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Effects of plant density and fertilisation on yield structure and yield elements of maize hybrids for biofuel production

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ABSTRACT

The article presents the results of studies of the influence of plant density and fertilisation on growth and development processes, elements of the yield structure and yield of maize hybrids of different maturity groups. These studies need to be optimised by taking into account new forms, application rates and timing of their application according to the stages of organogenesis and maturity groups of maize hybrids and their biological requirements. The highest linear measurements of plant height and cob attachment compared to the control variant ($t_f > t_{t0.05}$) were observed at the maximum intensification of technological methods of maize cultivation in the experimental variant with the combined application of zinc sulfate, ecoline zinc and ecoline boron on the background of $N_{100}P_{31}$, and plant density from 60 to 80 thousand plants/ha. plants/ha, which in maize hybrids DCS 3795 increased from 5.7 to 9.2%; DCS 3972 from 9.5 to 12.5%; DCS 4351 from 2.3 to 4.5%, respectively. As well as the highest water content of the cob of maize hybrids, which at a plant density of 60–80 thousand plants/ha was higher compared to the control variant ($t_f>t_{t0.05}$) in DCS 3795 by 30.0–32.0%; DCS 3972 by 28.5–35.0%; DCS 4351 by 32.7–33.2%. The highest yield increase was in maize hybrids compared to the control variant ($NIR_{0.05}$ fertiliser = 0.11 t/ha): DCS 3795–3.53 (42.1%), 3.79 (43.7%), 3.8 t/ha (44.6%); DCS 3972–4.16 (44.3%), 4.60 (47.2%), 4.24 t/ha (45.3%); DCS 4351–4.23 (45.2%), 4.0 (44.0%), 3.42 t/ha (40.6%), respectively. Thus, the highest yields were recorded for maize hybrids DCS 3795–8.67 and DCS 3972–9.74 t/ha at a density of 70 thousand plants/ha, and for hybrid DCS 4351–9.35 t/ha at a density of 60 thousand plants/ha.

Keywords: hybrids, maize, fertiliser, plant density, nitrogen, phosphorus, zinc sulphate, Ecoline Boron.

INTRODUCTION

Maize is one of the main grain crops in Ukraine and in the world, and its production is of interest to the food, processing, medical microbiological, brewing industries, as well as the fuel and energy sector of the country, as it is a high-energy feedstock for industrial bioethanol production (Rybka, 2010; Bogomaz, 2024).

Increasing corn productivity is possible only through intensification and biologisation of technology, which involves the use of the genetic and adaptive potential of the hybrid, the use of macro- and microelements, and adjusting plant density. These issues are particularly relevant in the context of global climate change, the shortage of organic fertilisers and the high cost of mineral fertilisers.

Given the undoubted importance of the known scientific developments on the study of the problems of growing corn for grain, taking into account an integrated approach to assessing the adaptive properties of hybrids, elements of technology and features of starch accumulation in grain will allow a qualitative assessment of the possibility of bioethanol production. After all, it is grain corn that has the highest ethanol yield per unit of production among cereals. The starch content in grain depends on both varietal characteristics and the technology of growing grain corn. Therefore, the development of a set of technological elements that increase the yield and quality of corn grain will ensure maximum starch yield for bioethanol production (Kamenschuk, 2012).

The yield of bioethanol from feedstock is usually calculated as ethanol yield. The ethanol yield is the amount of ethanol obtained from a ton of nascent carbohydrates in terms of starch. The theoretical yield is calculated using the alcoholic fermentation equation:

$$C_6H_{12}O_6 = 2C_2H_5OH + 2CO_2 \quad (1)$$

At the relative density of ethanol d420=0.78927, its theoretical yield is 54.79 liters (Blum at al., 2010). The yield of bioethanol depends primarily on the starch content of the grain, which in turn is determined by the maturity group, hybrid subspecies and cultivation technology. The higher starch content of mid-early and mid-season hybrids compared to early-season hybrids is explained by the fact that they are represented to a greater extent by the toothed subspecies, whose grain contains more starch (Dudka, 2012).

The starch content in the grain depended on the time of sowing. The early sowing period has a lower starch content, and the late sowing period has a higher starch content (Korchagina, 2011).

The use of biofuels and other renewable energy sources is considered and discussed primarily in the context of environmental protection and the desire to guarantee conditions for sustainable regional and local development (Polishkevych, 2011). The development of alternative energy sources opens up new prospects for corn on the Ukrainian market and the expansion of the area under cultivation in all regions favourable for its cultivation (Kamenschuk, 2012).

In the context of climate change and global warming, it is important to substantiate, develop and implement agrotechnical measures that help mitigate the negative effects of drought, heat and soil moisture deficit. Comprehensive zonal agronomic measures include methods and timing of sowing, as well as plant density and other technological factors (Dudka and Yakunin, 2023).

Due to their high biological plasticity, maize plants provide a high compensatory capacity for the implementation of individual productivity in interaction with environmental conditions. Corn provides high yields only when sufficient fertiliser is applied (Dudka and Yakunin, 2023; Lavrynenko et al., 2016; Marchenko et al., 2019).

There are several ways of applying fertilisers: basic, pre-sowing, and top dressing. It should be noted that the main nutrients for corn are nitrogen, phosphorus, potassium, zinc, magnesium, sulphur, boron, and copper (Palamarchuk and Demchuk, 2021; Palamarchuk and Telekalo, 2018; Kumar et al., 2007).

The highest starch content and its yield per unit area was provided by double foliar feeding of all hybrids with micronutrient fertilizer Ecolist Mono Zinc. The use of nutrients leads to an increase in the content of starch in corn grain from 70.5% to 71.68%, fat – from 3.12% to 3.50%, as well as nitrogen (from 1.58% to 1.68%), phosphorus (from 0.21% to 0.24%) and potassium (from 0.36% to 0.39%). (Palamarchuk and Demchuk, 2021).

Maize is sensitive to both macro- and micronutrients, especially zinc (Zn), manganese (Mn), copper (Cu) and boron (B). Nitrogen is a vital element for plants and the main determinant of corn yield. Its availability in sufficient quantities during the growing season is essential for optimal plant growth (Rahimizadeh et al., 2010; Mazur et al., 2023; Mazur et al., 2024).

