Acta Agrobotanica

Article ID: 748
DOI: 10.5586/aa.748

Publication History
Received: 2020-09-08
Accepted: 2021-02-27
Published: 2021-06-29

Handling Editor
Iwona Ciereszko; University of Bialystok, Poland; https://orcid.org/0000-0003-2694-7991

Authors' Contributions
OC and OL: performing experiments and analyzing data; MM and VH: designing the experiments, reviewing the manuscript, and performing statistical analysis; VL: collecting and analyzing data; IK: analyzing data and writing and finalizing the manuscript

Funding
This research did not receive any funding. The publication fee was paid by all authors.

Competing Interests
No competing interests have been declared.

ORIGINAL RESEARCH PAPER in PHYSIOLOGY

Weed Control and Winter Wheat Crop Yield With the Application of Herbicides, Nitrogen Fertilizers, and Their Mixtures With Humic Growth Regulators

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Abstract

The aim of the present study was to determine the efficacy of the application of mixtures containing various combinations of humic substances, with herbicides and nitrogen fertilizers, in weed control and optimizing the plant nutrition system. We also aimed to evaluate the influence of these substances on winter wheat productivity. Five Ukrainian winter wheat cultivars ('Kryzhynka,' 'Smuhlyanka,' 'Slavna,' 'Kubus,' and 'Mulan') were sown in a randomized complete block design, with three replications, in the years 2014–2019. The analysis of the effect of the compositions containing herbicides, with various physiologically active substances, in a mixture with humic preparations (Humifield, 4R Foliar concentrate) was performed by counting weeds per square meter in each experimental plot. The best performance in weed control, including perennial species, was obtained from using a mixture of Grodil Maxi herbicide with the humic preparation, Humifield. The crop treatment of this mixture resulted in a 23.6% reduction in weeds, compared to the treatment with the Grodil Maxi herbicide only. At the same time, the complex application of a number of herbicides in a mixture with the humic preparation, 4R Foliar concentrate led to the opposite effect. Various applications of mixtures of humates (4R Foliar concentrate, 5R SoilBoost) with nitrogen fertilizers (ammonium nitrate; carbamide-ammonium mixture) to optimize the winter wheat nutritional system and yield increases have been studied. The highest yield increase of 20%–22% was harvested in the plots treated with 5R SoilBoost and 4R Foliar concentrate plus ammonium nitrate. In addition, the efficacy of wheat crop foliar feeding with mixtures of humates, plus a carbamide-ammonia mixture, in different phases of vegetation has been established. A yield increase of 10.0%–21.4% resulting from the use of such compositions was obtained.

Keywords

tillering phase; pests; stem-extension phase of plants; surface and foliar application; air-dry biomass; perennial weed's species

1. Introduction

One of the ways to improve the technology of crop cultivation is to use chemicals to control biological processes with the help of plant growth regulators (Das et al., 2019; Moumita et al., 2019). The physiologically active substances of plant growth

regulators are both the object and tool of the biotechnologies used in the selection of high-yielding crop cultivars. The use of plant growth regulators, mainly of a humic nature, is an obligatory way for intensive technologies to maximize the genetic potential of plant productivity (Ekin, 2019; Shah et al., 2018; Trevisan et al., 2010). However, the action of these substances is strictly limited by the potential of the plant's genotype (Goryanina, 2019). This is because they are not universal agents that could result in the emergence of some new, noninherent properties of plants. It was established that these substances only help the plant to better fulfill the inherited potential that had previously remained unused in these particular conditions.

The main methods of using humic growth regulators in cereal cultivation are soil application, presowing seed treatment, and foliar application. All of these methods have a positive effect, but the best result is achieved when these methods are applied together. One of the main sources of humic input into the soil is the application of organic composts and fertilizers. In addition to the stimulating effect on the yield, there is also a positive effect on the mechanical, physical, and chemical properties of the soil. However, it is known that the use of organic fertilizers, particularly manure, is much more effective than that of humic agents (Bottinellia et al., 2017; Ihsanullah, 2013; Rose et al., 2014; Sarma et al., 2017; Turgay et al., 2011).

The presowing seed treatment with humates also contributes to better plant growth and development. In this case, we accelerated seed germination and improved root system development, which activates vegetative mass formation. Furthermore, humic acids can exhibit an antistress effect on plants when cultivated in unfavorable soil and weather conditions.

The use of humic acids significantly optimizes seed germination under conditions of salinity stress. Barley and wheat obtained positive results under these conditions. It was found that humic acids reduced the sodium input of plants in soils where their levels were evaluated. The absorption of other elements by plants remained practically unchanged (Jamal et al., 2011; Jarošová et al., 2016). The physiological effects of humic substances are also manifested in the optimization of osmotic processes and the regulation of the photosynthetic pigment content in young plants. In this regard, it is important to maintain the optimal solution concentration of humic substances, particularly fulvic acids (Delfine et al., 2005; Qin et al., 2016).

The foliar fertilization method of applying humic substances, particularly fulvic acid solutions, has a beneficial effect on plants, especially under drought conditions. Furthermore, studies (Muhammad et al., 2013; Zhang et al., 2016) have shown that the use of fulvic acid, along with abscisic acid for the foliar treatment, allowed wheat plants to reduce the evaporation of moisture, better adapt to the conditions of water stress, and provided a 7%–18% yield increase compared to the control. It was established that plant adaptation occurs mainly because of the interstitial conductibility and better balancing of both the aboveground mass and the root mass. However, while the foliar application of humic substances may not have a direct significant impact on the yield, it may exert a positive effect on grain quality, as well as optimize the inflow of macro- and microelements (Akhtar et al., 2015; Knapowski et al., 2015; Rodrigues et al., 2014). A considerable number of treatments and costs related to the application of humic substances can be a serious deterrent for their widespread use in certain soil and climatic conditions. This is because these agents cannot reduce nutritional imbalance in the absence of necessary nutrients (Ibrahim et al., 2016).

Humic substances have also been shown to be effective when used together with herbicides for weed control. Winter wheat is a cereal with a high yield potential. The main factors influencing the yield level are rates and methods of nitrogen fertilizer application, as well as the program of plant protection, which includes methods of weed control (Jańczak et al., 2005). Weed management incorporates agricultural practices that create a balance between cultivated crops and weeds. These practices include both biological and physical methods of weed control (Feledyn-Szewczyk & Jończyk, 2017).

