield stability and soil health (Yokamo et al., 2023). Therefore, researchers and fertilizer industry specialists are continuously seeking innovative approaches to improve fertilizer efficiency and sustainability. In crop production, it is important not only to prepare the soil and sow crops properly, but also to understand and implement full range of practices necessary for successful cultivation. One of the most important measures is fertilization. Nutrient application must be balanced, as both macronutrients and micronutrients act in combination, not in isolation. If the soil contains a deficiency or excess of one nutrient or microelement, the plant may struggle to absorb others (Fan et al., 2021; Singh et al., 2024).

Proper nutrient uptake by plants is also influenced by the soil itself, which consists of mineral particles, water, air, and organic matter, containing living organisms. Soil is a complex, dynamic, and living system which performs many vital functions. It is a source of biomass and a medium in which plant nutrients accumulate, are filtered, and undergo transformations (Turner, 2021; Cotrufo and Lavallee, 2022). Furthermore, organic matter of the soil is essential for nutrient availability and soil structure enhances fertility and resilience. However, soil quality is under threat from degradation, largely driven by intensive agricultural practices, which progressively undermine its ecological functions (Nikolaidis and Bidoglio, 2013; Singh et al., 2024).

Farmers and scientists have observed that intensive and unbalanced use of fertilizers and plant protection products accelerates soil degradation and reduces fertility, while low biological activity of the soil allows undecomposed plant residues to promote pathogen accumulation. Long-term field trials and meta-analyses indicate that mineral fertilizers, although initially increasing microbial biomass by around 15%, eventually disrupt the soil's biological balance. This leads to dependency on higher fertilizer inputs, declining crop quality, rising costs, and weakened soil ecosystems and microbial functions (Geisseler and Scow, 2014; Šimanský et al., 2022).

European policymakers responsible for agricultural output have recognized the risks associated with unregulated fertilizer use. Under the EU Fertilizer Regulation (EU Regulation, 2019/1009), only products listed in the official European Fertilizer Register may be placed on the market, ensuring compliance with safety and quality standards. In parallel, the evolving Common Agricultural Policy (CAP) increasingly supports soil-conserving practices. Future subsidies are expected to focus on certified eco-schemes and farming systems that prevent soil degradation and promote sustainability (EUR-Lex, 2019; EU CAP Network, 2023; Transport and Environment, 2020). One of the most advanced approaches to enhancing fertilizer efficiency while maintaining sustainability of agroecosystem is microbiology of the soil. Soil's biological activity, characterized by indicators such as microbial biomass carbon content, respiration, and enzyme activity, is a key indicator of soil health (Bhaduri et al., 2022; Mącik et al., 2020). Biofertilizers, i.e., microbial inoculants designed to diversify soil microbiota and activate natural processes, are strongly recommended for restoring degraded soils. These products significantly improve nutrient cycling and soil structure without polluting the environment or negatively impacting plants, animals, or humans (Kumar et al., 2021; Ammar et al., 2023). Biological preparations are regarded as soil improvement materials rather than fertilizers, as they have been created using natural processes that have successfully been going on in nature for millions of years. Environmental stresses caused by climate change and human activity limit plant growth and yields. The results show that the application of microbial fertilizers significantly increases soil's microbial diversity, maintains its microecological balance, and effectively improves its quality (Wei et al., 2024; Yusuf et al., 2025). The Use natural, nontoxic bio-stimulants to strengthen plants' natural defense systems offers a sustainable solution to improve crop performance under unfavorable conditions (Posmyk and Szafrańska, 2016).

The production and use of biological products in agriculture have significantly increased in recent decades, and this trend is expected to continue (Pisante et al., 2012; FAO, 2021; Zapka, 2023; National Research Council, 2002). This growth is largely driven by the need to remain competitive, improve depleted natural soil fertility, meet the demands of increasingly selective consumers, and address challenges related to intensive farming. The use of microbiological products provides opportunities to enhance farm productivity through environmentally friendly and cost-effective approaches. Each type of microorganism (bio-activator) performs a specific function in the soil, for example, by improving nutrient absorption or reducing the required amount of chemical fertilizers. In recent years, the most effective strategies have focused on incorporating biologically active substances into fertilizers, thereby advancing sustainable farming practices (Bargaz et al., 2018; Rashid et al., 2016; Stamenkovic and Beškoski, 2018; Sinkevičienė and Pekarskas, 2019; Díaz-Rodríguez et al., 2025). On the other hand, microorganisms grown under laboratory conditions can be sensitive to temperature fluctuations or competition with native soil microbes, which may limit their effectiveness under real field conditions (Zhao et al., 2024; Gonzalez and Aranda, 2023; Kapinusova et al., 2023).

Farmers and representatives of agribusiness s are encouraged to stay informed about current scientific advances in agriculture, follow expert recommendations, and adopt more sustainable and cost-effective practices. Partnerships between business and science are beneficial for both parties, as well as for nature (Kindangen et al., 2023; European Commission, 2025; SAI Platform, 2015; Masquelier et al., 2025).

Considering these challenges, the aim of this work is to develop a bulk NPK compound fertilizer with the biological additive Fosfix in the laboratory, scale up its production to industrial levels, and test it under field conditions. It is assumed that the use of this fertilizer will improve efficiency ofnutrient use by plantsand minimize the environmental impact of fertilization. The results of this study will contribute to expanding the range of bulk compound fertilizers with bioactivators and support the sustainability of agroecosystems.

2 Materials and methods

2.1 Production of bulk compound NPK fertilizers with Fosfix in the laboratory

Technical salts were used to produce bulk compound NPK fertilizers with micronutrients (5–15–30 + S + Zn for spring wheat and 12–11–22 + Na + S + B for sugar beets): potassium chloride (KCl) with a K_2O concentration of 60.0% (Belaruskalij Belarus); ammonium dihydrogen phosphate ($(NH_4)_2HPO_4$) with P_2O_5 concentration of 46.0% and N content of 18.0% (UAB "Lifosa," Lithuania); ammonium hydrogen phosphate ($NH_4H_2PO_4$) with P_2O_5 concentration of 52.0% and N content of 12.0% (UAB Lifosa, Lithuania); ammonium sulfate ($(NH_4)_2SO_4$) with N concentration of 21.0% and S concentration of 23.0% (Yara, Norway); and zinc sulfate monohydrate ($ZnSO_4{\cdot}H_2O$) with Zn concentration of 35.0% (Haida, China), sodium chloride (NaCl) with Na concentration of 39.3% (Belaruskalij, Belarus), boric acid (H_3BO_3) with B concentration of 17.5% (Eti Maden, Turkey).

The biological preparation Fosfix was used as a bioactive component, with *Bacillus* sp. bacteria as its active ingredient. The main purpose of the preparation is to release phosphorus into the soil and, with the help of bacteria, convert phosphorus compounds which are difficult to absorb into forms available to plants. The preparation is soil-friendly, with a pH of 6.5 (Bioenergy LT, 2018).

