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Efficacy of growth regulators for maize fields

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Abstract. At the current stage of agricultural development, it is paramount to introduce advanced technologies for maize cultivation. Special attention is required for the use of modern growth regulators in order to ensure stable increase in grain production. To protect maize from stress factors emerging in unfavorable meteorological conditions of the steppe zone (such as drought, high temperatures, negative impacts of pesticides, diseases, etc.), increasing attention is given to the application such physiologically active compounds as plant-growth regulators (PGRs). The experimental studies were carried out in 2021–2023 on the experimental field of the Dnipro State Agrarian-Economic University. The objective of the study was to identify the efficacies of the plant-growth regulators used in different doses on maize. The highest efficacy in the technology of maize cultivation was achieved by treating the maize plants with humates during the phase of 3–5 leaves. This treatment promoted a stable tendency towards growth, resulting in 5–7 cm increase in height (2.1–2.8%), 5–6% increase in leaf surface area, and increases in yield structure (13.6 cm in the cob length (5.1%), 18 grains (3.9%) in cob grain filling, and 29 g (9.1%) in mass of 1,000 grains), compared with the control without growth regulators. Somewhat lower efficiency according to all the aforementioned parameters was demonstrated by coating of seeds. Treatment of the seeds with growth regulators and microbial fertilizers in the phase of 3–5 leaves resulted in 7.3% to 18.7% increase in the yield, indicating their high efficacy, especially in unfavorable weather conditions. Therefore, the greatest gains in the grain yield was seen after using humate 400 g/ha + polyethylene glycol 360 g/ha – 1.08 t/ha; humate 800 g/ha + polyethylene glycol 240 g/ha – 1.19 t/ha; sodium metasilicate 600 g/ha – 1.23 t/ha; Pakt 500 g/ha – 1.23 t/ha; and Peram 100 mL/ha + Vympel PGR 500 g/ha – 1.12 t/ha. That is, of the sixty seven tested combinations of physiologically active compounds, no variant produced a grain-yield increase lower than 0.5 t/ha, and the variants with foliar feeding of the maize demonstrated no clear upward tendency in the yield after the PGRs had been introduced in doses above the norms. Studies of efficiency of the growth regulators and microbial fertilizers for maize confirmed that achievement of maximum grain yield is possible only by optimizing the vital factors at all stages of organogenesis of maize. When climatic elements develop with various amplitudes during a vegetative period, effectiveness of preparations is determined by their ability to enhance tolerance to the environmental stressors.

Keywords: maize; plant growth regulator; biometric parameters; yield.

Introduction

At the current development stage of agriculture, introduction of novel technologies of maize cultivation is of utmost importance. Use of modern growth regulators becomes strategically major to ensure a stable growth of grain production. Spread of negative factors in agriculture of the steppe zone, such as impaired crop rotations, intensive technological loading, and increase of weeds in maize fields, impose limitations on the potential of grain-crop farming. This determines importance of further improvement of maize-cultivation technologies with the purpose of neutralizing those issues and boosting nutrition of the plants with growth regulators. Use of such regulators advances the resilience of the plants against environmental stressors (Pashchak et al., 2021; Tkalich et al., 2022; Tsyliuryk, et al., 2022, 2023), which is critical in provision of productivity and tolerance of agricultural crops.

To protect maize from stressors emerging due to unfavorable meteorological conditions of the steppe zone (such as drought, high temperature, etc.), increasing attention is paid to the use of physiologically active compounds (Ostrowska et al., 2021; Noein et al., 2022; Yevtushenko et al., 2023). Those compounds can regulate growth processes, promote increases in grain yield and improvement of its qualitative characteristics, at the same time being environment-friendly and safe for health of people (Bahrabadi et al., 2022; Prasad, 2022; Sun et al., 2022; Godar et al., 2023). Recently, special attention is concentrated on compounds used to activate and stimulate the seeds and treat the vegetative plants. There is a variety of growth regulators worldwide, which increase plants' resilience to stressors, improve their biometric parameters and yield. Those agricultural crops include maize.

For example, exogenic application of salicylic acid (SA) significantly stimulated the plant growth, especially in saline soils. Therefore, SA can be considered a potential growth regulator for strengthening the plant's resilience against stress factors such as salinization (Gunes et al., 2007). The studies revealed new possibilities of effective application of physiologically active compounds in agriculture, in particular, to increase tolerance of maize to unfavorable environmental conditions and provide a stable yield.

Researchers who studied plant-growth regulators (PGR) (auxin, gibberellin acid, salicylic acid, and paclobutrazol) in drought conditions observed positive results, suggesting efficacy of those drugs. It was revealed that they promoted growth of the maize, and increases in the yield and its quality during dry periods. Auxin significantly increased height of the plants and leaf length, whereas paclobutrazol and salicylic acid substantially augmented the number of cobs and general amount of organic matter in maize (Mubarok et al., 2022). Those results indicate potential use of the said growth regulators as effective tools to boost tolerance and productivity of maize, especially against the background of water deficit. Plant-growth regulators based in rhizobacteria (PGPR) demonstrated a notable positive effect in maize fields, especially in combination with fertilizers such as poultry litter and urea (Lin et al., 2007). This combination improved the formation of the root system through synthesis of plant growth regulators, increased plants' height, content of chlorophyll in the leaves (expressed in SPAD parameters), area of the leaves, and biomass of the maize plants. All of this ultimately improved intake of water and nutrition elements by the root system.

Plant Growth-Promoting Rhizobacteria (PGPR) play an important role in balanced provision of plants with necessary nutrients, promoting their health and optimal development. Combined use of PGPR and fertilizers from natural sources, such as poultry litter and urea, is a promising direction for increasing productivity and vitality of maze fields.