At present, the use of herbicides in weed control has proven to be most effective. The effectiveness of different herbicide doses and foliar fertilization applications

in reducing weed infestation in winter wheat crops was presented in a previous study (Kraska et al., 2009). In that study it was shown the weed infestation level in the winter wheat canopy, measured by the number of dicotyledonous weeds, total number of weeds, and their air-dry weight, was significantly lower in the plots treated with the full herbicide dose, as well as with doses reduced by 25% and 50%. Consequently, the authors indicated the possibility of reducing herbicide doses in a winter wheat crop without the risk of increased weed infestation. At the same time, foliar application of fertilizers did not influence weed infestation levels in the crop canopy.

To the presented properties of humic substances, their ability to improve and accelerate the penetration of the active substance of the herbicide into weed plants should also be noted. In this way, these substances accelerate the destruction of weeds. In this regard, the use of varying compositions of herbicides and humic substances can have a significant effect on weed control (Zargar et al., 2016).

The vast majority of studies have shown that the use of humic substances to increase crop yields has had a positive effect. However, the issues of adapting the regulations for their application regarding the biological characteristics of the crops, soil and climatic conditions, methods and doses for applying the agents, as well as the phases of plant development, remain open.

Therefore, the aim of the present study was to determine the efficacy of the application of mixtures containing various combinations of humic growth regulators, along with herbicides and nitrogen fertilizers, in weed control and the optimization of the plant nutrition system. We also sought to evaluate the influence of these substances on winter wheat yield.

2. Material and Methods

The field experiment was carried out in the years 2014–2019 on the experimental field of the Poltava State Agrarian Academy (Ukraine) with five winter wheat cultivars – 'Kryzhynka,' 'Smuhlyanka,' 'Slavna,' 'Kubus,' and 'Mulan.' All five cultivars are Ukrainian breeds and recommended for cultivation in the forest-steppe zone of Ukraine. The soil used in the experimental plots was black soil with an average humus content of 4.9%–5.2%, pH = 6.3, P_2O_5 content 100–150 mg kg^{-1}, and K_2O content 160–200 mg kg^{-1}. The crop and accounting plot area was 0.32 ha. As the nitrogen content in the soil is low (54.4–81.0 mg kg^{-1}), one uses bean cultures in the main crop rotations, which can provide symbiotically fixed nitrogen. Soybeans were used in the experiments. After soybean harvesting, the stubble breaking with a John Deere 2623 disc harrow at depths up to 10–12 cm was plowed. The wheat was sown in the middle of the second 10-day period of September, without preliminary presowing cultivation, using a Horsch Pronto 6 AS seeder to a depth of 6–7 cm and a seeding density of 500 germinating seeds per square meter.

For the wheat cultivation, the herbicides (Granstar Pro, Grodil Maxi, Prima, Trigger, Tomigan) and humic growth regulators (Humifield, 4R Foliar concentrate, 5R SoilBoost) were used, as presented in Table 1. Ammonium nitrate and a carbamide-ammonia mixture were applied as nitrogen fertilizers.

A field experiment was set up according to a randomized block design with three replications.

The experimental design of this study of winter wheat yields, according to the fertilizer system and growth stimulators, included three directions, each of which contained several variants.

The 'Kryzhynka' cultivar was sown in the first experimental direction. The scheme of the experiment provided for the use of both herbicides only, and their mixtures with the Humifield and 4R Foliar concentrate humic agents for weed control (Table 2). The crops were treated with herbicides only as well as herbicides in a mixture with the humic preparations, Humifield and 4R Foliar concentrate. The process was carried out in the full tillering phase (BBCH 29–30). Chemical protection from pests and diseases during the heading phase (BBCH 50–59) was done using the sprayer, LEMKEN Albatros – 10/4000. This sprayer was equipped with a TeeJet AIXR VP

Table 1 Investigated herbicides and humic growth regulators.

No.	Title	Active substance	Active concentration
1	Granstar Pro	Tribenuron-methyl	750 g kg^{-1}
2	Grodil Maxi	Iodosulfuron + amidosulfuron + Mephenpyr-diethyl (safener)	25 g L^{-1} + 100 g L^{-1} + 250 g L^{-1}
3	Prima	Florasulam + 2-ethylhexyl 2,4-D	6.25 g L^{-1} + 452.5 g L^{-1}
4	Trigger	Tribenuron-methyl	500 g kg^{-1}
5	Tomigan	Fluroxypyr	250 g L^{-1}
6	Humifield	Potassium salt of humic acids	560–720 g kg^{-1}
7	4R Foliar concentrate	Humic acids + fulvic acids + ulmic acids + microelements	55% + 21% + 5% + 6%
8	5R SoilBoost	Humic acids + fulvic acids + ulmic acids + microelements	59% + 20% + 5% + 6%

Note: 1–5 – herbicides; 6, 7 – humic preparations.

Table 2 The effects of the herbicides, and their mixtures with humic growth regulators, on the weed density and winter wheat yield of the 'Kryzhynka' cultivar.

No.	Variants	Doses	Weed quantity 14 days after the treatment			Yield (t ha^{-1})
			Weed quantity (units m^{-2})		Weed biomass (g m^{-2})	
			Total	Perennial weeds		
1	Granstar Pro	20 g ha^{-1}	41.87	2.21	4.93	4.28
2	Grodil Maxi	100 g ha^{-1}	43.66	2.43	5.21	4.28
3	Prima	400 g ha^{-1}	39.83	2.24	5.05	4.14
4	Trigger + Tomigan	25 g ha^{-1} + 0.5 L ha^{-1}	36.92	2.12	5.79	4.30
5	Granstar Pro + Humifield	20 g ha^{-1} + 200 g ha^{-1}	41.87	2.11	5.61	4.19
6	Grodil Maxi + Humifield	100 g ha^{-1} + 200 g ha^{-1}	35.33	1.96	4.96	4.43
7	Prima + Humifield	400 g ha^{-1} + 200 g ha^{-1}	37.11	2.03	4.84	4.22
8	Trigger + Tomigan + Humifield	25 g ha^{-1} + 0.5 L ha^{-1} + 200 g ha^{-1}	39.77	2.13	5.51	4.30
9	Granstar Pro + 4R Foliar concentrate	20 g ha^{-1} + 2 kg ha^{-1}	48.00	2.91	6.76	4.92
10	Grodil Maxi + 4R Foliar concentrate	100 g ha^{-1} + 2 kg ha^{-1}	55.83	2.82	5.44	4.92
11	Prima + 4R Foliar concentrate	400 g ha^{-1} + 2 kg ha^{-1}	53.00	3.18	6.47	4.98
12	Trigger + Tomigan + 4R Foliar concentrate	25 g ha^{-1} + 0.5 L ha^{-1} + 2 kg ha^{-1}	52.77	3.13	6.37	4.97
LSD_{05}			11.2	0.58	1.29	0.34

nozzle. The capacity of one nozzle is 1.97 L min^{-1} at 3 bar pressure. The speed of the sprayer was 10 km h^{-1} and the amount of water used was 250 L ha^{-1}.