Compound NPK + S + Zn fertilizers were granulated in the laboratory using a drum granulator, the geometric parameters of which correspond to the dimensional proportions of granulators of this type used in industry. Granulation was carried out using the wet granulation method. The concentration of macro plant nutrients (N, P_2O_5, and K_2O) and physical properties of the resulting product were examined using standard fertilizer testing methods.

2.2 Properties of bulk compound NPK fertilizers with Fosfix prepared in the laboratory

Total nitrogen (N) concentration in both NPK fertilizers was determined using the Kjeldahl method with a Turbodog mineralizer and an automatic Vapodest 45 s distillation system (Gerhardt).

Sample digestion was performed with 96% sulfuric acid following the DIN EN ISO 9001 standard. The method provides an accuracy of ±0.5%. To determine the content of ammonium nitrogen, results were reported to the nearest 0.1% and expressed as the arithmetic mean of two parallel measurements, provided that the difference between them did not exceed 0.5% at a 95% confidence level. Potassium (K_2O) concentration in NPK fertilizers was analyzed using flame photometry with the PFP-7 device (Jenway). The flame was produced by burning a natural gas–air mixture at temperatures ranging from 1,500 to 2000 °C. Potassium levels were quantified based on a calibration curve prepared from aqueous KCl solutions of known concentrations. Phosphorus (P_2O_5) concentration was determined by the photocolorimetry method, involving the formation of a complex with molybdenum and measurement of UV–VIS absorbance at 440 nm, using a 10.0 mm cuvette. All measurements were carried out with a T70/T70 + spectrophotometer (PG Instruments Limited). The standard error of the absorbance values was ±0.004 Abs.

Granular fertilizers were fractionated using RETSCH woven sieves (DIN-ISO 3310/1), with mesh sizes: 1.0; 2.0; 3.15; 4.0; 5.0 mm, and the fraction amount was determined by weighing with an electronic balance WPS 210/C KERN ABJ (balance accuracy ±0.001 g).

To determine the static strength of granules, tests were performed using a device (IPG–2), with a maximum compressive strength of 200 N/granule (error ±1.6%). The strength was determined by crushing 20 granules and calculating the arithmetic mean, relative, standard and absolute errors according to the interval estimate.

The moisture content was determined using the electronic moisture analyzer HG53, which operates on the thermogravimetric principle, i.e., calculates weight loss upon heating the sample to constant mass.

The bulk density of fertilizer granules was determined using a graduated 100 cm^3 cylinder, which was filled with granules and by weighing with the electronic balance WPS 210/C KERN ABJ (balance accuracy ±0.001 g).

The hygroscopicity of NPK granular fertilizers was evaluated under controlled moisture conditions. Samples were stored in a desiccator for 9 days under two different environments: at 55–60% relative humidity maintained by saturated sodium nitrite ($NaNO_2$) and at 100% relative humidity maintained by distilled water, both at 20–25 °C.

To assess the viability of *Bacillus* sp. bacteria, a 2 g sample of fertilizer was dissolved in 100 mL of 0.9% NaCl solution. Then, 0.1 mL of this solution was inoculated onto a Petri dish and incubated at 28 °C for 24 h. During this period, bacterial growth occurred, and the number of viable colonies was subsequently counted (Mažylytė et al., 2022; ASTM International, 2020).

2.3 Field experiments of compound NPK fertilizer with Fosfix

A two-year field experiment (2022–2023) was conducted on deep gleyic, carbonate-leached soil. The agrochemical properties of the soil were as follows: pH_{KCl} – 6.4, organic carbon – 0.76%, P_2O_5–156 mg/kg, K_2O – 182 mg·kg^{-1}. The spring wheat (*Triticum aestivum* L.) of Triso variety and the sugar beet (*Beta vulgaris* L.) of Severa KWS variety were grown at the Rumokai Experimental Station, which is part of the Lithuanian Research Center for Agriculture and Forestry (LAMMC). The station is located in Klausučiai village, Vilkaviškis district, in the southwestern part of Lithuania (54.6211° N, 22.8470° E), near the town of Kybartai and close to the border with Poland. It plays an important role in agricultural research and technology development and is one of the key national facilities for long-term agronomic research and crop trials.

The spring wheat variety Triso was developed in Germany by the DSV seed company, and was registered in Lithuania in 2005. The grain is of a food type, medium-early, the plants of medium height, and resistant to lodging. The wheat grains of this variety mature in an average of 93 days. Severa KWS is a diploid, medium-yielding. This diploid sugar beet variety was developed in Germany by the KWS SAAT AG seed company. According to the breeder, sugar beets of this variety are resistant to rhizomania (a necrotic vein yellowing virus).

The indicators characterizing the quality of the spring cereal and sugar beet harvests were determined according to the standard methodologies used by LAMMC, which are based on Commission Regulation (EU) No 742/2010 and the guidelines of the International Commission for Uniform Methods of Sugar Analysis (ICUMSA).

2.4 Statistical analysis of results

All data are reported as means with measures of dispersion. For physical properties of the granular product (static strength, moisture, bulk density), results are presented as the mean with the 95%

confidence interval (CI). Agronomic and quality traits for wheat and sugar beet are presented as mean ± standard deviation (SD); standard error (SE) is additionally reported in tables to indicate the precision of the mean.

Because only two fertilizer treatments were compared (NPK vs. NPK + F), between-group differences were evaluated using two-sample (independent) *t*-tests, with $\alpha = 0.05$ taken as the threshold for statistical significance. Where relevant, non-overlapping 95% CI was also interpreted as supportive evidence of a meaningful difference. Sample size for field traits was $n = 30$ per treatment unless stated otherwise.

3 Results and discussion

3.1 Different methods of incorporating bacterial preparations into granular NPK fertilizers

For this study, a widely used and commercially available compound NPK 5–15–30 + S + Zn fertilizers were selected, with the expectation that, if results were positive, the laboratory findings could be applied to real-world production processes. To assess the feasibility of incorporating a bacterial preparation into the fertilizer and ensuring bacterial viability, experiments with bacterial additives were carried out under laboratory conditions. The experiment was structured into several approaches to determine the most effective method of incorporating the bacterial preparation.

First, an attempt was made to introduce the bacterial preparation into the wax hardener and to assess bacterial viability by simulating the actual conditions of wax preparation and application. The mixture of wax and bacteria was maintained in the laboratory for 12 h at a temperature of 90–100 °C. This method proved ineffective, as the bacteria did not survive exposure to wax at the working temperature.

Further studies were conducted by attempting to spray the bacterial preparation and wax onto granulated product through a single nozzle, with the reagents supplied from separate containers. The wax-to-bacteria ratio and drying temperature were adjusted to simulate real production conditions. However, the number of viable bacteria after application was found to be only 10^3 CFU·g^{-1}, which is significantly lower than the commonly recommended range of 10^6–10^9 CFU·g^{-1} (Dos Reis et al., 2024; Agake et al., 2022; Fusco et al., 2022).