Studies reported that not only did those drugs promote growth of maize, but also improved its physiological condition, which is crucial to yield and quality of cultivated production. Such an approach facilitated the use of water and other resources in maize cultivation, which is an important aspect against the backdrop of growing ecological challenges and needs in stable development of the agricultural sector.

Plant-growth regulator Vympel is very common and relevant in agriculture (Palamarchuk, 2018; Huang et al., 2021; Laslo et al., 2022). Studies conducted in this field experiment have confirmed the efficacy and benefits of Vympel in improving growth and development of plants. Vympel can promote growth stimulation, and therefore increases in sizes of the cobs and yield of maize. Studies revealed that this drug can have a positive effect on adaptation of the plants to stress conditions such as drought, cold, and can also boost their tolerance to pests and diseases. Results of the studies conducted in this direction suggest that Vympel is promising as an important tool to enhance the productivity and tolerance of agricultural crops. This results in better quality of grown products and stability in agroindustrial production.

Evaluating the significance and relevance of introduction of modern growth regulators into the production, and taking into account split opinions of researchers and producers, studies of efficacy of those drugs are an essential direction. We think that the main aspect would be studying effects of plant-growth regulators, such as Vympel K-2, Peram, Pakt, and Humate, on the growth and development of plants, and also their effects on the structure and productivity of maize, in particular. Studies in this direction will lead to a better understanding of action mechanisms of growth regulators and their interaction with the plants, which, in turn, will contribute to the development of more effective methods of crop cultivation. Analysis of effects of growth regulators on the processes of plant physiology and yield formation will help to identify optimal conditions of their application in order to maximize the positive effects on maize production. Such studies will promote development of agriculture, provision of food, and support stability of the production in the conditions of the climate change and varying environment. The results of the studies can also be a basis for development of new innovative products and technologies, oriented at increasing the efficiency of agriculture.

The objective of the study was to identify the effectiveness of the plant-growth regulators in different doses in maize cultivation at the steppe zone of Ukraine.

Materials and methods

Experimental studies were conducted on the experimental field of the Dnipro State Agrarian-Economic University in 2021–2023. During this period, we performed a systematic monitoring and experiments to study effects of various growth regulators on the development and yield of maize. The studies on the experimental field of the university had provided us with important data and results that can play an important role in the development of agriculture and modern methods of crop cultivation. This short period of studies allowed us to account for various aspects of influence of the growth regulators on the maize plants in different conditions and at different stages of their development.

Results of those studies can be a valuable contribution to agricultural practice, promoting development of more effective and stress-resistant methods of crop cultivation, which, in turn, will promote increases in yield and quality of maize.

The agrotechnology of cultivating maize, in particular the DN Halateia hybrid, corresponded to the generally approved recommendations for the steppe zone. Precursor of the maize had been winter wheat, and the main soil treatment, including subsoiling tillage, was conducted at the depth of 23–25 cm. In spring, soil was evened using spring-tooth harrow, and fertilizers in the $N_{30}P_{50}$ dose were introduced prior to sowing. Herbicides and plant-growth regulators were used using a hose-end sprinkler. Sowing was performed using a VEGA 8 PROFI seed drill. Account of the yield and additional observations were carried out according to the generally accepted methods (Steel et al., 1997; Ushkarenko et al., 2008).

This agrotechnology accounted for the specifics of the steppe zone and gave an opportunity to effectively cultivate maize, providing optimal conditions for its growth and development. Use of the appropriate technologies and fertilizers promoted formation of healthy plants and increase in yield. Such an approach to agrotechnology allows maximizing potential of crops and provides a stable and high yield according to the requirements of agriculture.

Scheme of the experiment included a three-year implementation of the following treatments of using the growth regulators: Vympel K-2, Peram, Pakt, Humate, and Vympel (Table 1). Those PGRs were applied to the seeds with the norm of the spray aquous solution in the amount of 10 L/t and introduced in the phase of 3–5 true leaves of maize in 250 L/ha norm of applied solution (Table 2).

Table 1
Composition of the drugs

Name	Composition	Manufacturer (country)
Humates	potassium humate of sodium with microelements (N – 1.0–10.0 g/L, P_2O_5 – 1.0–5.0 g/L, K_2O – 1.0–30.0 g/L, Zn – 0.1–5.0 g/L, B – 0.1–1.0 g/L, Cu – 0.1–5.0 g/L, Fe – 0.1–5.0 g/L, MgO – 0.1–10.0 g/L, Na – 1.0–5.0 g/L, Mn – 0.05–5.0 g/L, Mo – 0.01–1.0 g/L, Co – 0.01–1.0 g/L, organic compounds (in calculation to dry matter) – no lower than 20%, humic substances – no lower than 50.0 g/L)	SIC Ekolohia Ltd, (Ukraine)
Peram	plant-growth regulator (polyols – 100 ± 10 g/L, salts of aminoalcohols with replaced phenoxyacetic acids – 52–58 g/L)	private scientific-research enterprise Dolina (Ukraine)
Vympel K2	plant-growth regulator (triphosphate ether of adenine derivatives with ribose – 3.0 ± 0.2 g/L; polyols – 300 ± 30 g/L, humic acids – 60 ± 0.6 g/L, and carbonic acids of natural origin – 6.0 ± 0.6 g/L)	Dolina (Ukraine)
Vympel	plant-growth regulator (polyethylene glycols PEG-400 and PEG-1500, total content – 770 g/L, salt of humic acids – up to 30 g/L)	Dolina (Ukraine)
Pakt	anion surfactants – 19 g/L, polyols – 55 g/L, the complex INSECTO-protector – 750 g/L	Dolina (Ukraine)
PEO	polyethylene glycol, non-ionic polymers, represented by the formula $(CH_2–CH_2O)_n$, where n is the mean of oxyethylene groups; can contain 3% of silicon dioxide	Dolina (Ukraine)
Sodium silicate	sodium silicate, sodium salt of Na_2SiO_3 silicic acid	Zaporizhskloflius Ltd (Ukraine)

Potassium humate is a potassium salt of humic acid, soluble in water. It is essential for soil fertility and promotes active growth of plants. One the best sources of humic acid is brown coal known as leonardite.