The herbicidal efficacy was estimated by counting weeds per square meter in each experimental plot.

The 'Smuhlyanka' and 'Slavna' winter wheat cultivars were used in the second experimental direction (Table 3). In this experiment, we studied the effect of various mixtures of nitrogen fertilizers (ammonium nitrate) with the humic preparations, 5R SoilBoost and 4R Foliar concentrate, on wheat yield and its components. Crop fertilization with granular nitrogen fertilizers (ammonium nitrate) and a humic stimulator (5R SoilBoost) was carried out using the surface method on frozen-thawed soil (BBCH 21–24) with a DN218 spreader.

The 'Kubus' and 'Mulan' winter wheat cultivars were sown in the third experimental direction (Table 4). A liquid mixture of ammonium nitrate and urea

Table 3 The effects of the applied fertilizer system in the winter wheat yield, and yield components of the 'Smuhlyanka' and 'Slavna' cultivars.

No.	Variants	Doses (kg ha^{-1})	PT*	Grain weight per spike (g)*	Thousand-grain weight (g)*	Yield (t ha^{-1})*
1	Ammonium nitrate (control)	200	1.59/1.46	1.61/1.51	42.11/41.31	5.17/4.95
2	Ammonium nitrate + 5R SoilBoost	200 + 11	1.72/1.66	1.72/1.64	42.77/41.75	5.75/5.37
3	Ammonium nitrate + 4R Foliar concentrate + 4R Foliar concentrate	200 + 2 + 2	1.69/1.66	1.82/1.64	42.73/41.62	5.97/5.87
4	Ammonium nitrate + 5R SoilBoost + 4R Foliar concentrate + 4R Foliar concentrate	200 + 11 + 2 + 2	1.78/1.75	1.84/1.77	43.25/42.19	6.32/6.10
LSD_{05}			0.13	0.07	0.67	0.28

* Value before slash refers to 'Smuhlyanka' and after slash to 'Slavna.' PT – productive tillering.

Table 4 The winter wheat yield of the 'Kubus' and 'Mulan' cultivars as influenced by the fertilizer system.

No.	Variants	Doses (kg ha^{-1})	PT*	Grain weight per spike (g)*	Thousand-grain weight (g)*	Yield (t ha^{-1})*
1	CAM (control) + CAM	200 + 100	1.50/1.57	1.61/1.65	41.84/41.95	4.99/5.04
2	5R SoilBoost + CAM + CAM	11 + 200 + 100	1.61/1.66	1.68/1.73	41.98/41.89	5.49/5.45
3	(CAM + 4R Foliar concentrate) + (CAM + 4R Foliar concentrate)	(200 + 2) + (100 + 2)	1.70/1.68	1.74/1.76	42.24/41.89	5.75/5.77
4	5R SoilBoost + (CAM + 4R Foliar concentrate) + (CAM + 4R Foliar concentrate)	11 + (200 + 2) + (100 + 2)	1.76/1.69	1.80/1.77	42.55/42.35	5.93/6.12
LSD_{05}			0.07	0.08	0.72	0.42

* Value before slash refers to 'Kubus' and after slash to 'Mulan.' PT – productive tillering; CAM – carbamide-ammonia mixture.

(carbamide-ammonia mixture), at a rate of 200 kg and 100 kg of nutrients per hectare, was used as nitrogen fertilizer. The study involved a double application of foliar fertilization of a carbamide-ammonia mixture (CAM) only; once at the tillering phase (BBCH 23–28) and again at the stem-extension phase of the plants (BBCH 51–55) (Variant 1). This was also done in the form of a mixture with 4R Foliar concentrate (Variants 3 and 4) applied in a foliar method by the plant sprayer, LEMKEN Albatros – 10/4000.

The humic preparations only and nitrogen fertilizers only (Variant 2) were each applied sequentially, as shown in Table 4 (5R SoilBoost had a surface application and CAM had a foliar application).

The harvest from the accounting area was carried out with a Sampo Rosenlew 580 combine in the full maturity phase with a grain moisture content of 13.8%–14.5%. At the same time as yield account, the grain samples were taken to determine nongrain impurities and harvest moisture. The harvest was designed to have a standard grain moisture content of 14.0%.

The number of individual weeds was counted, while species composition and air-dry biomass of aboveground parts were estimated on the fourteenth day after herbicide application. This was performed on randomly selected areas (1.11 m × 0.30 m) at two nonadjacent repetitions of the experimental variants. After counting and determining the weed species on a single plot, the aerial parts of the plants were cut off, dried under a canopy, and the weed biomass was weighed.

The growing seasons of 2014–2019 had significant deviations from the average long-term means in rainfall intensity and distribution, as well as in temperature. The weather conditions during the experimental years are presented in Figure 1 and Figure 2. The peculiarity of the weather conditions in 2014 was the increase of the average long-term air temperature during spring by 3.1 °C, as well as the reduction of precipitation in July, which was 35.9%. In 2015, the average air temperature during

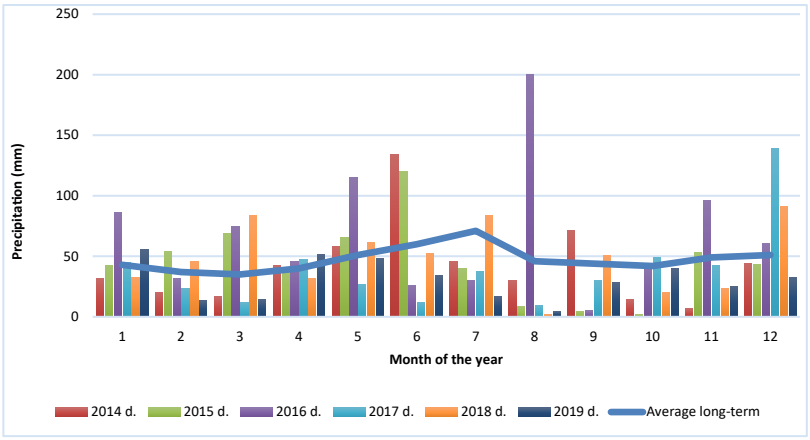

Figure 1 Average monthly precipitation during 2014–2019.