Then another method of introducing the bacterial preparation was chosen – introduction into the raw material mixture and granulation of the entire mixture together. When granulating NPK fertilizers under laboratory conditions, a mixture of 100 g of dry raw materials, calculated according to the material balance (KCl, $(NH_4)_2HPO_4$, $NH_4H_2PO_4$, $(NH_4)_2SO_4$, $ZnSO_4{\cdot}H_2O$), and the bacterial preparation Fosfix (rate 1.5 L·t^{-1}) was prepared, which was moistened with water (8 cm^3/100 g H_2O or 7.4%) and granulated (each experiment was performed in triplicate) using a laboratory drum granulator. Before that, the raw materials, which are in the form of granules (ammonium dihydrogen phosphate and ammonium hydrogen phosphate), were ground. In NPK fertilizers with the Fosfix additive produced in this way and thermostated at 80 °C for 24 h, the viability of *Bacillus* sp. bacteria was tested, The results showed that the bacteria remained viable under the tested conditions with the quantity of $4.5{\cdot}10^7$ CFU·g^{-1} (Figure 1a).

Having evaluated the results obtained on the viability of *Bacillus* sp. bacteria when added to the fertilizer raw material mixture before granulation together with the water used for irrigation, this wet granulation method was chosen for further studies.

3.2 Wet granulation and characterization of NPK 5–15–30 + S + Zn + Fosfix fertilizers

Since the granulated fertilizer samples from the bacterial viability study lacked high quality from a granulometric point of view, in order to improve the granulometric composition (which largely depends on the moisture of the raw materials), granulation was carried out using different amounts of water, constantly increased from 7.4 to 18%. To ensure the reliability of the results, mixtures with each different moisture content were granulated 3 times and the standard deviation of the results obtained was estimated. The granulated samples were dried under static conditions in an oven for 8 h at a temperature of 80 °C and classified according to the size of the granules. The commercial fraction of fertilizers, typically consisting of granules size from 2 to 5 mm, was separated. This size range is widely adopted in industrial practice and supported by existing European standards for physical characteristics (EN 1235 for sieve analysis) and optimal application (e.g., for modern spreading equipment). Afterwards, the most important properties of the bulk fertilizers' commercial fraction were examined, including granule strength, moisture, bulk density,

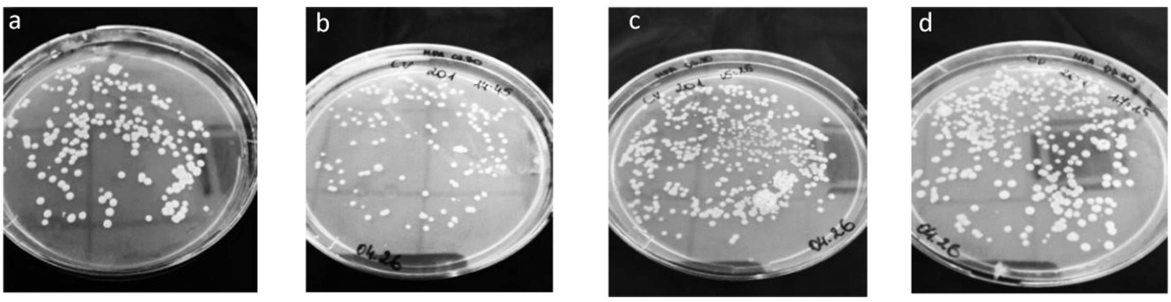

FIGURE 1
Bacillus sp. in NPK fertilizer 5–15–30 + S + Zn + Fosfix: **(a)** after 24 h of incubation at 80 °C (laboratory-manufactured fertilizer), **(b)** after the granulator, **(c)** after the dryer, **(d)** after the coating drum.

and hygroscopicity. Granuleswhich did not fall within the mentioned (2–5 mm) range, had to be returned to the granulation process at the raw material mixing stage as recycle.

The properties of the granulated product are determined by many factors (such as the type of raw materials, their ratio, moisture content, amount of recycle, granulation conditions, etc.), but these factors cannot all be changed simultaneously. Therefore, to obtain a better-quality product, the initial tests were carried out without using a recycle and with varying moisture contents in the raw material mixtures. The selection of optimal moisture content is best indicated by the proportion of the commercial fraction in the granulated product, which is calculated as a percentage after determining the granulometric composition of the entire sample. The data from the laboratory samples produced without recycle are presented in Table 1.

This table presents the data by which the physical properties (static strength, moisture, bulk density) of granular NPK 5–15–30 + S + Zn + Fosfix fertilizers were determined. The figures represent the average of the measured values and the 95% confidence interval (CI) with a probability of 95%. The results of granulometric composition show that in samples 1–4, most granules (63.6–87.42%) were smaller than 2 mm, indicating that the selected moisture content of 7.5–13% in the raw material mixture was unsuitable. During granulation, raw material mass was too dry, so few granules of commercial size were produced, mainly resulting in a fine, dry fraction.

In sample 5, where the moisture content was 14.4%, a large amount (47.64%) of fine fraction was also determined. However, the proportion of the commercial fraction was similar (44.78%) suggesting that the moisture content was close to optimal. When the moisture content was too high (samples 7–9), most granules (75.03–97.74%) exceeded 5 mm in diameter. Such oversized granules are hazardous to equipment and pose safety risks to operators. Therefore, selecting the optimal amount of water is very important. Otherwise, the granulation process must be stopped, all oversized agglomerates removed, and the equipment restarted. The highest part of commercial fraction (77.89%) was achieved at 15.5% moisture content (sample 6). Therefore, it can be stated that this amount of moisture was optimal for wetting the raw material mixture.

The discussed results showed sufficient measurement reliability, as narrow confidence intervals (CI) were obtained. Overall, the static strength of the commercial fraction granules in the samples ranged from 24.35 ± 1.08 to 40.30 ± 1.02 N per granule, and the narrow CI indicates that the measurements are quite accurate. The observed differences between the samples are statistically significant. The moisture values were low and stable (1.18 ± 0.08 to 1.31 ± 0.12%), although in relative terms (due to the small absolute values), they had the widest CI and showed the largest relative fluctuation (6–9%). Bulk density was the most constant property, ranging from 745.8 ± 14.5 to 754.9 ± 11.5 kg·m^{-3}, and the narrow CI indicates high reproducibility of the measurements.

When assessing the quality of a granular product, the following properties of commercial granular fertilizers are very important: granule strength, bulk density, and moisture content. Granule strength describes the compressive force that granules can resist and serves to evaluate the potential for disintegration into a fine powder, which can generate handling and application issues (e.g., dust formation, spreader clogging) during transport, storage, and field use (Fulton and Port, 2016). Bulk density indicates the volume occupied by a given mass of granules. Therefore, this value helps estimate transportation costs and provides an indirect indication of the granule's roundness and flowability, as denser and more spherical granules tend to pack and flow better. Higher values (closer to 1 g·cm^{-3}or 1,000 kg·m^{-3}) generally correspond to more uniform, spherical particles and improved mechanical behavior during handling. Additionally, higher density indicates fewer pores, greater uniformity, enhanced pellet strength, and a lower risk of dust formation (Lillerand et al., 2021; Ulusoy, 2023; Zhou et al., 2017).