The solution contains water, humic substances in concentrations ranging 80 to 100 g/L, fulvic acids, comprising 25% to 30% of the overall content of humic substances, and also macroelements and microelements such as iron (Fe), zinc (Zn), magnesium (Mg), boron (B), and copper (Cu). It may also contain extract of biohumus.

Potassium humate is most economically effective for treatment of seeds prior to sowing and foliar treatment during vegetation. This method can be used individually, as well as combined with pesticides and microbial fertilizers in mixed solutions. It is produced by the Ekolohia Scientific-Innovative Complex (SIC Ekolohia Ltd, Ukraine).

Vympel K2 is a new exclusive preparation, specifically developed to treat sunflower and maize. The main active components are triphosphate ether of adenine derivatives with 3 g/L of ribose, 300 g/L of polyols, 60 g/L of humic acids, and 6 g/L of carbonic acids of natural origin. The drug is considered low-toxic, classified to toxicity class 4, and was designed for pre-sowing treatment of seeds. Manufacturer is Dolina (Ukraine).

Peram is a plant-growth regulator (aqueous solution), containing 100 ± 10 g/L of polyols and 52–58 g/L of salts of aminoalcohols with replaced phenoxyacetic acids. Manufacturer is private scientific-research enterprise Dolina (Ukraine).

Polyethylene oxides PEO-1500 (54%) and PEO-400 (23%) are water-soluble non-ionic polymers, obtained by polymerization of ethylene oxide through ring-opening polymerization. They have a low molecular mass, which simplifies their penetration into the tissues and enables them to perform the transport function for all drugs used in conjunction with plant growth regulators (PGR). The drug organizes the free intracellular water, increases its biological activity, promotes acceleration of photosynthesis, transformation, and intensity of mineral nutrition. Polyethylene oxides 1500 exert high ability to form film. The polyethylene oxide is manufactured by Dolina (Ukraine).

Pakt is a super-wetting and adhesive agent, containing 19 g/L of anion surfactants, 55 g/L of polyols, and 750.0 g/L of the complex Insecto-protector. The pH is 2.60–3.60. It is manufactured by Dolina (Ukraine).

Pakt super-wetting sticker is a liquid drug with contact-system action, aimed at increasing the efficiency and enhancing the resistance of plant-protecting agents to precipitation. It was designed specifically for treatment of sunflower and maize. The main advantages of Pakt are as follows:

– equalizing sizes of droplets of applied fluid and extension of the region of coverage of the surface of the leaf and plant;

– decrease in surface tension of applied solutions for promotion of immediate distribution of the solutions on the leaf surface;

– acceleration and optimization of the process of absorption of systemic pesticides or other components of tank mixtures through the leaves;

– is applicable in unfavorable weather conditions;

– significant increase in the area of coverage and penetration to hard-to-access parts of the plants;

– increase in efficiency of treatment of densely pubescent or dust-covered plants;

– possibility of delivery using aerial and ground-based methods of low-volume spraying without compromising the quality of the treated plants;

– 15–25% decrease in volume of applied fluid and up to 12–15 km/h increase in the rates of movement of the sprinkler system;

– decrease in cost price of chemical treatments as a result of reducing the norms of applied drugs and water for preparing a spray solution.

As with specifics of the use, the recommended norm of the super-wetting agent is 100 mL per 100 L of water. Also, the solution is recommended to be prepared on the day of treatment. According to the WHO classification, Pakt super-wetting sticker is identified to toxicity class 4.

Each of the treatments of the experiment included use of a particular growth regulator at various stages of the development of maize in order to study their effects on the physiological processes and yields of the plants.

This scheme allowed us to compare efficiencies of various growth regulators, determine optimal time to utilize them, and reveal potential advantages of each of them for cultivation of maize. Results of those experiments can be a basis for designing recommendations regarding optimal use of growth regulators in agriculture.

On the treatments of the experiment with seed treatment, we used the PEO sticker for fixation of the drugs on the maize seeds so as to improve the contact with active agents.

Use of the PEO sticker is an important element of technology of seed coating. It helps in providing a better adherence of this agent to the seed surface. As a result, active agents more effectively enter the seeds and coat the seeds more uniformly.

Use of the PEO sticker improves the efficacy of seed treatment, enhancing the stability of PGRs against degradation and producing better results in various cultivation conditions. Such an approach to seed treatment is an important element of modern agricultural technologies, designed to maximize yield and quality of cultivated crops.