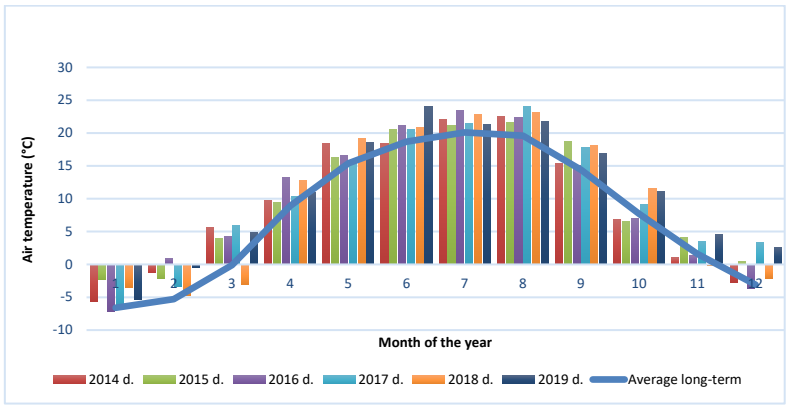

Figure 2 Average monthly air temperature (°C) during 2014–2019.

spring exceeded the long-term indicator by 1.8 °C and the amount of precipitation in July was lower by 43.8%. In 2016, a decrease in precipitation in June and July was recorded, which when compared with long-term data, was 33.9 mm and 40.9 mm, i.e., 56.5% and 57.6%, respectively. Moreover, in 2017 weather conditions were characterized by a significant decrease in precipitation in March (65.7%), May and July (47.6%), and June (80.3%) against the background of increased air temperatures. In general, for the spring period, the lack of moisture was 40.2 mm, i.e., 31.9%. This was also the case for two summer months where the lack of moisture measured 82.0 mm, i.e., 62.6%. Only the meteorological conditions of the 2018 growing season, both in terms of precipitation and temperature, were sufficiently favorable for the growth and development of winter wheat plants. In 2019, the air temperature in the spring period exceeded the long-term average by 2.9 °C, while the amount of precipitation was within the long-term value. Among the summer months, the highest increase of the long-term average air temperature was 4.7 °C measured in June. Regarding precipitation, during the period of the highest moisture consumption by winter wheat plants, June and July, 34.2 mm and 17.1 mm, respectively, of rain actually fell. This is less than the long-term indicator, which is 31.0 mm and 60.0 mm, respectively.

Statistical data processing was carried out using descriptive statistics, regression, and analysis of variance in STATISTICA 10.0 software. The significance of the experimental data was evaluated using analysis of variance (ANOVA) to calculate the least significant difference LSD_{05}.

3. Results

Experiment 1 allowed us to analyze the effect of herbicide action with different active substances (Variants 1–4) and their mixtures, along with the humic agents, Humifield (Variants 5–8) and 4R Foliar concentrate (Variants 9–12). The resulting effect of these treatments was observed on the total number of weeds in the wheat plantings and on the crop yield (Table 2). The dicotyledonous wintering weed species predominated in the winter wheat canopy, particularly *Delphinium consolida* L., *Capsella bursa-pastoris* L. Med., *Matricaria perforata* Mérat, *Viola arvensis* Murr., *Descurainia sophii* L., *Fumaria schleicherii* Soy-Willem, *Galium aparine* L., and *Thlaspi arvense* L. Single plants of dicotyledonous perennial weeds, such as *Cirsium setosum* Willd. and *Convolvulus arvensis* L., were also present in the canopy.

The wheat cultivar 'Kryzhynka' was used in Experiment 1. The results obtained in the experiments showed that the best performing variant was treated with Trigger + Tomigan (25 g ha^{-1} + 0.5 L ha^{-1}) and yielded a total weed quantity equal to 36.92 units per square meter of the field. The highest total number of weeds (43.66 units m^{-2}), including perennial species (2.43 units m^{-2}), was observed after the field treatment with the Grodil Maxi herbicide (100 g ha^{-1}). The effectiveness of this herbicide was 18.3% lower than that of the Trigger + Tomigan combination.

We also studied the different variations of herbicide combination along with humic growth regulators to increase their effectiveness. Humates are known to facilitate better and faster penetration of the active substance of the herbicide into weed plants, which accelerates their destruction.

The addition of 200 g ha^{-1} of the Humifield humic preparation to the Granstar Pro and Prima herbicides had no effect on the number of weeds in the crops, while the Trigger + Tomigan + Humifield mixture had a slight, 7.7%, increase. The most promising results were achieved in the variant treated with the mixture of Grodil Maxi + Humifield. The treatment of crops with this mixture resulted in a 23.6% reduction in weeds when compared to the treatment with the Grodil Maxi herbicide only (Table 2).

However, along with the inhibitory effect of the Grodil Maxi + Humifield mixture, there was also an anti-stress effect of the 4R Foliar concentrate on all the components of agrocenosis. The analysis of the weed number in the variants of Experiments 9–12 shows that the complex application of the herbicide mixtures and this humic preparation leads to the opposite effect. By the time the crop was harvested, the number of weeds in the fields that were treated using the 4R Foliar concentrate with any of the herbicides: Granstar Pro, Grodil Maxi, Prima, or Trigger + Tomigan, was increasing. The most significant increases of 33% and 43% was observed in the weed numbers using the Prima + 4R Foliar concentrate and Trigger + Tomigan + 4R Foliar concentrate mixtures, respectively.

The use of herbicides and their mixtures with humic preparations significantly changed the patterns of coexistence of agrocenosis components. Firstly, this concerns the nature of the correlations between the yield level and the number of weeds per unit area. In the experiments where only herbicides, as well as those in a mixture with the humic preparation Humifield were used, the correlations between these indicators were not found. However, when the 4R Foliar concentrate was a component of the mixture with the herbicide, a direct correlation was observed with a strong relationship between the number of perennial weeds and the winter wheat yield (Figure 3).