The data presented in Table 1 show that at the optimal moisture content (15.5%), the highest crushing strength of the granules in the commercial fraction was recorded, reaching 41.41 N per granule. This crushing strength is sufficiently high and is consistent with the findings of other researchersclaiming that fertilizer particle strength is influenced by moisture of granules (Xin et al., 2023; Macák and Krištof, 2016). The numerical values of the bulk density of the granules depend slightly on the moisture content of the granules of the commercial fraction but they differ by no more than 10 kg·m^{-3}. This is expected, as bulk density is primarily influenced by granule shape and the type of raw materials used. The moisture content of the granulated product in all samples remained below 2%, which complies with standard requirements for bulk fertilizers.

TABLE 1 Parameters of NPK 5–15–30 + S + Zn + Fosfix granulated fertilizers (with ±CI data).

Sampl. No.	Humidity of raw materials, %	Granulometric composition, %			Properties of commercial granules (size 2–5 mm)		
		>5 mm	2–5 mm	<2 mm	Static strength, N per granule	Humidity, %	Bulk density, kg·m^{-3}
1	7.5	1.28	11.30	87.42	24.35 ± 1.08	1.18 ± 0.08	745.8 ± 14.5
2	10.5	1.30	11.55	87.15	30.15 ± 1.21	1.18 ± 0.11	746.2 ± 14.0
3	11.0	5.92	20.46	73.62	34.75 ± 1.22	1.29 ± 0.08	745.9 ± 12.4
4	13.0	7.10	29.30	63.60	34.90 ± 1.18	1.28 ± 0.09	748.2 ± 13.8
5	14.4	7.58	44.78	47.64	40.30 ± 1.02	1.25 ± 0.10	751.1 ± 12.6
6	15.5	20.30	77.89	1.81	40.21 ± 1.20	1.30 ± 0.09	754.2 ± 15.0
7	16.1	59.14	39.90	0.96	39.61 ± 1.17	1.31 ± 0.08	753.8 ± 12.3
8	16.4	75.03	24.21	0.76	36.28 ± 1.15	1.31 ± 0.12	754.9 ± 11.5
9	18.0	97.74	2.26	–*	–*	–*	–*

The amount of commercial fraction is insufficient to determine the parameters.

Next, to determine the best granulation conditions, the influence of the recycle fraction on the properties of the granulated product was investigated. Since, under real production conditions, a certain amount of recycle is required to maintain process stability (ensuring a balance between the raw material feed and the recycle flow, while preventing equipment overload), 20, 40, and 60% recycle fractions (consisting of particles smaller than 1 mm) were added to the raw material mixture. The initial moisture content of the raw materials was selected based on previous granulation results, while all other conditions were kept constant. However, like in other studies, using recycle in this study required adjustments to the moisture content to prevent excessive fines or agglomeration (Mefteh et al., 2013; Hidayat et al., 2025). At this stage of the study, the moisture content of the raw material mixtures and the resulting properties of the granulated product are presented in Table 2 as the average of the measured values and the 95% confidence interval (CI) with a probability of 95%.

The data presented in Table 2 show that when using 20, 40, or 60% recycle, a moisture content of 13% in the raw material mixture is insufficient for successful granulation, as a very large amount (55.52–78.59%) of fine fraction is formed. When using 20 and 40% recycle, the best granulometric composition results were obtained with a raw material moisture content of 15.0–16.5%. In such cases, the commercial fraction constituted 54–74% of the total sample mass. When 18% moisture was used for hydration of raw materials with 20% recycle (sample 13), extremely large and round balls formed during granulation; therefore, this moisture level was not used in further studies. A 17% moisture content was also too high, as the amount of commercial fraction decreased significantly in sample 20. When using 60% recycle, the highest amount of commercial fraction (73.92%) was obtained with a 16.5% raw material moisture content.

The data characterizing the commercial fraction properties (Table 2) show that when the commercial fraction yield is highest, high-quality granules are obtained, as their static strength ranges from 26.06 to 37.41 N per granule. The numerical values of bulk density are very similar in all cases but remain relatively low. The moisture content of the final product with the use of return is slightly higher than when granulating without return but does not exceed 2%.

Analyzing statistical reliability of the presented granule properties, it can be stated that the static strength of the commercial fraction increased significantly when the amount of recycle was increased from 20% (28.43 ± 0.62 N per granule) to 40–60% (36.00 ± 2.53 to 39.76 ± 2.34 N per granule). However, no statistically significant difference was observed between the 40 and 60% recycle groups due to overlapping confidence intervals. Moisture content remained stable across all groups, but the highest value (1.54 ± 0.07) was obtained when using 60% recycle, the CI of which almost did not overlap with the lower values of the 20% group, indicating a potentially significant increase in moisture content. Bulk density values (738.4 ± 23.8 to 763.2 ± 12.6 $kg \cdot m^{-3}$) showed substantial overlap in the confidence intervals of the groups, suggesting no statistically significant differences and that the addition of different amounts of recycle (20, 40, or 60%) does not affect the bulk density of the granules.

When summarizing the influence of recycle on the granulated product, it can be stated that adding the recycle had a positive effect on the granulometric composition, but other product properties did not change. It was determined that to obtain the highest yield of the commercial fraction when using recycle (especially at 60%), more moisture had to be added to the raw materials. From a practical perspective, a higher moisture content in the raw materials extends the drying time and complicates operation of the equipment. Therefore, when granulating NPK fertilizers under real production conditions, it is advisable to use less than 60% recycle.

In addition to the previously discussed properties of granular fertilizers, hygroscopicity (the tendency of a substance to absorb moisture from air) is also an important parameter (YARA, 2025; Baird

TABLE 2 Parameters of NPK 5–15–30 + S + Zn + Fosfix granulated fertilizers with the use of recycle (with ±CI data).