Table 2
Scheme of the experiment on studying efficacy of growth regulators in maize fields

Physologically active substances and their rates	Introduction phase
1. Control (no drugs)	seed coating
2. Humate – 200 g/t	seed coating
3. PEO – 240 g/t	seed coating
4. Vympel-K2 – 500 g/t	seed coating
5. Vympel-K2 – 1,000 g/t	seed coating
6. Peram – 10 mL/t	seed coating
7. Peram – 20 mL/t	seed coating
8. Peram – 30 mL/t	seed coating
9. Humate – 65 g/t + PEO – 160 g/t	seed coating
10. Humate – 65 g/t + PEO – 240 g/t	seed coating
11. Humate – 65 g/t + PEO – 360 g/t	seed coating
12. Humate – 65 g/t + PEO – 600 g/t	seed coating
13. Humate – 130 g/t + PEO – 160 g/t	seed coating
14. Humate – 130 g/t + PEO – 240 g/t	seed coating
15. Humate – 130 g/t + PEO – 360 g/t	seed coating
16. Humate – 130 g/t + PEO – 600 g/t	seed coating
17. Humate – 200 g/t + PEO – 160 g/t	seed coating
18. Humate – 200 g/t + PEO – 240 g/t	seed coating
19. Humate – 200 g/t + PEO – 360 g/t	seed coating
20. Humate – 200 g/t + PEO – 600 g/t	seed coating
21. Humate – 400 g/t + PEO – 160 g/t	seed coating
22. Humate – 400 g/t + PEO – 240 g/t	seed coating
23. Humate – 400 g/t + PEO – 360 g/t	seed coating
24. Humate – 400 g/t + PEO – 600 g/t	seed coating
25. Humate – 800 g/t + PEO – 160 g/t	seed coating
26. Humate – 800 g/t + PEO – 240 g/t	seed coating
27. Humate – 800 g/t + PEO – 360 g/t	seed coating
28. Humate – 800 g/t + PEO – 600 g/t	seed coating
29. Humate – 200 g/t + PEO with glycerine – 240 g/t	seed coating
30. Humate – 200 g/ha	phase of 3–5 leaves
31. PEO – 240 g/ha	phase of 3–5 leaves
32. Humate – 65 g/ha + PEO – 160 g/ha	phase of 3–5 leaves
33. Humate – 65 g/ha + PEO – 240 g/ha	phase of 3–5 leaves
34. Humate – 65 g/ha + PEO – 360 g/ha	phase of 3–5 leaves
35. Humate – 65 g/ha + PEO – 600 g/ha	phase of 3–5 leaves
36. Humate – 130 g/ha + PEO – 160 g/ha	phase of 3–5 leaves
37. Humate – 130 g/ha + PEO – 240 g/ha	phase of 3–5 leaves
38. Humate – 130 g/ha + PEO – 360 g/ha	phase of 3–5 leaves
39. Humate – 130 g/ha + PEO – 600 g/ha	phase of 3–5 leaves
40. Humate – 200 g/ha + PEO – 160 g/ha	phase of 3–5 leaves
41. Humate – 200 g/ha + PEO – 240 g/ha	phase of 3–5 leaves
42. Humate – 200 g/ha + PEO – 360 g/ha	phase of 3–5 leaves
43. Humate – 200 g/ha + PEO – 600 g/ha	phase of 3–5 leaves
44. Humate – 400 g/ha + PEO – 160 g/ha	phase of 3–5 leaves
45. Humate – 400 g/ha + PEO – 240 g/ha	phase of 3–5 leaves
46. Humate – 400 g/ha + PEO – 360 g/ha	phase of 3–5 leaves
47. Humate – 400 g/ha + PEO – 600 g/ha	phase of 3–5 leaves
48. Humate – 800 g/ha + PEO – 160 g/ha	phase of 3–5 leaves
49. Humate – 800 g/ha + PEO – 240 g/ha	phase of 3–5 leaves
50. Humate – 800 g/ha + PEO – 360 g/ha	phase of 3–5 leaves
51. Humate – 800 g/ha + PEO – 600 g/ha	phase of 3–5 leaves
52. Humate – 200 g/ha + PEO with glycerine–240 g/ha	phase of 3–5 leaves
53. Sodium silicate – 600 g/ha	phase of 3–5 leaves
54. Pakt – 500 g/ha	phase of 3–5 leaves
55. Pakt – 1000 g/ha	phase of 3–5 leaves
56. Pakt – 1500 g/ha	phase of 3–5 leaves
57. Pakt – 300 g/ha	phase of 3–5 leaves
58. Pakt – 2500 g/ha	phase of 3–5 leaves
59. Pakt – 250 g/ha	phase of 3–5 leaves
60. Peram – 100 mL/ha	phase of 3–5 leaves
61. Peram – 200 mL/ha	phase of 3–5 leaves
62. Peram – 300 mL/ha	phase of 3–5 leaves
63. Peram – 100 mL/ha + Vympel PGR – 500 g/ha	phase of 3–5 leaves

Arrangement of the plots in the experiment was systematic. The sowing area on each plot accounted for 42 m² (4.2 × 10 m), and the area for account was 28 m² (2.8 × 10 m). The total area allocated for the study equaled 0.67 ha, with three repetitions.

Biometric measurements were carried out using the generally accepted study methods. In particular, height of the plants was measured using a special measuring ruler that allows accurately identifying distance from soil to the top of the plant. The area of the leaf surface was determined by the grid count method, or the grid method, which is one of the ways of identifying the area of maize-leaf surface. The main steps of the grid method are: division of the leaves into small equally sized and shaped segments or parts using a grid; measurement of the area of each segment uses software for image analysis; and identification of the general area of the leaf. Once the leaf area of each segment is measured, the areas are added up so as to determine the area of the entire maize leaf.

The measurement of the maize yield was conducted in the phase of complete grain ripeness, for each plot (10 m^2 account area), with the following conversion into 100% purity and 14% grain moisture. Mass of 1,000 maize grains was identified using a SeedCount special device.