This confirms that the humic preparation, 4R Foliar concentrate mixed with herbicides simultaneously stimulated the growth and development of winter wheat plants, and also increased the resistance of weed plants to the destructive action of herbicides. As a result of such use of mixture, the number of weeds in the wheat canopy increased by 9.8%–51.2%, including perennial ones by 16.0%–50.0%, when compared to the plots treated with herbicides only. This, in turn, acted as a limiting factor for the maximum realization of the biological potential of grain crop productivity.

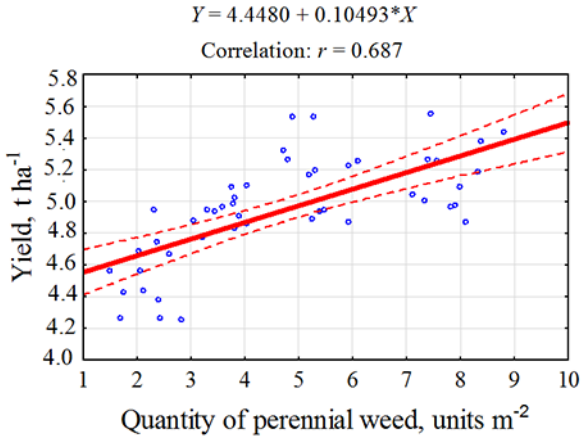

Figure 3 Linear regression graph of weed infestation of a winter wheat canopy cultivar, 'Kryzhynka,' under the mixture of herbicides and 4R Foliar concentrate treatment.

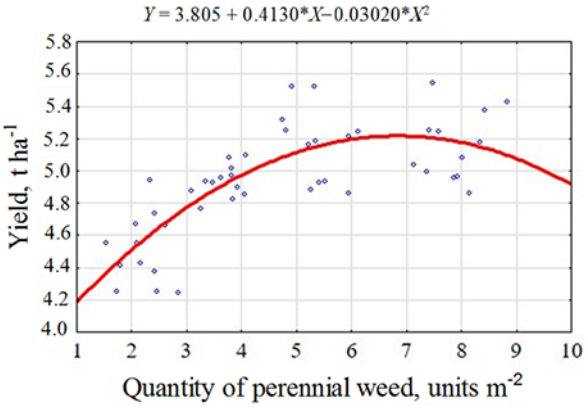

Figure 4 Non-linear regression graph of weed infestation in the winter wheat canopy cultivar, 'Kryzhynka,' under the mixture of herbicides and 4R Foliar concentrate treatment.

To clarify the established dependence, the obtained results were also processed using the nonlinear estimation method. The parabolic type dependence was established, which indicates the positive effect of the growth stimulator, 4R Foliar concentrate on the winter wheat yield (Figure 4). However, at the same time, the use of such a mixture caused the weeds to increase their level of resistance against the phytotoxic action of herbicides.

We studied the relationship of herbicide action with various active substances and their mixtures with the humic agents, Humifield and 4R Foliar concentrate with wheat yield. Analyzing the effectiveness of herbicide-only treatments in the winter wheat canopy, we found that irrespective of the herbicide type and its active substance, almost the same yield (4.14–4.30 t ha^{-1}) was obtained in all the treated variants (Table 2). The highest yield (4.3 t ha^{-1}) was obtained from the combined use of the herbicides Trigger + Tomigan (Variant 4), where the least number of weeds per square meter of field (36.92 units m^{-2}) was observed. However, such a correlation was not naturally determined in all the other herbicide applications.

The use of herbicides in the mixtures with Humifield (200 g ha^{-1}) was almost ineffective towards the level of crop yield. However, a significant yield increase was observed in the plots sprayed with herbicide mixtures, along with the 4R Foliar concentrate, at a dose of 2.0 kg ha^{-1} (Variants 9–12). The yields of these variants were approximately the same (4.92–4.98 t ha^{-1}), but it was much higher than in the plots treated with herbicides only (4.14–4.30 t ha^{-1}). As can be seen from the data given above, the yield increase is, on average, 16.5% with the use of herbicide

compositions that included the 4R Foliar concentrate humic preparation. The highest yield increase of 20.3% was obtained when treating winter wheat crops with the mixture of Prima + 4R Foliar concentrate despite the highest number of weeds (53.00 units m^{-2}, including perennials, 3.18 units m^{-2}) observed in this plot.

Regression analysis showed an inverse relationship between the air-dried weight of weeds and the winter wheat yield ($r = -0.64–0.69$). It also confirmed the significant negative effect of the degree of development of weed vegetative mass on the state of winter wheat crops under unstable moisture conditions.

In Experiments 2 and 3, we investigated the possibility of using humates to optimize plant nutrition systems by surface application and spraying the leaf-stem mass with combinations of nitrogen fertilizers and humic preparations.

In Experiment 2, ammonium nitrate was used as the nitrogen fertilizer and wheat cultivars, 'Smuhlyanka' and 'Slavna' were used as the test crops. Pure ammonium nitrate (200 kg ha^{-1}) was applied only to the control plot. The experimental scheme is presented in Table 3.

As can be seen from the data given in the above-mentioned table, the use of 5R SoilBoost granular growth regulator, at the rate of 11 kg ha^{-1}, in the mixture with 200 kg ha^{-1} of ammonium nitrate increased the yield of 'Smuhlyanka' by 11.2%. Foliar fertilization of 4R Foliar concentrate (2 + 2 kg ha^{-1}) was applied twice during the growing period and, along with the ammonium nitrate application, led to an increase of the wheat yield of the 'Smuhlyanka' cultivar by 15.5% (Variant 3). The highest yield increase (22.2%) was due to the foliar treatment of crops with the 4R Foliar concentrate. This humic preparation at a dose of 2 kg ha^{-1} was introduced twice; once at the tillering phase and again at the early earing phase, along with ammonium nitrate and 5R SoilBoost (Variant 4).

A similar pattern was observed in the variants of the experiment with the 'Slavna' wheat cultivar. In Variant 4, the fertilizer system turned out to be the most effective. The yield of the 'Slavna' wheat increased by 23.2% compared to that of the control (4.95 t ha^{-1}).

As shown in Table 3, the treatment of 'Smuhlyanka' and 'Slavna' wheat crops, with the mixtures presented in Variant 4, contributed to yield increases of 22.2% and 23.2%, respectively, when compared to the yield of the control plot. Furthermore, the grain yield of the 'Smuhlyanka' cultivar rose by 12% due to the increased productive tillering and grain weight per spike increased by 14.3%. Meanwhile, the 1,000-grain weight contributed to a grain yield of 2.7%. A similar dependence was observed for the 'Slavna' cultivar. A 20% increase of productive tillering and a 17.2% increase in grain weight per spike created conditions that were conducive to a higher yield of this wheat cultivar. Notably, the 1,000-grain weight had a relatively low contribution (2.1%) to the yield components (Table 3).