Mineral fertilisers themselves have a heterogeneous effect on growth, vegetation and reproductive quality. For some periods, nitrogen is important, in particular in the early stages before the active stem growth phase, while for other stages, phosphorus and potassium are important, in particular for the phenostases of male and female inflorescence formation and grain filling (Pavlichenko and Grabovsky, 2022; Pavlichenko, 2022).

However, the use of traditional mineral fertilisers alone is insufficient, as plants have a high demand for micronutrients, the market for which is currently developing rapidly as the content of available forms of micronutrients in soils is decreasing (Hovenko and Antal, 2022). It has been found that corn absorbs a significant amount of trace elements during the growing season: up to 80 g/ha of manganese, 350–400 g/ha of zinc, about 70 g/ha of boron, and 50–60 g/ha of copper (Pavlichenko and Grabovsky, 2022).

Boron ensures the uninterrupted supply of carbohydrates and starch from the leaves to other plant organs, including the kernel, while the corn stalk itself does not contain starch. Concentrated in the nucleus and mitochondria, zinc participates in cell division and mitochondrial formation, affects the synthesis and content of hydrocarbons (starch), phospholipids, organic acids, phenols, and accumulates in young tissues and embryos (Yaroshko, 2014).

There are two important stages in the development of maize plants (critical phases) in terms of macro- and microelements: three to five and seven to eight leaves (Voloshchuk et al., 2019; Yatsenko et al., 2023; Mostovenko et al., 2022).

Scientists have found that about 60% of Ukrainian soils are characterised by low availability of mobile forms of zinc, which can lead to a limitation of corn yield potential and, in some cases, to a decrease in immunity and diseases (Polianchykov et al., 2017).

Thus, a single application of even the most optimal dose of fertiliser in all respects is virtually impossible to provide plants with the necessary microelements during the growing season (Branitskyi et al., 2022; Myronova et al., 2023; Vdovenko et al., 2024; Korobko et al., 2024; Mazur et al., 2023; Mazur et al., 2024). This is a prerequisite for obtaining the planned yields of maize hybrids with appropriate seed quality to maximise the starch yield per unit of feedstock for bioethanol production.

The objective of the research was to determine the effect of fertilisation, foliar feeding and crop density on the growth and development of maize hybrids, and the formation of grain productivity and yield elements.

MATERIALS AND METHODS

The technology for growing maize hybrids is generally accepted for the soil and climatic conditions of the zone. Plots are randomised, replicated four times. The area of the accounting plot is 50 m^2 (Vovkodav, 2001).

The research was carried out in the conditions of FLORA A.A. in Kryzhopil in 2023 and 2024. In 2023, hydrothermal conditions were quite favourable for the growth and development of corn. Intensive precipitation in spring allowed for significant replenishment of moisture reserves, and precipitation that also occurred during the growing season contributed to the intensive growth processes of this crop. The hydrothermal conditions in 2024 were not entirely satisfactory for the growth and development of maize plants. This was due to high temperatures during all months of the growing season, including 9.9 °C in April, 14.7 °C in May, 19.0 °C in June, 20.9 °C in July, 21.3 °C in August, and 14.8 °C in September. The average temperature was 17 °C. This is 2.5 °C higher than the long-term average temperature and 0.8 °C higher than the temperature in 2023.In addition, it should be noted that precipitation in 2024 was lower than in many years compared to the long-term average in most months of the growing season. In particular, in April, there was 13.2 mm less precipitation compared to the long-term average, in July 30.8 mm less, in August 40.4 mm less, and in general, during the growing season, there was 64.5 mm less precipitation compared to the long-term average and 72.5 mm less compared to the conditions in 2023.

According to the modern classification, the soil of the experimental plot where the research was carried out is podzolised, warm, shortly freezing medium loamy chernozem. The relief is flat. The reaction of the soil solution in the salt extract is close to neutral 6.8–7.1. The amount of absorbable bases is 33–39 mg/eq. per 100 g of soil with a predominance of calcium. Absorbed sodium is very low – 0.5–1.5 % of the absorption capacity. The soil is clayey and loamy, has a fine-grained structure, is easy to cultivate, has good air permeability and moisture capacity, and is capable of accumulating significant moisture reserves. The content of total nitrogen in horizon A is 0.23–0.26%, and its total reserve is 20–30 t/ha, of easily hydrolysed nitrogen – 60–110 mg per 1 kg of soil, and of nitrified nitrogen – 30–40 mg/kg of soil. These data indicate that the soil is well supplied with total nitrogen. The chernozem soils have mostly low levels of mobile phosphorus – 15–20 mg/kg of soil, although the gross amount of phosphorus is high at 0.18–0.24%. The content of exchangeable potassium in these soils is quite high – 300–350 mg/kg of soil. In general, the soil of the experimental plot is favourable for crop cultivation in terms of fertility, mechanical composition, physical and chemical properties.

According to the research methodology, a three-factor field experiment was laid out in the conditions of FLORA A.A. in Kryzhopil village in 2023 and 2024: Factor A – hybrids: 1. DKS 3795 (FAO 250); 2. DKS 3972 (FAO 300); DKS 4351 (FAO 350). Factor B – seeding rates: 1. 60 thousand/ha; 2. 70 thousand/ha; 3. 80 thousand/ha. Factor C – fertilisers: 1. Control (no fertilisers); 2. N-100, P-31 (background); 3. Background + zinc sulphate (8 kg/ha before cultivation); 4. Background + ecoline zinc (1 litre/ha at the microstage BBCH 14–15); 5. Background + zinc sulphate (8 kg/ha before cultivation) + ecoline boron (1 l/ha at the microstage of BBCH 61–63); 6. Background + zinc sulphate (8 kg/ha before cultivation) + ecoline zinc (1 litre/ha at microstage bbch 14–15) + ecoline boron (1 litre/ha at microstage BBCH 61–63).

The determination of linear plant measurements: total height, cob height, and structural analysis of the crop (10 cobs in each replication), was carried out according to generally accepted methods for for maize (Lebid at al., 2008).

Determination of the weight of 1000 grains. It was carried out according to the methodology. Two samples of 500 grains were taken. They were weighed on a laboratory balance with further calculation according to DSTU 4138-2002 (DSTU 4138-2002).