The soil cover of the experimental plot was represented by ordinary chernozem, low-humus, and average-loamy. Thickness of the humus horizon was 38.0–43.0 cm. Humus content was 3.6% in the first, 0–30 cm, layer and 3.31% in 20–40 cm layer. Absorbed bases were represented mostly by potassium 20.4 mg/eqv. and magnesium 7.8 mg/eqv. per 100 g of soil. The degree of saturation of soil with bases was 94.2%. Therefore, this reaction of the soil solution was close to neutral (pH 6.6–6.8). The total content of nutrients in the first layer of soil was within the following ranges: total nitrogen – 0.15–0.19, phosphorus – 0.11–0.14, and potassium – 2.0–2.4%.

The weather conditions for maize cultivation were in general favorable throughout the vegetative periods of 2021–2023. Hydrothermal coefficient in the period of maximal water intake by the plants (July–first half of August) equaled 0.7 in 2013, 0.9 in 2014, and 0.8 in 2015. The HTC (hydrothermal coefficient) was below 0.7, indicating soil-air drought, which harmfully impacts the formation and filling of grain.

The data were analyzed using Statistica 10.0 (StatSoft Inc., USA). The data of yield are presented in tables as x ± SD (x ± standard deviation). Differences between values in the control and experimental variants were identified using the Tukey's test, where the differences were considered significant at $P < 0.05$ (accounting for the Bonferroni's correction).

Results

Use of plant-growth regulators positively influenced the tendencies towards increase in height and area of the leaf surface of the maize plants. Therefore, using humates for seed coating increased the height by 2 cm (1.0%) in the phase of 13–14 leaves and by 6 cm (2.4%) in the phase of silking. The area of the leaf surface increased by 5–6%. After using humates in the phase of 3–5 leaves, the height of the maize plants increased by 5–7 cm (2.1–2.8%) compared with the control. In the variant with application of Pakt and Peram in the phase of 3–5 leaves, the height of the plants in the phase of panicle drop was 245 cm, i.e. 3 cm (1.2%) taller than in the control. Similarly to the height, there was increase in the leaf-surface area of the maize plants. This, in turn, gave the plants an opportunity to obtain more photosynthetically active radiation, and further positively affected the productivity of this grain crop (Table 3).

The indicated peculiarities of the formation of photosynthetic surface area, growth of the plants significantly reflected in the structural elements of their yield and productivity. Parameters of the structural elements of maize yield after humate seed coating somewhat increased compared with the control variants. In particular, the length of the cob (12.9 cm in the control) increased to 13.2 cm (a 2.3% increase), and after treatment in the 3–5 leaves phase, it increased to 13.6 cm (a 5.1% increase). As with grain filling of the cobs of the maize plants following humate-coating of the seeds, it increased by 5 (1.1%), and in the variant with its introduction in the phase of 3–5 leaves it increased by 18 (3.9%), compared with the control.

Another important parameter of grain-yield formation of maize is mass of 1,000 seeds, which had a notable tendency towards variation, depending on the examined factors. Therefore, mass of 1,000 grains in the variants of the experiments with seed coating also demonstrated a tendency towards increase compared with the control without their application. The indicated parameter accounted for 306 g, and following the introduction in the phase of 3–5 leaves it equaled 317 g, which was 18 and 29 g, or 5.8% and 9.1% higher than in the control, respectively. Sprinkling of the maize with Pakt and Peram in the phase of 3–6 leaves promoted increases, measuring 0.6 cm (4.7%) in the cob length, 12 grains (2.7%) in grain filling of the cob, and 18 g (6.1%) in mass of 1,000 grains, compared with the control. Inferring from the presented analysis, we can state a stable tendency towards increase in grain filling and size after using the plant-growth regulators, which ultimately resulted in higher grain yield.

As revealed by the studies of elements of technology of maize cultivation, formation of maximum maize-grain yield is possible when vital factors are optimized at all stages of organogenesis. During the existing amplitude development of the climatic elements during vegetation, the effectiveness of technological methods is determined by their ability to optimize agroecological regimes in agrocenoses.

The following combinations of the experiment treatments with seed coating provided the greatest yield: humate 65 g/t + PEO 160 g/t – 0.69 t/ha; humate 65 g/t + PEO 360 g/t – 0.71 t/ha; humate 65 g/t + PEO 600 g/t – 0.77 t/ha; humate 130 g/t + PEO 240 g/t – 0.78 t/ha; humate 200 g/t + PEO 360 g/t – 1.06 t/ha; humate 200 g/t + PEO 600 g/t – 0.91 t/ha; humate 800 g/t + PEO 360 g/t – 0.8 t/ha. Somewhat lower, but significant increases in the yield were observed in the treatments with Vympel – K2 (500 g/ha) – 0.32 t/ha, and Peram 20 mL/t – 0.55 t/ha, but increase of the PGR rate up to 30 mL/t reduced the increase to 0.25 t/ha. Increasing the rate of humate from 65 to 200 g/ha heightened the yield by 3–7%, but the seeds humate treatment with the 800 g/ha resulted in no such increase. We have to note that the plant is more supported by mean doses rather than small or very high ones. The lowest effect was exerted by humate 200 g/t and PEO 240 g/t, when the yield increased by 3.8% and 5.1%, respectively, but within the experiment error. We should note that in the treatment with only one PGR, the yield increased not that greatly as it did after using two PRG combined, which indicates synergism.