In Experiment 3, a liquid carbamide-ammonia mixture (CAM) was used as a nitrogen fertilizer, and 'Kubus' and 'Mulan' wheat cultivars were used as the test crops. The control plot was treated with a carbamide-ammonia mixture. The experimental scheme is presented in Table 4.

The carbamide-ammonia mixture is a fertilizer with a large number of advantages over solid nitrogen fertilizer. These include: an even fertilizer application to the soil, minimal nutrient loss, and reduced environmental pollution. With three forms of nitrogen in its content, CAM, unlike ammonium nitrate, can provide prolonged plant nutrition with nitrogen in the forms of nitrate, ammonium, and amide. As a result of soil microorganism activity, the amide nitrogen is converted to the ammonium form and then to the nitrate form. Furthermore, due to the absence of free ammonia in the CAM, it does not evaporate into the atmosphere when applied to the soil.

The creation of different CAM mixtures with humic preparations that had a foliar application method increased the yield of both wheat cultivars (Table 4). Thus, the 'Kubus' winter wheat cultivar, having a top dressing in the frost and thawed soil with 5R SoilBoost (11 kg ha^{-1}), increased the grain yield by 10%, while the 'Mulan'

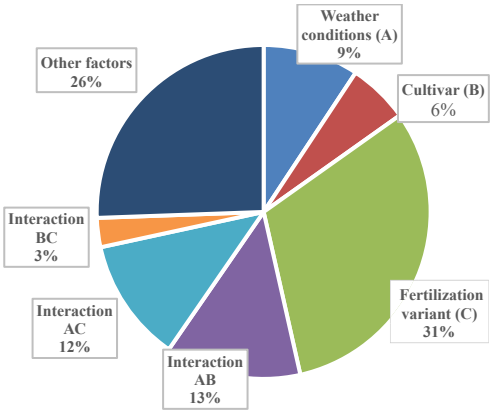

Figure 5 The factors affecting the productivity tillering formation of the wheat cultivars' agrobiocenosis.

cultivar increased by 8.1% (Variant 2) when compared to the control (CAM). Foliar fertilization of wheat crops with 4R Foliar concentrate, in combination with CAM at the tillering phase and the early earing phase (2 kg ha^{-1}), increased the yield of the 'Kubus' and 'Mulan' cultivars by 15.2% and 14.5%, respectively. The highest yield increase of the 'Kubus' and 'Mulan' wheat cultivars (18.8% and 21.4%, respectively) was obtained from the application of 5R SoilBoost (11 kg ha^{-1}) soil activator and a treatment of 4R Foliar concentrate mixed with the CAM liquid nitrogen fertilizer that was applied to the foliage twice.

The results presented in Table 4 determine the effect of wheat treatments with the mixtures of humic preparations, and a carbamide-ammonia mixture, on the main components of the yield using the 'Kubus' and 'Mulan' wheat cultivars as examples. It can be assumed that the cultivar qualities of these crops ('Kubus' and 'Mulan') are less sensitive to this variety of fertilizer as the yield increase was only 11.8% and 7.3%, respectively. However, an insignificant yield increase of these wheat cultivars that were fertilized with the mixtures presented in Variant 4, was determined by the spike density per unit area, the grain weight per spike, and to a lesser extent, by the 1,000-grain weight (1.7% for the 'Kubus' cultivar and 0.9% for the 'Mulan' cultivar).

The effect of different variants of fertilization on yield components and their contribution to the grain yield per unit area were also evaluated in this study. The key component of wheat yield is productive tillering, defined as the number of tillers that produce spikes and seeds. The results of the dispersion analysis showed that productive tillering is the characteristic most sensitive to the growing factors. The share of the influencing factors, including cultivar properties (6%), fertilization variant (31%), meteorological conditions (9%), and the interaction of all factors (28%) in this indicator formation was 74% (Figure 5).

An important component of the yield structure is the grain weight per spike. The level of plant mineral nutrition, along with weather conditions and cultivar properties, are the main factors affecting the formation of this yield component. According to the dispersion analysis in our study, we found that weather conditions had the greatest impact on grain weight per spike (42%). The effect of cultivar properties, fertilization method, and the interaction of all factors on this indicator was 35% of the trait dispersion (Figure 6).

Thus, the yield diagram has a much more differentiated appearance, leading to the conclusion that the effect of the weather conditions on the yield formation of the studied wheat cultivars is most significant (76%), as shown in Figure 7. This differentiation is explained by the complex system of direct correlations between the yield and its components, which are characterized by weak or medium strength (Table 5).

Figure 8 shows the yield equations of the studied wheat cultivars and the graphs of yield dependence on productive tillering and grain weight from the spike.

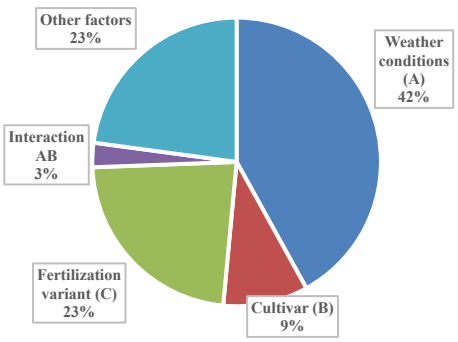

Figure 6 Factors affecting the formation of grain weight per spike.

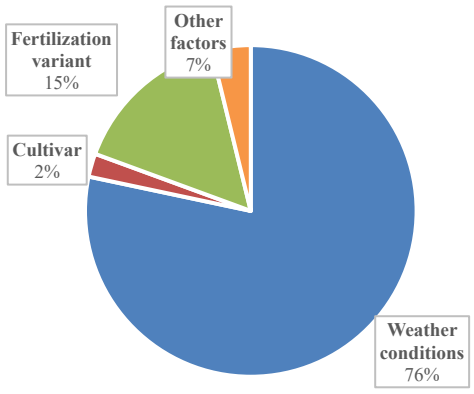

Figure 7 Factors affecting the formation of the winter wheat yield.

Table 5 Correlation coefficients between yield and its components.