Harvest accounting. It was carried out by continuous threshing of grain from each plot with subsequent conversion to 100 per cent purity and 14 per cent basic moisture content (Vovkodav, 2001). The experimental data were processed using dispersion, correlation and regression methods of analysis on a personal computer using special application programmes for Windows - 2003/2010: Excel-7.0, Mathcad 2000 (Moiseychenko and Yeshchenko, 1994).

The method of small samples was used to determine the arithmetic mean values (x) and the deviation of the arithmetic mean values (± Sx). The data in the tables are presented in the form of x ± Sx (mean ± standard deviation). Statistical evaluation of differences was performed using Student's t-test. The difference was considered significant if the calculated criterion for the reliability of the difference (experimental) is equal to or exceeds the standard value of the Student's t-test. The results of the average values were considered statistically significant at * $P < 0.05$ (Moiseychenko and Yeshchenko, 1994).

RESULTS AND DISCUSSION

During two years of research, it was found that the lowest linear measurements of plant height and head height, as well as their ratio, were observed in the control variant (without fertilizers) at a plant density of 60 thousand plants/ha. In hybrids: DKS 3795 – 198.5; 86.0 cm; 0.43; DKS 3972 – 211.0; 94.0; 0.45; DKS 4351 – 221.0; 97.0; 0.44 (Table 1).

The maximum increase in plant density to 80 thousand plants/ha provided, as in the variant (70 thousand plants/ha), an increase in linear measurements of plant height and head attachment in hybrids, which was more significant than in the previous variant: in DCS 3795 by 2.3 and 2.4%; DCS 3972 – 2.0 2.6%; DCS 4351 – 2.0 and 2.5%. The application of mineral fertilisers in the norm of $N_{100}P_{31}$ provided a more significant increase in plant height and head attachment compared to the control (t_f>$t_{t0.05}$) with an increase in density from 60 to 80 thousand plants/ha in hybrids: DKS 3795 by 6.4 and 6.5%; 6.1 and 6.5%, 2.3; 6.5 and 6.9%, 2.3%; DKS 3972 – 5.8 and 6.0%; and 5.5 and 5.4%; 5.5 and 5.9%; DKS 4351 – 3.7 and 5.4, 2.2%; 3.0 and 5.7, 2.3% and 3.0; 6.1, 4.3%.

The application of zinc sulphate (ZnSO4) on the background of $N_{100}P_{31}$ provided a significant (t_f>$t_{t0.05}$) increase in linear measurements of plant height and head attachment with an increase in plant density from 60 to 80 thousand plants/ha in hybrids compared to the control variant: DKS 3795 by 8.9 and 8.5% and 9.0 and 9.3, 2.3%; 8.6 and 9.3, 2.3%; DKS 3972 by 7.5 and 8.3%; 7.2 and 7.7%; 7.1 and 8.1%; DKS 4351 by 5.0 and 6.7, 2.3%; 3.9 and 7.9, 4.4% and 4.1 and 7.9, 4.4%. Our results are to some extent confirmed by other scientists who claim that maize plants are very sensitive to zinc (Zn) deficiency (they can withstand a yield of 350–400 g/ha) (Dolomanov, 2015). However, taking into account the insignificant increases from 2.3 to 9.3% of linear measurements of plant height and ear attachment and their ratio, we can assume that the soil of the experimental plot is provided with a certain amount of zinc.

Compared to the previous variant of application, ecoline zinc on the background of $N_{100}P_{31}$ provided a slight decrease in linear measurements of plant height and head attachment and varied from 2.3 to 9.2%, which, in our opinion, is due to the smaller amount of its application per ha compared to the previous variant of research. The highest significant (t_f> $t_{t0.05}$) increases in linear measurements

Table 1. Plant height and cob attachment (cm), as well as their ratio in maize hybrids depending on plant density and fertiliser, by 2023–2024

Hybrid (factor A)	Fertiliser (factor C)	Plant density, thousand plants/ha (factor B)								
		60			70			80		
		1	2	3	1	2	3	1	2	3
DCS 3795	Control (without fertilizers)	198.5±2.2	86.0 ±1.1	0.43±0.01	201.0±2.2	87.0±1.1	0.43±0.01	203.0±2.2	88.0±1.1	0.43±0.01
	$N_{100}P_{31}$ (background)	212.0±2.3*	92.0±1.2*	0.43±0.01	214.0±2.3*	93.0±1.2*	0.44±0.01	217.0±2.3*	94.5±1.2*3	0.44±0.01
	Background + Zinc Sulphate	218.0±2.3*	94.0±1.2*	0.43±0.01	221.0±2.4*	96.0±1.2*	0.44±0.01	222.0±2.4*	97.0±1.2*	0.44±0.01
	Background + EcoLine Zinc	217.0±2.3*	93.0±1.2*8	0.43±0.01	219.0±2.3*	95.0±1.2*	0.43±0.01	221.0±2.4*	96.0±1.2*	0.44±0.01
	Background + Zinc sulphate + Ecoline Bor	219.0±2.3*	95.0±1.2*	0.43±0.01	221.5±2.4*	97.5±1.3*	0.44±0.01	222.5±2.4*	98.5±1.2*	0.44±0.01
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	220.5±2.4*	96.5±1.3*	0.44±0.01	223.5±2.4*	98.5±1.3*	0.44±0.01	222.5±2.4*	99.5±1.3*	0.45±0.01
DCS 3972	Control (without fertilizers)	211.0±2.3	94.0±1.2	0.45±0.01	213.0±2.3	95.5±1.2	0.45±0.01	214.5±2.3	96.5±1.2*	0.45±0.01
	$N_{100}P_{31}$ (background)	224.0±2.4*	100.0±1.3*	0.45±0.01	225.5±2.4*	101.0±1.3*	0.45±0.01	227.0±2.5*	102.5±1.3*	0.45±0.01
	Background + Zinc Sulphate	228.0±2.5*	102.5±1.3*	0.45±0.01	229.5±2.5*	103.5±1.4*	0.45±0.01	231.0±2.5*	105.0±1.4*	0.45±0.01
	Background + EcoLine Zinc	227.0±2.5*	102.0±1.3*	0.45±0.01	229.0±2.5*	103.5±1.4*	0.45±0.01	230.0±2.5*	104.5±1.4*	0.45±0.01
	Background + Zinc sulphate + Ecoline Bor	228.5±2.5*	103.5±1.4*	0.45±0.01	230.0±2.5*	105.0±1.4*	0.46±0.01	232.0±2.5*	106.0±1.5*	0.46±0.01
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	229.5±2.5*	104.5±1.4*	0.46±0.01	231.0±2.5*	106.0±1.5*	0.46±0.01	232.5±2.5*	107.0±1.5*	0.46±0.01
DCS 4351	Control (without fertilizers)	221.0±2.4	97.0±1.3	0.44±0.01	224.0±2.4	98.5±1.3	0.44±0.01	225.0±2.4	99.5±1.3	0.44±0.01
	$N_{100}P_{31}$ (background)	229.5±2.5*	102.5±1.3*	0.45±0.01	231.0±2.5*	104.5±1.4*	0.45±0.01	232.0±2.5*	106.0±1.5*	0.46±0.01
	Background + Zinc Sulphate	232.0±2.5*	105.5±1.4*	0.45±0.01	233.0±2.5*	107.0±1.5*	0.46±0.01	234.5±2.5*	108.0±1.5*	0.46±0.01
	Background + EcoLine Zinc	231.0±2.5*	104.0±1.4*	0.45±0.01	233.0±2.5*	106.5±1.5*	0.46±0.01	235.5±2.5*	108.0±1.5*	0.46±0.01
	Background + Zinc sulphate + Ecoline Bor	233.0±2.5*	107.0±1.5*	0.46±0.01	234.5±2.6*	108.5±1.5*	0.46±0.01	236.5±2.6*	108.5±1.5*	0.46±0.01
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	234.5±2.6*	107.5±1.5*	0.46±0.01	236.5±2.6*	109.0±1.5*	0.46±0.01	238.5±2.6*	110± 1.6*	0.46±0.01