Treatment of the maize with the PGRs in the phase of 3–5 leaves produced a significant increase in the yield, equaling 7.3% to 18.7%, indicating efficiency of the growth regulators and microbial fertilizers, and favorable weather conditions. The highest gains in the maize yield were achieved in the following variants: humate 400 g/ha + PEO 360 g/ha – 1.08 t/ha; humate 800 g/ha + PEO 240 g/ha – 1.19 t/ha; sodium silicate 600 g/ha – 1.23 t/ha; Pakt GD 500 g/ha – 1.23 t/ha; and Peram 100 mL/ha + Vympel PGR 500 g/ha – 1.12 t/ha. No treatment resulted in yield increase below 0.5 t/ha of the studied PGRs, i.e. we did not identify the PGRs with the lowest efficacy parameters. We observed no clear upward tendency in yield following rate increasing in the treatments with foliar feeding of the maize.

Discussion

Studies by domestic authors, in particular Laslo et al. (2022), confirmed the positive effect of compositions of the Vympel-2 regulator and the Orakul multicomplex on maize plants. The studies revealed that addition of a mixture of the PGRs in the phase of 3–5 leaves in combination with pre-sowing seed treatment produced better results than in the variants where vegetative treatment was conducted in the phase of 7–8 leaves. Those results indicate heightened stimulating effect of the compositions at early growth and development stages of plants. The researchers also pointed out that the mid-season hybrid Lauro FAO 330 exerted more productivity and was recommended for cultivation in the zone of the Central Forest Steppe.

Similar results were obtained by Yevtushenko et al. (2023), who considered that increasing resilience of the plants to unfavorable environmental factors is an important characteristic of the action mechanism of a growth regulator. This means enhancing tolerance to water deficiency, temperature drops, damages, and diseases and pests of the plants. Many researchers, both in Ukraine and abroad, have confirmed that modern growth regulators can enhance yield of the main agricultural crops by 10–39%. Foreign researchers, in particular Godar et al. (2023), are among those who support this hypothesis. They think that plant-growth regulators are synthesized compounds that became an important technical guarantee of agricultural production. Studies by such researchers such as Huang et al. (2021), Noein et al. (2022), Sun et al. (2022), Bahrabadi et al. (2022), and Prasad (2022) also corroborated this position. They confirmed significance of growth regulators as a tool of providing resilience and yield in agriculture. Such a consensus among scientists, in both domestic and foreign studies, indicates significance and potential of using growth regulators in order to boost efficiency of agricultural production.

Low temperature slows the growth of maize sprouts and limits their productivity in the field conditions. To solve this problem, researchers, particularly Wang et al. (1996) and Rymen et al. (2007), proposed using maize-seed coating with plant growth regulators (PGR).

The studies revealed that coating seeds with gibberellin acid (GA) and kinetin promoted germination of seeds and development of sprouts during low temperature in the root zone (10 °C). Gibberellin acid (GA) was found to be more effective than kinetin in provision of germination and development of maize. Those conclusions underscore the importance of using plant-growth regulators to produce optimal germination and development of crops, especially in low temperatures, which aids in increasing agricultural yield.

Table 3
Productivity of maize depending on growth regulators in 2020–2023 (x ± SD, n = 8)