	Plant densities (mln ha^{-1})	Productive tillering (stem plant^{-1})	Stem density (stems ha^{-1})
Plant densities (mln ha^{-1})	-	0.19	0.24
Productive tillering (stem plant^{-1})	0.19	-	0.21
Stem density (stems ha^{-1})	0.24	0.21	-
Grain weight per spike (g)	-	0.65	0.25
Thousand-grain weight (g)	-	0.32	0.25
Yield (t ha^{-1})	-	0.28	0.42

Theoretically, the presented equation has the form of a quadratic function; however, in the conditions of unstable and insufficient moisture, the linear dependence is most often observed (Figure 9). The lack of moisture and its uneven distribution do not allow the plants to form an abundant number of sprouts or excess grain weight from the spike.

4. Discussion

In the present study, the effects of the studied factors, namely the use of fertilizers containing various combinations of humic growth regulators with herbicides and nitrogen fertilizers, on weed infestation as well as the yield and its components, largely depended on the composition of the mixtures and the timing of their application, rather than on cultivar properties of culture. However, the greatest

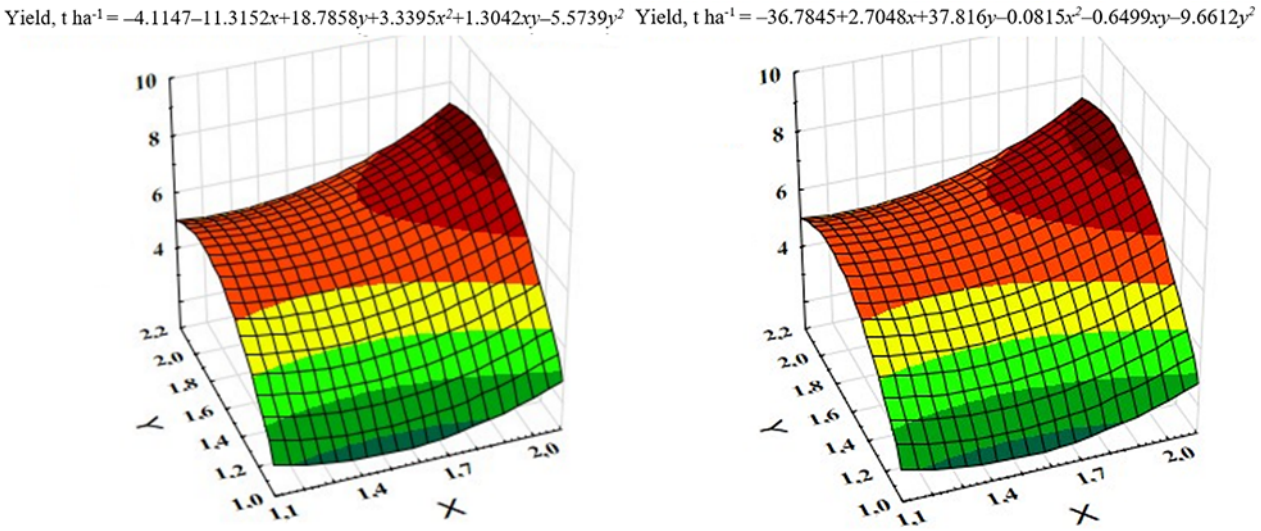

Figure 8 The regression graph of the winter wheat yield, depending on the elements of the yield structure, for the 'Smuhlyanka' and 'Slavna' (left) and 'Kubus' and 'Mulan' (right) cultivars. Note: *X* – productive tillering; *Y* – grain weight per spike (g).

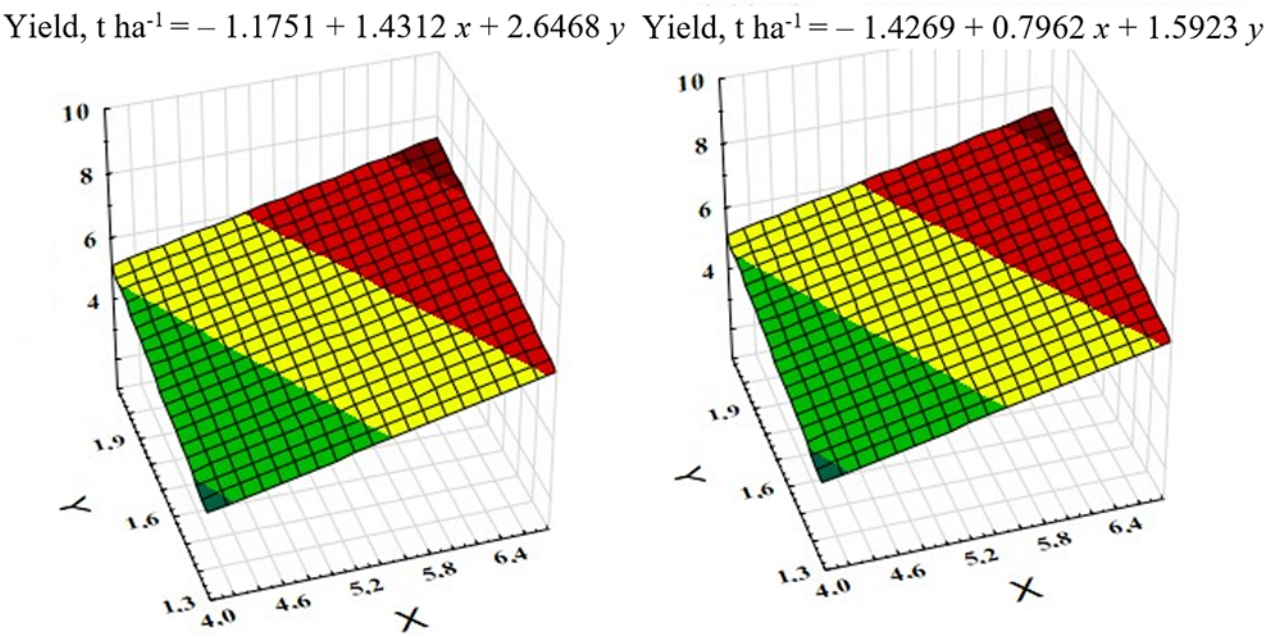

Figure 9 The graphs of the winter wheat yield depending on the elements of the yield structure under the conditions of unstable moisture for the 'Smuhlyanka' and 'Slavna' (left) and 'Kubus' and 'Mulan' (right) cultivars. Note: *X* – productive tillering; *Y* – grain weight per spike (g).

impact on productivity was made by weather conditions (mainly temperature and precipitation) (Figure 1, Figure 2).