Sampl. No.	Moisture of raw materials, %	Granulometric composition, %			Properties of commercial fraction (2–5 mm) granules		
		>5 mm	2–5 mm	<2 mm	Static strength, N per granule	Humidity, %	Bulk density, $kg \cdot m^{-3}$
		20% recycle					
10	13.0	8.17	36.31	55.52	28.43 ± 0.62	1.25 ± 0.08	738.4 ± 23.8
11	15.0	6.83	62.08	31.09	32.59 ± 1.72	1.31 ± 0.14	747.5 ± 13.9
12	16.5	23.4	72.57	4.03	32.70 ± 1.53	1.38 ± 0.10	754.3 ± 13.7
13	18.0	100.00	–	–	–*	–*	–*
		40% recycle					
14	13.0	5.12	17.63	77.25	32.36 ± 2.53	1.22 ± 0.05	746.4 ± 7.32
15	15.0	6.32	65.63	28.05	39.06 ± 1.12	1.35 ± 0.11	752.8 ± 5.38
16	16.5	45.16	53.51	1.33	39.41 ± 1.55	1.39 ± 0.09	760.2 ± 9.71
		60% recycle					
17	13.0	0.79	20.62	78.59	37.14 ± 2.45	1.28 ± 0.09	753.5 ± 19.5
18	15.0	1.22	63.89	34.89	38.16 ± 2.39	1.38 ± 0.04	752.9 ± 17.7
19	16.5	19.70	73.92	6.38	39.76 ± 2.34	1.39 ± 0.08	761.8 ± 12.9
20	17.0	57.04	41.24	1.72	38.19 ± 1.76	1.54 ± 0.07	763.2 ± 12.6

*– The amount of commercial fraction is insufficient to determine the parameters.

et al., 2023). It was evaluated by storing the granules under two controlled humidity conditions: in a desiccator above water (extreme conditions, i.e., 24.8–25.8 °C, equilibrium relative humidity 100%) and above a saturated sodium nitrite solution (favorable conditions, i.e., 24.8–25.8 °C, equilibrium relative humidity 59–62%). The results obtained are presented in Figure 2. They show that in all cases, fertilizers produced with and without recycle are highly hygroscopic when stored above water (Figure 2a).

Under these conditions, the fertilizer mass increased by more than 160% within 9 days and continued to rise, causing the granules to lose their shape as they began to dissolve due to the large amount of absorbed water vapor. This is not as fast a process as in the case of calcium nitrate or ammonium nitrate, which was studied and described by Ch. Sigtryggsson, but it is still very obvious (Sigtryggsson et al., 2020) When stored above a saturated sodium nitrite solution, NPK fertilizers exhibited a mass change of only 7–8% within 9 days, and the granules maintained their shape (Figure 2b).

Thus, under favorable conditions, the granules are less hygroscopic; however, even a 7–8% mass increase from absorbed water vapor can compromise granule quality. These data must be considered. Therefore, during the process of fertilizer production moisture-protection measures (e.g., by applying coating materials such as wax, adding polyhalite or other materials to fertilizer) are recommended to ensure safe storage and transportation (Albadarin et al., 2017; Baird et al., 2023). Additionally, in real conditions, storage conditions must be continuously monitored, as increased relative humidity can cause the fertilizer to absorb excessive moisture and become unsuitable for use (Moore and González-León, 2020). The concentration of the main elements in the granulated NPK fertilizers produced under laboratory conditions was also determined to assess the compliance of the fertilizer composition with the specified formula (5–15–30). The analysis results of all samples varied slightly, and the following average values were obtained: 4.7% N, 14.9% P_2O_5, and 30.1% K_2O, which confirm the composition of the target product.

3.3 Bacterial survival during the industrial production of NPK 5–15–30 + S + Zn + Fosfix fertilizers

The results discussed show that, by using the wet granulation method and adding a bacterial preparation to the raw material mixture, it was possible to granulate NPK fertilizer with viable bacteria that meet the indicators of bulk fertilizers in accordance with EC Regulation 2003/2003 under laboratory conditions. Therefore, after evaluating the available data, trial granulation was carried out under real production conditions at a fertilizer production plant. Figure 3 presents a block diagram of the process line, showing the main equipment and the movement of three types of flows – materials, hot air, and cold air – throughout the entire production cycle. This flow management is essential for both technological efficiency and environmental protection. The technological process of granular fertilizer production integrates the stages of raw material preparation, granulation, drying, sieving, cooling, coating, and air cleaning. The process begins with the supply of raw materials from tanks, followed by a mixing system designed to homogenize the components. The resulting mixture is directed to a drum granulator, where granules are formed. In the next stage, the granules enter a rotary dryer, where they are dried with hot air. After being used, hot air is collected and cleaned through a hot air cleaning system, thereby ensuring compliance with environmental requirements. The dried granules pass through primary sieves, where they are separated into a commercial fraction (2–5 mm) and a recycle fraction (less than 2 mm), the latter being returned to the mixing system for further processing.

The selected commercial granules enter cooling sieves, where they are cooled with cold air. This is followed by secondary sieving, and the finished product is further processed with wax in a coating drum to improve its physical properties and storage stability. The final product is then stored in containers designated for the final product. Cold air used in the cooling, sieving, and coating processes is collected through

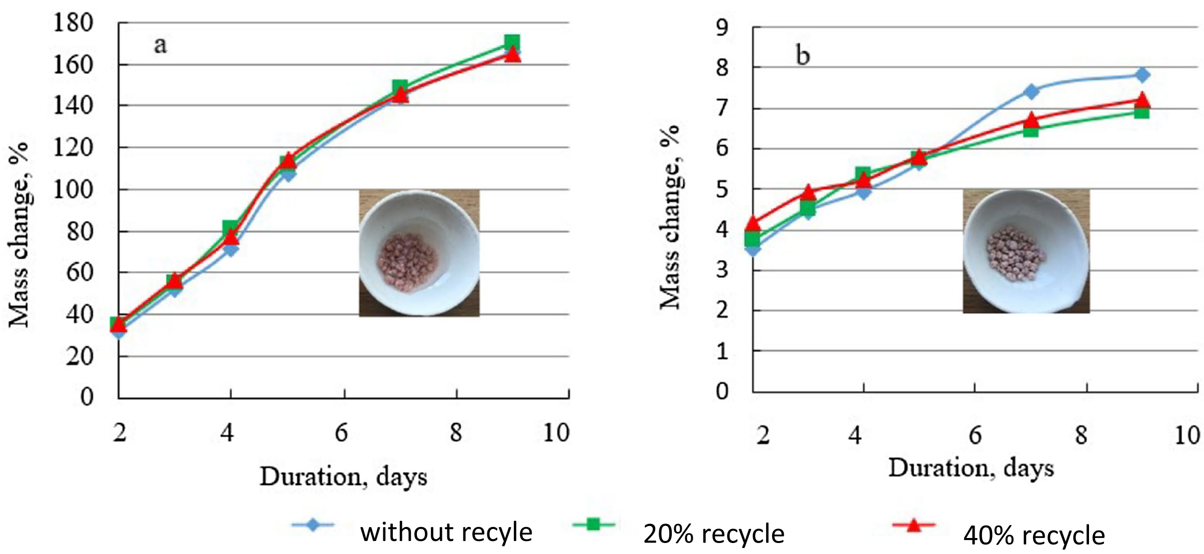

FIGURE 2
Hygroscopicity of granular NPK 5–15–30 + S + Zn + Fosfix fertilizers: **(a)** above water, **(b)** above saturated sodium nitrite solution.