Physologically active substances and their rates	Yield, t/ha	Deviation of the mean from the control, %
1. Control (without coating)	5.06 ± 0.11[a]	–
2. Coating with humate – 200 g/t	5.25 ± 0.12[b]	3.8
3. Coating with PEO – 240 g/t	5.33 ± 0.12[b]	5.1
4. Coating with Vympel-K2 500 g/t	5.38 ± 0.13[b]	6.0
5. Coating with Vympel-K2 1000 g/t	5.45 ± 0.13[b]	7.1
6. Coating with Peram 10 mL/t	5.48 ± 0.13[b]	7.6
7. Coating with Peram 20 mL/t	5.61 ± 0.14[b]	9.8
8. Coating with Peram 30 mL/t	5.31 ± 0.13[b]	4.7
9. Coating with humate – 65 g/t + PEO 160 g/t	5.75 ± 0.14[bc]	12.0
10. Coating with humate – 65 g/t + PEO 240 g/t	5.65 ± 0.14[bc]	10.4
11. Coating with humate – 65 g/t + PEO 360 g/t	5.77 ± 0.14[bc]	12.3
12. Coating with humate – 65 g/t + PEO 600 g/t	5.83 ± 0.14[bc]	13.2
13. Coating with humate – 130 g/t + PEO 160 g/t	5.77 ± 0.13[bc]	12.3
14. Coating with humate – 130 g/t + PEO 240 g/t	5.84 ± 0.14[bc]	13.3
15. Coating with humate – 130 g/t + PEO 360 g/t	5.56 ± 0.13[b]	9.0
16. Coating with humate – 130 g/t + PEO 600 g/t	5.63 ± 0.14[bc]	10.1
17. Coating with humate – 200 g/t + PEO 160 g/t	5.75 ± 0.14[bc]	12.0
18. Coating with humate – 200 g/t + PEO 240 g/t	5.70 ± 0.13[bc]	11.2
19. Coating with humate – 200 g/t + PEO 360 g/t	6.12 ± 0.15[c]	17.3
20. Coating with humate – 200 g/t + PEO 600 g/t	5.97 ± 0.15[c]	15.2
21. Coating with humate – 400 g/t + PEO 160 g/t	5.79 ± 0.15[bc]	12.6
22. Coating with humate – 400 g/t + PEO 240 g/t	5.76 ± 0.13[bc]	12.1
23. Coating with humate – 400 g/t + PEO 360 g/t	5.80 ± 0.14[bc]	12.7
24. Coating with humate – 400 g/t + PEO 600 g/t	5.73 ± 0.14[bc]	11.7
25. Coating with humate – 800 g/t + PEO 160 g/t	5.66 ± 0.13[bc]	10.6
26. Coating with humate – 800 g/t + PEO 240 g/t	5.75 ± 0.14[bc]	12.0
27. Coating with humate – 800 g/t + PEO 360 g/t	5.86 ± 0.14[bc]	13.6
28. Coating with humate – 800 g/t + PEO 600 g/t	5.58 ± 0.13[b]	9.3
29. Coating with humate – 200 g/t + PEO with glycerine 240 g/t	5.41 ± 0.13[b]	6.5
30. Control (without the treatment in the phase of 3–5 leaves)	5.32 ± 0.12[b]	–
31. Spraying in the phase of 3–5 leaves with humate – 200 g/ha	6.07 ± 0.14[c]	12.3
32. Spraying in the phase of 3–5 leaves with PEO – 240 g/ha	5.82 ± 0.13[bc]	8.6
33. Spraying in the phase of 3–5 leaves with humate – 65 g/ha + PEO 160 g/ha	5.91 ± 0.14[c]	10.0
34. Spraying in the phase of 3–5 leaves with humate – 65 g/ha + PEO 240 g/ha	6.07 ± 0.14[c]	12.3
35. Spraying in the phase of 3–5 leaves with humate – 65 g/ha + PEO 360 g/ha	5.76 ± 0.13[bc]	7.6
36. Spraying in the phase of 3–5 leaves with humate – 65 g/ha + PEO 600 g/ha	5.85 ± 0.13[bc]	9.0
37. Spraying in the phase of 3–5 leaves with humate – 130 g/ha + PEO 160 g/ha	6.18 ± 0.14[c]	14.0
38. Spraying in the phase of 3–5 leaves with humate – 130 g/ha + PEO 240 g/ha	6.08 ± 0.14[c]	12.5
39. Spraying in the phase of 3–5 leaves with humate – 130 g/ha + PEO 360 g/ha	5.91 ± 0.14[c]	10.0
40. Spraying in the phase of 3–5 leaves with humate – 130 g/ha + PEO 600 g/ha	6.01 ± 0.14[c]	11.5
41. Spraying in the phase of 3–5 leaves with humate – 200 g/ha + PEO 160 g/ha	6.24 ± 0.14[c]	14.7
42. Spraying in the phase of 3–5 leaves with humate – 200 g/ha + PEO 240 g/ha	6.08 ± 0.14[c]	12.5
43. Spraying in the phase of 3–5 leaves with humate – 200 g/ha + PEO 360 g/ha	6.20 ± 0.15[c]	14.2
44. Spraying in the phase of 3–5 leaves with humate – 200 g/ha + PEO 600 g/ha	6.33 ± 0.15[cd]	16.0
45. Spraying in the phase of 3–5 leaves with humate – 400 g/ha + PEO 160 g/ha	6.01 ± 0.14[c]	11.5
46. Spraying in the phase of 3–5 leaves with humate – 400 g/ha + PEO 240 g/ha	5.82 ± 0.13[bc]	8.6
47. Spraying in the phase of 3–5 leaves with humate – 400 g/ha + PEO 360 g/ha	6.40 ± 0.14[cd]	17.0
48. Spraying in the phase of 3–5 leaves with humate – 400 g/ha + PEO 600 g/ha	6.01 ± 0.13[c]	11.5
49. Spraying in the phase of 3–5 leaves with humate – 800 g/ha + PEO 160 g/ha	6.31 ± 0.14[cd]	15.7
50. Spraying in the phase of 3–5 leaves with humate – 800 g/ha + PEO 240 g/ha	6.51 ± 0.14[d]	18.2
51. Spraying in the phase of 3–5 leaves with humate – 800 g/ha + PEO 360 g/ha	5.88 ± 0.13[bc]	9.5
52. Spraying in the phase of 3–5 leaves with humate – 800 g/ha + PEO 600 g/ha	6.40 ± 0.14[cd]	17.0
53. Spraying in the phase of 3–5 leaves with humate – 200 g/ha + PEO with glycerine 240 g/ha	6.29 ± 0.13[cd]	15.4
54. Spraying in the phase of 3–5 leaves with sodium silicate – 600 g/ha	6.55 ± 0.14[d]	18.7
55. Spraying in the phase of 3–5 leaves with Pakt – 500 g/ha	6.19 ± 0.13[cd]	14.0
56. Spraying in the phase of 3–5 leaves with Pakt – 1000 g/ha	6.23 ± 0.13[cd]	14.6
57. Spraying in the phase of 3–5 leaves with Pakt – 500 g/ha	6.55 ± 0.14[d]	18.7
58. Spraying in the phase of 3–5 leaves with Pakt – 1500 g/ha	6.39 ± 0.13[cd]	16.7
59. Spraying in the phase of 3–5 leaves with Pakt – 300 g/ha	6.28 ± 0.13[cd]	15.3
60. Spraying in the phase of 3–5 leaves with Pakt – 2500 g/ha	5.97 ± 0.12[c]	10.9
61. Spraying in the phase of 3–5 leaves with Pakt – 250 g/ha	5.74 ± 0.12[bc]	7.3
62. Spraying in the phase of 3–5 leaves with Peram – 100 mL/ha	5.98 ± 0.12[c]	11.0
63. Spraying in the phase of 3–5 leaves with Peram – 200 mL/ha	5.88 ± 0.12[bc]	9.5
64. Spraying in the phase of 3–5 leaves with Peram – 300 mL/ha	6.32 ± 0.13[cd]	16.0
65. Spraying in the phase of 3–5 leaves with Peram – 100 mL/ha + Vympel PGR 500 g/ha	6.44 ± 0.14[cd]	17.4

Note: different letters indicate values that significantly differ one from another in Table 2 according to the results of the Tukey's Test ($P < 0.05$) with the Bonferroni's correction.