Note: 1 – plant height, cm; 2 – height of attachment of the upper productive cob; 3 – index of the ratio of the height of the cob attachment to the plant height.

of plant height and ear attachment, as well as their ratio, were observed at the maximum intensification of technological methods of maize cultivation in the experiment variant with the combined application of zinc sulphate, ecoline zinc and ecoline boron on the background of $N_{100}P_{31}$ in hybrids: DCS 3795 – 9.0 and 10.8, 2.3%; 9.0 and 11.7, 2.3%; 8.8 and 11.6, 4.5%; DCS 3972 – 8.1; 10.0 and 2.3% and 7.8 and 10.0 and 2.3%; 7.7 and 9.8, 2.3%; DCS 4351 – 5.8 and 9.8, 4.3%; 5.3 and 9.6, 4.3 and 5.7 and 9.5; 4.3%, respectively. Thus, in this variant of research, the maximum increases in plant height and head attachment, as well as their ratio, were noted, which varied from 2.3 to 11.7%.

Thus, the maximum plant height and cob attachment obtained by us is associated with the combined application of macro- and microelements, which is confirmed by the results of studies by a number of scientists who note that the use of foliar fertilisation with microelements in combination with nitrogen fertilisers during the maize growing season increases plant adaptability to adverse environmental stressors and improves the intensity of growth processes and productivity (Sirokha, 2014).

Our results are in line with the data of scientists who note that microelements such as zinc (Zn), boron (B) and manganese (Mn) have a significant impact on the intensive growth and development of the root system. Thanks to these trace elements, maize plants increase their root system by 20 per cent or more. The absorption of nutrients begins with adsorption, which takes place on the surface of the cells of the root system. After that, a complex process of active and passive transport into the cell begins (Ivanchuk, 2014).

Table 2 shows the effect of plant density and fertilisation on the elements of yield structure in maize hybrids. It was found that the number of rows of grains is a trait that changes slightly under the influence of the technological methods of cultivation that were studied. That is, the number of rows of grains is a genetically determined trait that changes least under the influence of growing conditions. To a greater extent, fertilisation and plant

Table 2. Effect of plant density and fertilisation on yield structure elements in maize hybrids, by 2023–2024

Hybrid (factor A)	Fertiliser (factor C)	Plant density, thousand plants/ha (factor B)								
		60			70			80		
		1	2	3	1	2	3	1	2	3
DCS 3795	Control (without fertilizers)	14.1±0.2	23.7±0.5	250.5±3.6	14.1±0.2	21.2±0.5	244.7±3.5	14.1±0.2	19.5±0.4	231.2±3.2
	$N_{100}P_{31}$ (background)	14.2±0.2	31.7±0.6*	306.7±4.5*	14.2±0.2	29.3±0.6*	296.8±4.4*	14.2±0.2	26.9±0.5*	278.0±3.8*
	Background + Zinc Sulphate	14.4±0.2	33.0±0.6*	310.8±4.6*	14.4±0.2	30.1±0.6*	302.7±4.6*	14.4±0.2	27.1±0.6*	287.1±4.2*
	Background + EcoLine Zinc	14.3±0.2	32.4±0.6*	308.1±4.6*	14.3±0.2	30.0±0.6*	301.7±4.6*	14.3±0.2	27.0±0.6*	287.0±4.2*
	Background + Zinc sulphate + Ecoline Bor	14.4±0.2	33.4±0.6*	312.1±4.6*	14,4±0.2	30.2±0.6*	305.1±4.5*	14.4±0.2	27.9±0.6*	289.7±4.2*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	14.4±0.2	33.4±0.6*	313.4±4.6*	14.4±0.2	30.2±0.6*	306.6±4.5*	14.4±0.2	27.9±0.6*	291.9±4.4*
DCS 3972	Control (without fertilizers)	15.1±0.2	25.5±0.5	249.7±3.5	15.1±0.2	22.6±0.5	237.2±3.5	15.1±0.2	20.6±0.4	229.6±3.2
	$N_{100}P_{31}$ (background)	15.1±0.2	34.1±0.6*	310.4±4.6*	15.1±0.2	32.2±0.6*	295.9±4.4*	15.1±0.2	30.8±0.6*	274.4±3.8*
	Background + Zinc Sulphate	15.3±0.2	35.1±0.7*	311.2±4.6*	15.3±0.2	32.0±0.6*	306.7±4.6*	15.3±0.2	30.8±0.6*	273.1±3.8*
	Background + EcoLine Zinc	15.2±0.2	34.6±0.6*	311.5±4.6*	15.2±0.2	31.8±0.6*	303.5±4.5*	15.2±0.2	30.7±0.6*	271.0±3.8*
	Background + Zinc sulphate + Ecoline Bor	15.3±0.2	35.0±0.7*	313.1±4.6*	15.3±0.2	32.0±0.6*	306.8±4.6*	15.3±0.2	31,1±0.6*	273.0±3.8*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	15.3±0.2	35.0±0.7*	313.4±4.6*	15.3±0.2	32.1±0.6*	306.8±4.6*	15.3±0.2	31.1±0.6*	274.0±3.8*
DCS 4351	Control (without fertilizers)	16.0±0.2	23,4±0.5	250.9±3.6	16.0±0.2	21.9±0.5	222.3±3.5	16.0±0.2	20.6±0.4	210.9±3.2
	$N_{100}P_{31}$ (background)	16.2±0.2	32.7±0.6*	292.5±4.4*	16.2±0.2	30.8±0.6*	265.2±4.1*	16.2±0.2	29.5±0.6*	233.7±3.7*
	Background + Zinc Sulphate	16.3±0.2	33.4±0.6*	296.2±4.5*	16.3±0.2	31.9±0.6*	266.8±4.1*	16.3±0.2	29.9±0.6*	237.3±3.7*
	Background + EcoLine Zinc	16.3±0.2	33.3±0.6*	291.8±4.4*	16.3±0.2	31.5±0.6*	263.7±4.1*	16.3±0.2	29.7±0.6*	232.7±3.7*
	Background + Zinc sulphate + Ecoline Bor	16.3±0.2	34.1±0.6*	299.0±4.5*	16.3±0.2	32.3±0.6*	269.3±4.1*	16.3±0.2	30.0±0.6*	239.4±3.7*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	16.3±0.2	34.1±0.6*	301.1±4.5*	16.3±0.2	32.0±0.6*	273.9±4.3*	16.3±0.2	30.2±0.6*	239.5±3.7*