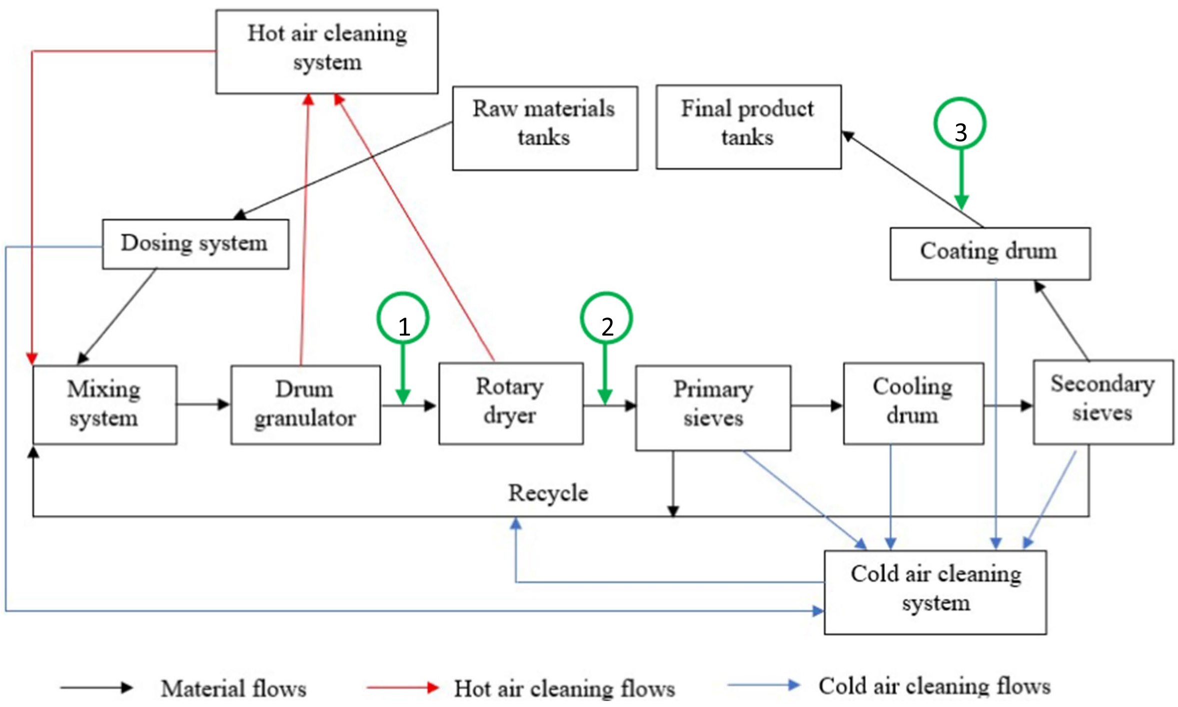

FIGURE 3
Schematic block diagram of NPK fertilizer production with main processes, flows and sample control points: 1 – after the granulator; 2 – after the dryer 3 – after the coating drum.

a cold air cleaning system, thus reducing the emission of dust and other particulates into the environment.

Since temperature fluctuations occur during the process of granulating NPK fertilizers under industrial conditions, and other external factors influence the process, the activity of bacteria in the product granulated under industrial conditions was additionally analyzed. For this analysis, samples were taken at three points along the technological line: after the granulator; from the belt conveyor after the dryer, where the highest temperature (300–350 °C) is maintained for 15–20 min; and from the belt conveyor after the coating drum, where the final product is already located. The results obtained from the bacterial survival study are presented in Figure 1 and Table 3.

To manufacture bioinoculants, microbial biomass must be produced in high concentrations under aseptic conditions, typically reaching a minimum of $1{\cdot}10^{8}$ CFU·mL^{-1} (this means that 0.1 mL of the solution contains approximately $1{\cdot}10^{7}$ CFU, i.e., 10 million viable cells). According to a patent description, application rates of *Bacillus subtilis* inoculants range from $1{\cdot}10^{6}$ to $5{\cdot}10^{15}$ CFU·ha^{-1}, with an optimal spore density falling between $1{\cdot}10^{7}$ and $1{\cdot}10^{11}$ CFU·ha^{-1} (Seevers et al., 2014) Literature sources recommend applying *Bacillus* spp. to soil at concentrations of approximately $1{\cdot}10^{7}$ CFU·g^{-1} of soil to ensure effective colonization (Qian et al., 2023; Mawarda et al., 2022). Additionally, healthy arable soils typically contain bacterial populations ranging from 10^{6} to 10^{9} CFU·g^{-1}, suggesting that inoculation should aim to reach or exceed the upper end of this natural range (TerraSoil, 2024).

Based on the data presented in Table 3 and the visual information in Figure 1, it can be concluded that the bacteria survived with a mortality rate of 10–15%.

Since such bacterial viability results are in line with the recommendations, it can be assumed that the industrial wet granulation process, in which the bacteria are introduced into the raw material mixture, is suitable for producing various fertilizers with the bioactive additive Fosfix.

3.4 The effect of a biological additive on the growth and properties of spring wheat

Further studies on industrial granular NPK 5–15–30 + S + Zn + Fosfix fertilizers were conducted to determine the effectiveness of *Bacillus* sp. bacteria. The research took place at the Rumokai testing station, using Triso variety of spring wheat for the study. Fertilization was carried out using the same rates (350 kg·ha^{-1}) of two fertilizer types: NPK 5–15–30 + S + Zn (NPK) and NPK 5–15– 30 + S + Zn + Fosfix (NPK + F). To simulate real conditions of wheat cultivation, herbicides (MCPA super + Sekator) and an additional application of ammonium nitrate (NH_4NO_3) at a rate of 251 kg·ha^{-1} were also used.

The research results, presented in Table 4, demonstrate that the biological additive Fosfix increased the tillering capacity of spring wheat. The number of productive stems increased from 406 pcm·m^{-2} in the NPK group to 476 pcm·m^{-2} in the NPK + F group (17.2%). The number of nonproductive stems increased by 94.4%. Although this increase is higher in the NPK + F group, the increase in the number of productive stems indicates a positive effect. In addition, plants fertilized with NPK + F were generally taller (52.4 cm compared to 50.2 cm) and had slightly longer spikes (6.6 cm compared to 6.4 cm) than the NPK group. The observed increases in straw and spike length were consistent and showed low variability (values of SD ≤ 0.7 cm,

TABLE 3 Viable bacterial counts at different processing stages and time points in NPK 5–15– 30 + S + Zn + Fosfix fertilizer samples.

After the granulator		After the dryer		After the coating drum	
Time	Concentration of bacteria, CFU·g^{-1}	Time	Concentration of bacteria, CFU·g^{-1}	Time	Content of bacteria, CFU·g^{-1}
14:45	$3.4 \cdot 10^7$	14:45	$7.3 \cdot 10^6$	14:45	$3.1 \cdot 10^7$
15:15	$6.1 \cdot 10^6$	15:15	$2.5 \cdot 10^7$	15:15	$9.8 \cdot 10^6$
15:45	$1.3 \cdot 10^7$	15:45	$1.3 \cdot 10^7$	15:45	$1.1 \cdot 10^7$
16:15	$1.6 \cdot 10^7$	16:15	$6.8 \cdot 10^6$	16:15	$1.7 \cdot 10^7$
16:45	$9.2 \cdot 10^6$	16:45	$1.7 \cdot 10^7$	16:45	$8.7 \cdot 10^6$
17:15	$7.5 \cdot 10^6$	17:15	$1.5 \cdot 10^7$	17:15	$2.3 \cdot 10^7$

TABLE 4 Biometric data of spring wheat.