Some other researchers, in particular Durval et al. (2014), state that using biostimulator on maize, containing 0.5 g of L-1 indole-butyric acid, 0.9 g of L-1 kinetin and 0.5 g of L-1 of gibberellins acid, increased the diameter of the maize stem, number of grains in the cob grain rows, and number of grains on the cob. However, studies also revealed that this bio-stimulator did not significantly affect the yield of maize due to decrease in mass of grains. This means that although the bio-stimulator promoted certain aspects of growth and development of the plants, it does not always lead to increase in yield through complex interactions between various yield parameters. Results of the study emphasized the necessity of a thorough analysis and consideration of various factors when using bio-stimulators in cultivation of maize to optimize yield and quality of the products.

Plant-growth regulators were observed to be an effective means of introducing intensive technologies of maize cultivation, especially in the conditions of water deficit in soil, as confirmed by the studies by Barbosa et al. (2019). The development of maize and yield largely depends on period of sowing, genotype of plants, and use of growth regulators. The second sowing period, which did not have a water deficit, provided a better development and higher yield of the maize hybrids. Growth regulators such as trinexapac-ethyl and clomazone led to higher yield of maize grain, at the same time reducing height of the plants and their condition. Those results indicate the potential of growth regulators for improvement of efficiency of maize cultivation, especially in the stress conditions due to water deficit. They can be an important component of integrated approaches to enhance yield and resilience of agricultural crops against negative environmental factors.

However, growth stimulators were observed to exert opposite results regarding their efficacy in the study conducted at the Federal University of Lavras, Minas Gerais, Brasil, which evaluated the effects of treatment of seeds with Stimulate® biostimulator (5 mg/kg) and Cellerate® liquid fertilizer (10 mg/kg) (Ferreira et al., 2014). There was observed increased activity of enzymes malate dehydrogenase and catalase in the hybrid seeds that had been treated with high concentration of Stimulate 6 months before sowing, respectively. At the beginning of growth and development of maize plants, there was seen intensive growth of the stem and roots of the maize. At the same time, increase in the Cellerate concentration reduced the germination energy and germination rate after the seeds had been treated prior to sowing. In general, treatment of the seeds had no effect on maize yield in general.

According to the data of Bulegon et al. (2019), use of Azospirillum brasilense and plant regulators did not protect maize from intoxication with the mesotrione herbicide at the initial stage of development, and also did not increase yield. Those results suggest that efficiency of growth stimulators can depend on particular cultivation conditions, including soil type, climatic conditions, and other factors. It is important to conduct further studies and take into account various aspects when using such drugs for optimization of maize cultivation.

Opportunities of increasing maize productivity and optimizing the use of nutrients by applying plant-growth regulators were studied on maize hybrids Pioneer 3906 and Fabregas (Hütsch et al., 2018). At the stage of development of 3–5 leaves, there were used inhibitors of gibberellins biosynthesis – paclobutrazol (PBZ) and chlorocholine chloride (CCC) and gibberellin acid (GA3).

Three weeks after introduction of PBZ, growth of the stems of two maize hybrids significantly slowed, which led to 44% decrease in height of the plants of Pioneer 3906 and 36% decrease in the Fabregas hybrids. Plants with slowed growth had larger area of the leaves and reduced rates of transpiration. Use of GA3 caused greater growth of the shoots, but at the same time there was seen decrease in area of the leaves and increase in the intensity of transpiration a week before blossom. Treatment with CCC had no effect on height of the plants, area of the leaves, and transpiration rates. Use of the PAC growth regulator did not increase the efficiency of using nitrogen, phosphorus, and potassium on maize. There was seen significant improvement of distribution of assimilates in grain, as reflected in the higher yield index.

The indicated statements were also confirmed by our studies. In particular, treatment of maize with growth-regulating substances and microbial fertilizers in the phase of 3–5 leaves led to a significant yield increase, ranging 7.3% to 18.7%, indicating their high efficacy, especially in unfavorable weather conditions. Therefore, the highest increase in grain yield was produced by humate 400 g/ha + PEO 360 g/ha – 1.08 t/ha; humate 800 g/ha + PEO 240 g/ha – 1.19 t/ha; sodium silicate 600 g/ha – 1.23 t/ha; Pakt 500 g/ha – 1.23 t/ha; and Peram 100 mL/ha + Vympel PGR 500 g/ha – 1.12 t/ha. That means, of the sixty seven studied combinations of drugs, we did not determine a variant with increase in grain yield below 0.5 t/ha, and the variants with foliar nutrition of maize were found to have no clear upward tendency in yield from increasing the norms of the introduced PGRs.

Conclusions

The highest efficiency in the maize cultivation technology was produced by treatment of the maize plants with humates in the phase of 3–5 leaves. This promoted a stable upward tendencies, specifically, 5–7 cm (2.1–2.8%) in height of the plants, 5–6% in the area of the leaf lamina and elements of the yield structure (13.6 cm (5.1%) in length of the cob, 18 grains (3.9%) in grain filling of the cob, and 29 g (9.1%) in mass of 1,000 grains) and 1.23 t/ha (18.7%) in grain yield.

According to all the aforesaid parameters, somewhat poorer performance was displayed by the technology of seed coating. In particular, maximum increase in the yield grain amounted to 1.06 t/ha (17.3%). Taking into account the climate changes, continuous emergence of new promising plant-growth stimulators and hybrids of maize, studies in this direction should be further continued to identify the most effective drugs.

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