The results of our research show considerable efficiency of herbicide only applications in weed elimination and the absence of a direct correlation with wheat productivity. On the plot that was treated with only herbicides (Trigger + Tomigan) at the rates shown in Table 2, the total weed number, including perennial weeds, was the lowest. This treatment also positively affected the yield, which was 4.30 t ha^{-1}. This was the highest yield among the plots where only herbicides were used. Notably, the number of weeds on the plot treated with the herbicide Grodil Maxi was the highest, but the yield essentially remained at the same level (4.28 t ha^{-1}).

The ambiguous effect of crop treatment using mixtures of herbicides with Humifield and 4R Foliar concentrate humic substances should be noted. Adding Humifield to herbicides strengthened the herbicidal action, assisted in weed reduction, and increased productivity. However, when a mixture of herbicides with 4R Foliar concentrate was used, the number of weeds increased considerably, but the productivity, on an average of 16.5%, grew simultaneously.

The absence of a significant effect on the level of weed infestation in the winter wheat canopy when a mixture of herbicide with bromoxynil and the humic growth regulator, Crop Booster was used has been noted in a previous study (Soltani et al., 2015). Similarly, the authors of other studies (Kraska et al., 2009) did not observe any effect of applications with the foliar fertilizers, Insol 3 and FoliCare on the weed infestation level in the wheat canopy. Foliar fertilizers Insol 3 (1 L ha^{-1}) and FoliCare (20 kg ha^{-1}) were applied at the full recommended doses twice during the growing season (BBCH development stage 23–25 and 33–35).

Nevertheless, the application of humic substances reduced the negative effect of some herbicides. For example, the sulfonylurea herbicide Granstar Pro increased wheat yield by 22.5%, as shown in Bezuglova et al. (2019).

Among the many reasons for the low yield of grain crops, in addition to weed infestation, many researchers point to a low level of soil organic matter due to the indiscriminate use of mineral fertilizers, which disrupts the soil's chemical composition. However, the benefits of the application of humic substances were successfully demonstrated for barley and wheat cultivation in a previous study (Marenych et al., 2020). Presowing seed treatment of these crops with Ultra Boost for seeds (31% humic acid, 5.6% fulvic acid, and 1.83% ulmic acid) and 1R Seed treatment (10% humic acid, 3% fulvic acid, and 1% ulmic acid) at a rate of 1 kg t^{-1}, contributed to an increase in barley yield by 8.8%–12.7% and wheat by 28.3%.

However, the greatest efficiency of humate action can be achieved by combining them with mineral fertilizers, because they increase the utilization of nutrients from mineral fertilizers. Therefore, it was shown that the combination of fertilizers containing humic acid, NPK, zinc, sulfur, and manganese has a significant effect on the biological yield of wheat, which saw an increase of 48.6% (Ahmad et al., 2018).

To solve the problem of low efficiency of grown crops, various methods of application and a variety of combinations of mineral fertilizers and humic acids can be used. Using corn crops, Aziz et al. (2019) applied various doses (2 kg ha^{-1}, 3 kg ha^{-1}, and 4 kg ha^{-1}) of humic acid, phosphorus, potassium, and nitrogen (half of the nitrogen was applied at the time of sowing, and the remaining half was applied at the second and third irrigation, respectively). This method of introducing mineral fertilizers, in combination with various doses of humic acid, resulted in an increase in corn yield by 58.2% in the plots where the highest dose of 4 kg ha^{-1} of humic acid was applied.

The relationship between the yield of various doses of potassium (K) (0, 1, and 2 kg ha^{-1}) in K_2SO_4 (50% K_2O) fertilizer, when used together with different doses of humic acid (0, 2, and 4 kg ha^{-1}) (85% HA), was reported by Dinçsoy and Sönmez (2019). The highest biological and grain yields were detected when humic acid and potassium were applied at rates of 4 kg ha^{-1} and 1 kg ha^{-1}, respectively. Meanwhile, the yield increases were 36.83% (biological yield) and 14.74% (grain yield).

To confirm the effectiveness of the complex use of humic acid and various doses of urea in wheat cultivation, Anwar et al. (2016) analyzed the yield and yield components in plots treated with various doses of humic acid only, various doses of urea, and their complex application. For each fertilizer application variant, the yield increase was 10% when treated with humic acid (15 kg ha^{-1}) only, and 86.7% with 150 kg ha^{-1} nitrogen application. The application of humic acid at a rate of 15 kg ha^{-1}, and nitrogen fertilizer at a rate of 150 kg ha^{-1}, showed a significant (44.4%) increase in biological yield, while the grain yield increased twofold relative to the control (without fertilizers). The effectiveness of the application of humic acid

and urea at the indicated doses, relative to the treatment with only nitrogen fertilizers, was estimated by the yield, which increased by 4.6%.

In our experiment, the use of humic mixtures with nitrogen fertilizers had a significant effect on increasing the grain yield per unit area. The data in Table 3 and Table 4 show the significant effectiveness of the mixtures used in the study, both in grain yield and its components. The increase in grain yield in the plots treated with mixtures of nitrogen fertilizers with various humic growth regulators was 22.2%–23.5% compared to plots treated with only ammonium nitrate (200 kg ha^{-1}) and 18.8%–21.4% when a mixture of only carbamide-ammonium was applied.

Many authors have indicated that the effect of yield components on yield quantity cannot be unambiguously determined, and a precise determination of optimal crop parameters is difficult because of the specific properties of cultivars and different cultivation conditions. Dogan (2009) reported that the grain number per spike has a positive effect on yield. In some papers on both spring and winter wheat, the negative correlation between 1,000-grain weight and the number of grains per spike has been emphasized (Harasim et al., 2016).

In our experiment, all three components of the yield: Spike density per unit area, number of grains per spike, and 1,000-grain weight, affected the increase in the yield of growing wheat cultivars on the plots treated with the mixtures of humic growth regulators and nitrogen fertilizers.

5. Conclusions

The most efficient forms of herbicide application for weed control in winter wheat canopies are mixtures with humic substances. Furthermore, the efficacy of winter wheat treatment with the proposed mixtures for optimizing the nutrition system of plants and increasing crop yields was shown. It was found that all three yield components (spike density per unit area, number of grains per spike, and 1,000-grain weight) positively influenced winter wheat productivity. Moreover, winter wheat yield was found to be significantly dependent on the weather conditions that occurred during the study period.

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