Fertilizer	Number of productive stems, pcm·m^{-2}	Non–productive stems, pcm·m^{-2}	Straw length, cm	Spike length, cm	Number of grains per spike, pcs
NPK	406	18	50.2 ± 0.66* ± 0.33**	6.4 ± 0.19* ± 0.09**	28.0 ± 0.49* ± 0.22**
NPK + F	476	35	52.4 ± 0.59* ± 0.31**	6.6 ± 0.12* ± 0.07**	26.8 ± 0.45* ± 0.25**

*Standard deviation (SD) values (n = 30 replicates) **Standard error (SE) values (n = 30 replicates).

and values of SE ≤ 0.35 cm), indicating reliable measurements. The number of grains per spike decreased slightly (26.8 for NPK + F compared to 28.0 for NPK), but the change was small in relation to the variation among replicates.

Similar findings were obtained in a study on the effects of NPK and biofertilizers on the growth, yield, and nutrient uptake of wheat, where a microbial consortium consisting of *Azotobacter chroococcum*, *Bacillus subtilis*, and *Pseudomonas fluorescens*, applied with 75% of the recommended fertilizer dose, significantly enhanced wheat germination, plant growth, nutrient uptake, and yield parameters (Parunandi et al., 2023).

C. Joshi reported that a microbial consortium consisting of *Azotobacter*, *Bacillus*, and *Pseudomonas* spp., applied with 50% of the recommended NPK dose, significantly increased wheat plant height (115.6 cm), tiller number (119.1), and grains per spike (47.3), resulting in the highest grain yield (55.7 kg·ha^{-1}) and nutrient uptake, thus confirming the positive effect of biofertilizers on crop performance under reduced chemical input (Joshi et al., 2024).

After using the biological additive, the yield of spring wheat grains increased by 0.2 t·ha^{-1} and the weight of 1,000 grains by 0.21 g. The observed increases in grain yield and 1,000 grain mass were consistent and showed low variability (SD ≤ 0.15 t·ha^{-1} for yield and ≤0.5 g for 1,000 grain mass), indicating a modest positive effect of the additive, while the variations in protein, starch, and gluten content were small in relation to the variability among replicates, suggesting no significant impact on grain quality (Table 5).

Our study observed an increase in grain yield (~5%) and 1,000-grain weight (~0.5%) after application of NPK + F, which is consistent with results from the region of Northwest China, which showed that average increases in grain yield can be achieved using other fertilization technologies. Straw strip mulching increased yield by 13.4%, while whole-ground plastic film mulching increased it by 21.2%. The increase in 1000-grain weight ranged from 1.8 to 5.5%, and minimal changes in protein, starch, and gluten content did not indicate significant differences in grain quality parameters (Chai et al., 2025). However, this contrasts with the findings of Kayin et al. (2015), who noted an increase in protein and gluten content with *Bacillus subtilis* application, potentially due to differences in bacterial strains, environmental conditions, or fertilizer formulations.

3.5 The effect of a biological additive on the growth and properties of sugar beet

Following the analysis of the influence of NPK 5–15–30 + S + Zn + Fosfix fertilizers on spring wheat, a different brand of fertilizers, NPK 12–11–22 + Na + S + B (NPK) and NPK 12–11– 22 + Na + S + B + Fosfix (NPK + F), was produced by a fertilizer industry company. These fertilizers were then tested at the Rumokai testing station of the LAMMC branch using sugar beets of Severa KWS variety.

Fertilization was carried out in two ways: using a fertilizer rate of 700 kg·ha^{-1} of NPK and 163 kg·ha^{-1} of NH_4NO_3, and using a fertilizer rate of 700 kg·ha^{-1} of NPK + F and 163 kg·ha^{-1} of NH_4NO_3. To maintain realistic growing conditions, herbicides (Kontact, Ethosat, Goltix, and Poweroil), the insecticide Proteus, and the fungicide Maredo were also applied during the sugar beet growing season. The obtained research data are presented in Tables 6–8.

The data presented in Table 6 indicate that the use of the biological additive Fosfix had a positive effect on the germination and plant density of sugar beet. In fields fertilized with NPK + F, initial germination was higher (25.2% ± 1.8 SD; ±0.33 SE) compared to the NPK variant (19.2% ± 1.8 SD; ±0.35 SE), and this difference exceeded the standard error, indicating a reliable increase. Although final germination was similar in both variants (85.3% for NPK and 85.9% for NPK + F), the NPK + F variant exhibited a slightly higher plant density at harvest (109.6 thousand units·ha^{-1}) compared to the NPK variant (106.7 thousand units·ha^{-1}). Furthermore, the average weight of one root was higher in the NPK + F variant (0.911 kg) than in the NPK variant (0.882 kg). These findings align with other studies that observed a significant increase in root dry matter and overall root yield of sugar beet when biofertilizers were applied, highlighting the positive impact of microbial inoculants on sugar beet root biomass development (Amin et al., 2013; Çınar and Ünay, 2021). The observed increase in initial field germination with NPK + F in our study (~31%)

TABLE 5 Spring wheat grain yield and grain quality.

Fertilizer	Grain yield, t·ha^{-1}	1,000-grain mass, g	Protein, %	Starch, %	Gluten, %
NPK	3.9 ± 0.15* ± 0.04**	41.24 ± 0.50* ± 0.09**	16.7 ± 0.9* ± 0.15**	62.4 ± 1.3* ± 0.23**	34.9 ± 1.1* ± 0.20**
NPK + F	4.1 ± 0.15* ± 0.03**	41.45 ± 0.48* ± 0.09**	16.3 ± 0.8* ± 0.14**	62.7 ± 1.3* ± 0.20**	33.8 ± 1.0* ± 0.20**

*Standard deviation (SD) values (*n* = 30 replicates) ** Standard error (SE) values (*n* = 30 replicates).

TABLE 6 Sugar beet germination.

Fertilizer	Initial field germination, %	Final field germination, %	Density of crops at harvest, thous. pcs·ha^{-1}	Weight of one root, kg
NPK	19.2 ± 1.8* ± 0.35**	85.3 ± 2.0* ± 0.37**	106.7 ± 3.8* ± 0.69**	0.882 ± 0.06* ± 0.009**
NPK + F	25.2 ± 1.8* ± 0.33**	85.9 ± 1.9* ± 0.34**	109.6 ± 3.5* ± 0.64**	0.911 ± 0.05* ± 0.007**

* Standard deviation (SD) values (*n* = 30 replicates) ** Standard error (SE) values (*n* = 30 replicates).