Note: 1 – number of rows of grains, pcs; 2 – number of grains in a row, pcs; 3 – weight of 1000 grains, g.

density influenced the number of grains per row and the weight of 1000 grains. The highest number of rows of grains, grains in a row and weight of 1000 grains was noted in the experiment variant, where the combined application of zinc sulphate, ecoline zinc and ecoline boron on the background of $N_{100}P_{31}$ at plant density from 60 to 80 thousand pcs/ha was carried out, the elements of the yield structure were higher ($t_f > t_{t0.05}$) compared to the control variant in terms of the number of grains in a row and weight of 1000 grains in hybrids: DCS 3795 by 29.0, 20.0% and 29.8 and 20.2%; 30.1, 20.8%; DCS 3972 – 27.1, 20.3% and 29.6, 22.7%; 33.8, 16.2%; DCS 4351 – 31.4 and 16.7%; 31.6 and 18.8%; 31.8 and 11.9%, respectively.

The results of our research confirm the previously obtained data that Zn affects protein synthesis, structure and strength of cell walls. Sufficient Zn nutrition optimises the water balance of plants, improving drought and heat resistance. During the V4-6 period, the future crop is formed – the size of the cobs, the number of rows and grains, and the overall graininess of the cob. With insufficient zinc, a significant slowdown in growth was observed due to reduced internodes, deterioration of cob lakeiness, or lack of setting in maize plants with a significant zinc deficiency (Gospodarenko, 2015).

It is zinc that ensures plant resistance to stress factors, affects productivity, cob fullness and the number of grains in it, as well as product quality.

This also applies to such a trace element as Boron, which has a positive effect on flowering and heading, as well as respiration. Boron deficiency inhibits plant growth. Due to the lack of boron, especially on light soils, internodes are reduced, heads of cabbage are deformed and partially free of seeds, grey, oblong necrotic spots appear on the leaves, young leaves curl, and the leaf surface is much smaller. Boron improves the composition of nutrients in plants and their condition, Boron has a particularly positive effect on fertilisation because it promotes the growth of the pollen tube, increases the quality and quantity of pollen, forms more seeds per cob, and increases yields (Gospodarenko, 2015).

Corn is a borophilic crop, as it removes 130–150 g/ha of boron from the soil. Boron ensures an uninterrupted supply of carbohydrates and starch from the leaves to other plant organs, including the kernel. Boron deficiency causes inhibition of plant growth and development, shortening of internodes, and deformation of cobs that partially do not contain grain (Korchagina, 2011).

Table 3 presents the calculated traits of the yield structure elements of maize hybrids, namely the number of grains per ear and the weight of grains per ear, the first trait being the product of the number of rows of grains by the number of grains in a row, and the second trait being the product of the number of grains per ear by the weight of 1000 grains.

Taking into account the polygenic nature of their origin, the variability of these traits depended to a greater extent on the technological methods of cultivation that were studied in the experiment.

The lowest values of the elements of the crop structure were observed in the control variant (without fertilisers) and changed with increasing plant density from 60 to 80 thousand plants/ha in hybrids: DKS 3795 – 333.1 pcs. 84.0 g; 297.9 pcs. 73.11 g; 273.3 pcs. 63.4 g; DKS 3972 – 383.1 pcs. 96.1 g; 339.5 pcs. 80.9 g; 309.4 pcs. 71.4 g; DKS 4351 – 373.6 pcs. 94.2 g; 349.6 pcs. 78.1 g; 328.8 pcs. 69.7 g, respectively.

The highest increases compared to the control variant ($t_f > t_{t0.05}$) of the elements of the crop structure were noted in the variant of the experiment, where the combined application of zinc sulphate, Ecoline Zinc and Ecoline Boron on the background of $N_{100}P_{31}$ was carried out with an increase in plant density from 60 to 80 thousand plants/ha in hybrids: DKS 3795 by 29.9 and 43.8%; 31.1 and 45.1%; 32.0 and 46.0%; DKS 3972 – 28.5 and 42.9%; 30.8 and 46.3%; 34.9 and 45.3%; DKS 4351 – 32.7 and 43.7%; 33.3 and 45.5%; 33.2 and 40.7% more compared to the control variant, respectively.