TABLE 7 Sugar beet root crop and sugar content.

Fertilizer	Root crop yield, t·ha^{-1}	Base sugar yield, t·ha^{-1}	Sugar content, %	Biological sugar yield, t·ha^{-1}
NPK	94.07 ± 4.5* ± 0.82**	107.7 ± 5.0* ± 0.91**	18.32 ± 0.50* ± 0.09*	17.23 ± 0.55* ± 0.10**
NPK + F	99.85 ± 3.5* ± 0.64**	113.3 ± 3.8* ± 0.70**	18.15 ± 0.40* ± 0.07**	18.12 ± 0.45* ± 0.08**

* Standard deviation (SD) values (*n* = 30 replicates) ** Standard error (SE) values (*n* = 30 replicates).

TABLE 8 Quality of sugar beet root quality and white sugar yield.

Fertilizer	Potassium concentration, mmol/100 g^{-1}	Sodium concentration, mmol/100 g^{-1}	α-amino nitrogen concentration, mg/100 g^{-1}	White sugar, t·ha^{-1}
NPK	3.73 ± 0.20* ± 0.04**	0.22 ± 0.03* ± 0.01**	8.40 ± 0.40* ± 0.07**	14.72 ± 0.55* ± 0.10**
NPK + F	4.08 ± 0.18* ± 0.03**	0.26 ± 0.02* ± 0.01**	9.10 ± 0.35* ± 0.06**	15.31 ± 0.50* ± 0.09**

* Standard deviation (SD) values (*n* = 30 replicates) ** Standard error (SE) values (*n* = 30 replicates).

is notably higher than the gains reported in studies using bacterial seed treatments, which typically improved germination by about 10–17% under comparable fertilizer regimes, thus underscoring the strong positive effect of the biological additive in our conditions (Demyanyuk et al., 2020).

The yield increase of root crops using NPK 12–11–22 + Na + S + B fertilizers with the biological additive Fosfix was 5.78 t·ha^{-1}. The yield increase of root crops with standard sugar content was 5.6 t·ha^{-1}, and the yield increase of biological sugar content was 0.89 t·ha^{-1}. However, sugar content decreased by 0.17% (Table 7). The obtained root crop yields (94.07 t·ha^{-1}for NPK and 99.85 t·ha^{1} for NPK + F) fall within the upper range of values reported in literature under enhanced fertilization regimes, though they remain below the maximum yield levels of ~132 t·ha^{-1}achieved under optimized potassium fertilization (Xie et al., 2022). These differences exceeded the standard error (SE ≤ 0.1 t·ha^{-1}), indicating that the observed increases are statistically reliable.

Similarly, the biological sugar yield observed in our study (17.23–18.12 t·ha^{-1}) is comparable to the 11–18 t·ha^{-1} range reported by Varga et al. (2021) under varying nitrogen fertilization and crop density treatments, confirming that the addition of Fosfix produces a competitive impact on sugar beet root and sugar yield. By contrast, the sugar content remained high in both treatments (~18%), exceeding values commonly reported in similar studies (14.9–15.6%), which indicates that the additive improved yield parameters without compromising accumulation of sucrose.

According to the data presented in Tables 7, 8, it can be concluded that incorporating the bacterial additive Fosfix into NPK 12–11–22 fertilizerimproved many indicators of sugar beet quality compared to the treatment without the additive.

The white sugar yield increased from 14.7 to 15.3 t·ha^{-1}, and this difference exceeded the standard error (SE ≤ 0.1 t·ha^{-1}), indicating a statistically reliable effect. Root quality parameters such as potassium, sodium, and α-amino nitrogen also showed slight increases, but all values remained within the typical ranges reported by Varga et al. (2021). Similarly, the white sugar yield in our study (14.7–15.3 t·ha^{-1}) aligns with the 12–16 t·ha^{-1} interval described by Xie et al. (2022), confirming that the biological additive improved productivity without compromising root quality.

Summarizing the results on the influence of the biological preparation Fosfix on the quality parameters of spring wheat (*Triticum aestivum* L.) Triso and sugar beet (*Beta vulgaris* L.) Severa KWS, it can be stated that this preparation, based on *Bacillus* sp. bacteria, had a more pronounced effect on sugar beet indicators, particularly improving field germination, root yield, and white sugar output. This can be explained by different yield targets. In the case of sugar beet, the harvested product is the root crop, which is directly located in the rhizosphere; therefore, any improvement of the root zone (e.g., P/K mobilization, hormone production) directly contributes to the yield. In contrast, the final product of wheat is grain, which is often limited by light, heat, or moisture factors, so improvements in the rhizosphere do not always fully translate into higher grain yield.

Furthermore, the microbiota of sugar beet is usually weakly or not at all mycorrhizal, making it more dependent on the availability of plant-growth-promoting rhizobacteria such as *Bacillus* sp. Wheat, on the other hand, often already hosts an abundant natural microbiota, so the additional effect of *Bacillus* sp. is typically smaller than in sugar beet.

4 Conclusion

Laboratory experiments demonstrated that optimal conditions for granulating NPK 5–15– 30 + S + Zn + Fosfix fertilizer were achieved when the raw material mixture contained 15–16.5% moisture and up to 40% return material. Under these conditions, strong and uniform granules were produced, and the biological additive Fosfix did not interfere with the granulation process. Importantly, *Bacillus* sp. bacteria remained viable throughout wet granulation, indicating that this technology can be successfully scaled to industrial production without compromising product quality.

Field trials revealed that the effect of Fosfix was crop-specific. In spring wheat (*Triticum aestivum* L. Triso), the additive increased the number of productive tillers, plant height, and spike length, leading to modest gains in grain yield (+0.2 $t{\cdot}ha^{-1}$) and thousand kernel weight (+0.21 g), while quality parameters such as protein and gluten content were slightly reduced. In sugar beet (*Beta vulgaris L. severa* KWS), the additive showed a stronger and more consistent effect: initial field germination, root weight, plant density, and total root yield all increased, resulting in an additional 5.78 t/ha of roots and 0.89 $t{\cdot}ha^{-1}$ of biological sugar yield, without compromising sucrose accumulation.

Overall, these results indicate that incorporating *Bacillus*-based bioadditives into compound mineral fertilizers is a feasible and effective strategy. By maintaining bacterial viability during granulation and improving crop productivity under field conditions, such fertilizers combine technological robustness with agronomic benefits. The stronger effect observed in sugar beet suggests that root crops, which are more directly influenced by rhizosphere processes, may benefit more than cereals. In this way, Fosfix-enriched fertilizers contribute both to sustainable crop intensification and to improving soil–plant interactions, aligning with the goals of environmentally friendly and efficient agriculture. Future research should focus on optimizing the efficiency of bacterial utilization and ensuring their viability and activity during incorporation into fertilizers, in order to maximize both agronomic effectiveness and sustainability.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RŠ: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. MG: Formal analysis, Investigation, Methodology, Visualization, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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