This is in line with the results of research by a number of scientists, in particular, maize plants, as already mentioned, are very sensitive to zinc (Zn) deficiency and moderately sensitive to boron (B) deficiency (70 g/ha) (Adamenko, 2015).

Table 3. Number of kernels (pcs) and grain weight per ear (g) in maize hybrids depending on fertiliser and plant density, 2023–2024

Hybrid (factor A)	Fertiliser (factor C)	Plant density, thousand plants/ha (factor B)					
		60		70		80	
		1	2	1	2	1	2
DCS 3795	Control (without fertilizers)	333.1± 4.9	84.0±1.0	297.9± 4.5	73.11±1.0	273.3± 4.2	63.4±0.9
	$N_{100}P_{31}$ (background)	449.7± 6.3*	138.4± 1.4*	415.7± 5.4*	123.8± 1.2*	381.6± 5.4*	106.5± 1.2*
	Background + Zinc Sulphate	473.1± 6.5*	147.4± 1.4*	432.2± 5.8*	131.2± 1.3*	388.4± 5.5*	111.9± 1.2*
	Background + Ecoline Zinc	462.8± 6.3*	143.0± 1.4*	428.4± 5.6*	129.6± 1.3*	385.6± 5.5*	111.0± 1.2*
	Background + Zinc sulphate + Ecoline Bor	473.1± 6.5*	146.0± 1.4*	432.6± 5.7*	131.3± 1.3*	401.9± 5.7*	116.8± 1.2*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	475.4± 6.5*	149.4± 1.4*	432.9± 5.7*	133.2± 1.3*	401.9± 5.7*	117.5± 1.2*
DCS 3972	Control (without fertilizers)	383.1± 5.4	96.1±1.2	339.5± 4.9	80.9±1.0	309.4± 4.7	71.4±1.0
	$N_{100}P_{31}$ (background)	514.4± 6.8*	160.2± 1.5*	485.6± 6.7*	144.1± 1.4*	465.2± 6.3*	128.0± 1.3*
	Background + Zinc Sulphate	534.8± 6.8*	166.9± 1.5*	487.5± 6.7*	149.9± 1.4*	469.2± 6.3*	128.5± 1.3*
	Background + EcoLine Zinc	525.4± 6.5*	164.1± 1.5*	482.8± 6.7*	146.9± 1.4*	466.0± 6.3*	126.7± 1.3*
	Background + Zinc sulphate + Ecoline Bor	534.9± 6.8*	167.5± 1.5*	487,9± 6.7*	150.0± 1.4*	475.2± 6.5*	130.1± 1.3*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	535.7± 6.8*	168.4± 1.5*	490.5± 6.7*	150.6± 1.4*	475.8± 6.5*	130.6± 1.3*
DCS 4351	Control (without fertilizers)	373.6± 5.3	94.2±1.2	349.6± 4.9	78.1±1.0	328.8± 5.1	69.7± 0.9
	$N_{100}P_{31}$ (background)	528.9± 6.9*	155.1± 1.5*	498.2± 6.6*	132.4± 1.4*	477.9± 6.5*	112.0± 1.2*
	Background + Zinc Sulphate	543.6± 6.9*	161.3± 1.5*	520.0± 6.9*	138.9± 1.4*	487.4± 6.6*	115.9± 1.2*
	Background + EcoLine Zinc	542.0± 6.9*	158.5± 1.5*	513.5± 6.9*	135.7± 1.4*	488.3± 6.6*	112.8± 1.2*
	Background + Zinc sulphate + Ecoline Bor	555.0± 7.1*	166.3± 1.5*	524.7± 6.9*	141.9± 1.4*	488.2± 6.6*	117.1± 1.2*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	555.0± 7.1*	167.4± 1.5*	521.6± 6.9*	143.2± 1.4*	492.3± 6.7*	117.6± 1.2*

Note: 1) number of kernel, pcs; 2) grain weight per ear (g).

It is known that zinc deficiency leads not only to a slowdown in plant growth due to reduced internodes and reduced cob water content, but also to cob formation (Sanin, 2011).

Trace elements act as activators and initiators of biochemical processes (growth, reproduction, seed maturation, formation of reproductive organs, etc.) in the body, participate in metabolic processes such as photosynthesis and respiration, assimilation and fixation of nitrogen, sulphur, protein metabolism (form complexes with nucleic acids and other compounds), transport, sugars, redox processes, regulate the state of protoplasm, synthesis of vitamins, pigments, and enzymes (Adamenko, 2015).The results of experimental studies confirm the previous conclusions and complement the positive effect of boron on the graininess of corn cobs.

According to the results of research (Palamarchuk at al., 2013), seed treatment with microelements has a positive effect on the formation of cobs and increases their number. The maximum indicators of the elements of the crop structure (number of cobs per plant and grain yield per cob) were observed on the background of $N_{100}P_{31}$ with the combined application of zinc sulphate, Ecoline Zinc and Ecoline Boron and a density of 60 thousand plants/ha in maize hybrids: DCS 3795 - 1.1, 84.9%; DCS 3972 - 1.2, 85.9%; and DCS 4351 - 1.2, 85.8%, respectively. This is at a significant level higher compared to the control variant ($t_f > t_{t0.05}$) by 27.2 and 6.1%, 33.3 and 6.8%, 33.3 and 6.8% (Table 4).

Thus, this variant has the highest number of cobs per plant and grain yield per cob. Literature data (Sanin, 2011) indicate a positive effect of foliar fertilisation with microelements, especially zinc-containing ones, on the level of grain yield

Table 4. Number of cobs (pcs.) and grain yield per cob (%) in maize hybrids depending on fertiliser and plant density, 2023–2024

Hybrid (factor A)	Fertiliser (factor C)	Plant density, thousand plants/ha (factor B)					
		60		70		80	
		1	2	1	2	1	2
DCS 3795	Control (without fertiliser)	0.8± 0.002	79.7±0.9	0.8± 0.002	79.7±0.9	0.7± 0.001	79.4±0.9
	$N_{100}P_{31}$ (background)	0.9± 0.002	80.9±0.9	0.9± 0.002	81.0±0.9	0.8± 0.002	80.9±0.9
	Background + Zinc Sulphate	1.1± 0.003*	82.8±0.9	1.1± 0.003*	82.7±0.9	1.0± 0.002*	82.4±0.9
	Background + Ecoline Zinc	1.0± 0.002*	82.2±0.9	1.0± 0.002*	82.2±0.9	0.9± 0.002	81.9±0.9
	Background + Zinc sulphate + Ecoline Bor	1.1± 0.003*	84.9±0.9*	1.1± 0.003*	84.8±0.9*	1.0± 0.002*	84.7±0.9*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	1.1± 0.003*	84.9±0.9*	1.1± 0.003*	85.0±0.9*	1.0± 0.002*	84.9±0.9*
DCS 3972	Control (without fertiliser)	0.8± 0.002	80.1±0.9	0.8± 0.002	80.0±0.9	0.6± 0.001	80.0±0.9
	N_{100}, P_{31} (background)	0.9± 0.002	81.3±0.9	0.9± 0.002	81.4±0.9	0.7± 0.001	81.3±0.9
	Background + Zinc Sulphate	1.2± 0.003*	83.8±0.9	1.2± 0.003	83.4±0.9	0.9± 0.002*	83.1±0.9
	Background + EcoLine Zinc	1.1± 0.003*	83.2±0.9	1.1± 0.003*	82.9±0.9	0.8± 0.001	82.6±0.9
	Background + Zinc sulphate + Ecoline Bor	1.2± 0.003*	85.7±0.9*	1.2± 0.003*	85.7±0.9*	0.9± 0.002*	85.3±0.9*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	1.2± 0.003*	85.9±0.9*	1.2± 0.003*	86.0±0.9*	0.9± 0.002*	85.7±0.9*
DCS 4351	Control (without fertiliser)	0.8± 0.002	80.0±0.9	0.7± 0.001	79.9±0.9	0.6± 0.001	79.9±0.9
	N_{100}, P_{31} (background)	0.9± 0.002	81.6±0.9	0.8± 0.001	81.3±0.9	0.7± 0.001	81.3±0.9
	Background + Zinc Sulphate	1.2± 0.003*	83.4±0.9	1.1± 0.003*	83.2±0.9	0.9± 0.002*	82.9±0.9
	Background + EcoLine Zinc	1.1± 0.003*	82.9±0.9	1.0± 0.002*	82.3±0.9	0.8± 0.001	82.2±0.9
	Background + Zinc sulphate + Ecoline Bor	1.2± 0.003*	85.2±0.9*	1.1± 0.003*	85.1±0.9*	0.9± 0.002*	85.0±0.9*
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	1.2± 0.003*	85.8±0.9*	1.1± 0.003*	85.5±0.9*	0.9± 0.002*	85.4±0.9*

Note: 1) number of cobs per plant, pcs; 2) grain yield per cob, %.

of maize hybrids. In particular, (Popovych and Navrotska, 1986), state that the use of foliar fertilisation of maize plants increases grain yield by 0.3–0.4 or even 1.1–2.0 t/ha, i.e. by 15–20%.

The results of research by a number of scientists (Sanin, 2011) indicate that boron plays an important role in the formation of flowers, pollen (increases fertility), pollination (improves pollen germination in pollen tubes), heading, seed production, growth point development (in particular, meristem cells) and respiration.

With an increase in density to 70 thousand plants/ha, a slight decrease in the number of cobs per plant and grain yield per cob was observed: DKS 3795 – 1.1 pieces; 85.0%; DKS 3972 – 1.2 pieces; 86.0%; and DKS 4351 – 1.1 pieces; 85.5%. However, this was higher compared to the control variant ($t_f > t_{t0.05}$) by 27.3 and 6.2%, 33.3 and 7.0%, 36.4 and 6.5%, respectively. Further thickening of the crops to 80 thousand plants/ha provided a decrease in the elements of the yield structure, in particular the number of cobs and grain yield per cob in hybrids DKS 3795 – 1.0 pcs. and 84.9%; DKS 3972 – 0.9 pcs. and 85.7%; and DKS 4351 – 0.9 pcs. and 85.4%. However, this was higher compared to the control variant ($t_f > t_{t0.05}$) by 30.0 and 6.5%, 33.3 and 6.7%, 33.3 and 6.4%, respectively.

The yields of maize hybrids depending on fertilisation and plant density are presented in Table 5.

Yield is a polygenic trait that consists of a large number of elements of the yield structure, including those presented in Tables 1–3. Thus, the highest level of yield was observed in the variant of the experiment, where the maximum intensification of technological methods of corn cultivation was applied with the combined application of zinc sulphate, Ecoline Zinc and Ecoline Boron on the background of $N_{100}P_{31}$ with an increase in density from 60 to 80 thousand plants/ha, the yield was in corn hybrids: DCS 3795 – 8.39, 8.67, 8.52 t/ha; DCS 3972 – 9.39, 9.74, 9.35 t/ha and DCS 4351 – 9.35, 9.09, 8.42 t/ha. It was higher compared to the control variant ($NIR_{0.05}$ fertiliser = 0.11 t/ha) in hybrids: DCS 3795 by 3.53 (42.1%), 3.79 (43.7%), 3.8 t/ha (44.6%); DCS 3972 by 4.16 (44.3%), 4.60 (47.2%), 4.24 t/ha (45.3%); DCS 4351 by 4.23 (45.2%), 4.0 (44.0%), 3.42 t/ha (40.6%), respectively.

These results are supported by the findings of a number of scientists who note that plants that are sufficiently supplied with trace elements

Table 5. Yield of corn hybrids depending on plant density and fertiliser, t/ha in 2023–2024

Hybrid (factor A)	Fertiliser (factor C)	Plant density, thousand plants/ha (factor B)		
		60	70	80
DCS 3795	Control (without fertiliser)	4.86	4.88	4.72
	$N_{100}P_{31}$ (background)	7.91	8.10	7.73
	Background + Zinc Sulphate	8.23	8.54	8.12
	Background + EcoLine Zinc	8.08	8.44	8.06
	Background + Zinc sulphate + Ecoline Bor	8.25	8.55	8.47
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	8.39	8.67	8.52
DCS 3972	Control (without fertiliser)	5.23	5.14	5.11
	$N_{100}P_{31}$ (background)	8.93	9.38	9.16
	Background + Zinc Sulphate	9.31	9.52	9.21
	Background + EcoLine Zinc	9.05	9.45	9.07
	Background + Zinc sulphate + Ecoline Bor	9.35	9.64	9.32
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	9.39	9.74	9.35
DCS 4351	Control (without fertiliser)	5.12	5.09	5.0
	$N_{100}P_{31}$ (background)	8.66	8.41	8.02
	Background + Zinc Sulphate	9.0	8.82	8.30
	Background + EcoLine Zinc	8.84	8.61	8.08
	Background + Zinc sulphate + Ecoline Bor	9.30	9.00	8.39
	Background + Zinc sulphate + Ecoline Zinc + Ecoline Bor	9.35	9.09	8.42
HIP_{05}: A – 0.08; B – 0.08; C – 0.11; AB – 0.13; AC – 0.19; BC – 0.19; ABC – 0.33				

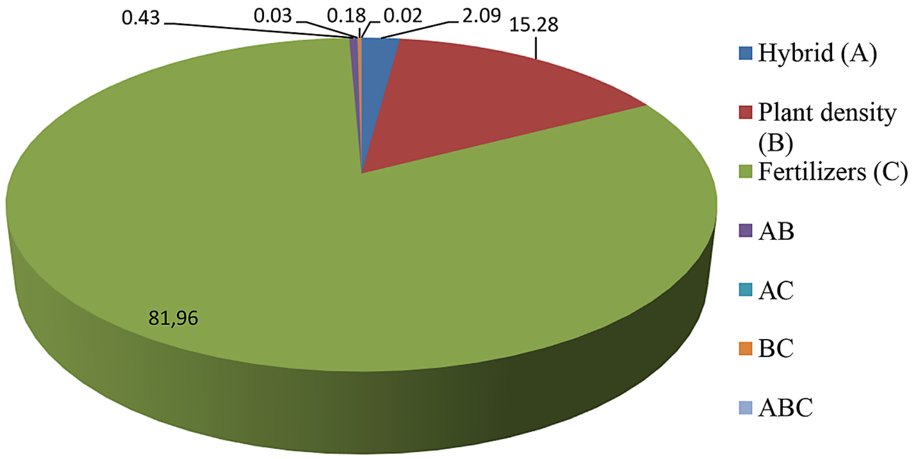

Figure 1. Shares of influence of fertiliser, plant density and hybrid traits on maize yield, %

absorb basic fertilisers (NPK) 10–30% better (Yamkovyi, 2014).

Among the trace elements, zinc is the most easily absorbed by maize plants. It is a part of many enzymes (regulating hydrocarbon, fat, phosphorus metabolism and vitamin biosynthesis), participates in the formation of chlorophyll, and promotes the synthesis of vitamins (B, B6, P and C) (Yaroshko, 2014).

Thus, our further research requires studying the effect of this trace element on starch content for bioethanol production.

Thus, the highest yield level in hybrid DCS 3795 – 8.67 t/ha, as well as in hybrid DCS 3972 – 9.74 t/ha was observed at a density of 70 thousand plants/ha, and in hybrid DCS 4351 – 9.35 t/ha was observed at a density of 60 thousand plants/ha. Both an increase to 80 thousand plants/ha and a decrease in plant density to 60 thousand plants/ha in the early and mid-early hybrids DKS 3795 and DKS 3972 led to a decrease in yield. In the hybrid DCS 4351, increasing the density to 70 and 80 thousand plants/ha also led to a decrease in yield.

In addition, it is necessary to note the variant of the experiment, which was as close as possible to the previous one in terms of yield, but this variant had fewer measures for plant nutrition. In particular, the variant with zinc sulphate and Ecoline Bor on the background of $N_{100}P_{31}$ provided a yield of 60–80 thousand plants/ha in maize hybrids: DCS 3795 – 8.25, 8.55, 8.47 t/ha; DCS 3972 – 9.35, 9.64, 9.32 t/ha and DCS 4351 – 9.3, 9.0, 8.39 t/ha. This is higher compared to the control variant ($NIR_{0.05}$ fertiliser = 0.11 t/ha) in maize hybrids: DCS 3795 by 3.39, 3.67, 3.75 t/ha; DCS 3972 by 4.12, 4.5, 4.21 t/ha; DCS 4351 by 4.18, 3.91, 3.39 t/ha, respectively. Thus, almost the same yield was obtained compared to the previous variant, but this variant used fewer technological methods for fertilising corn.

The shares of influence of hybrid characteristics, plant density and fertilisation on maize yield are shown in Figure 1.

It should be noted that the highest share of fertiliser influence on maize yield was 81.96%. The share of plant density was lower and amounted to 15.28%, hybrid traits contributed 2.09% to the yield level, and the effect of the interaction of hybrid traits on plant density (0.43%) and plant density on fertilisation (0.18%) was also significant.

CONCLUSIONS

As a result of the research, it was found that the maximum intensification of technological methods of corn cultivation (combined application of zinc sulphate, Ecoline Zinc and Ecoline Boron on the background of $N_{100}P_{31}$) provided:

1. The highest increases in linear measurements of plant height and cob attachment, as well as their ratio at a plant density of 80 thousand/ha, which increased compared to the control variant ($t_f > t_{t0.05}$) in hybrids: DCS 3795 by 9.2, 12.5, 4.5%; DCS 3972 by 7.8, 9.8, 2.3%; DCS 4351 – by 5.7, 9.5, 4.5%.
2. The highest cob water content of maize hybrids, which at a plant density of 60 - 80 thousand plants/ha was higher compared to the control variant ($t_f > t_{t0.05}$) in DCS 3795 by 142.3 (30.0%); 135 (31.0%); 128.6 (32.0%); DCS 3972 – by 152.6 (28.5%); 151.0 (30.8%); 166.4 (35.0%); DCS 4351 – 181.4 (32.7%); 172.0 (32.9%); 163.5 (33.2%).

3. The highest level of yield in maize hybrids, which at a plant density of 60–80 thousand plants/ha was higher compared to the control variant ($NIR_{0.05}$ fertiliser = 0.11 t/ha) in hybrids: DCS 3795 by 3.53 (42.1%), 3.79 (43.7%), 3.8 t/ha (44.6%); DCS 3972 by 4.16 (44.3%), 4.60 (47.2%), 4.24 t/ha (45.3%); DCS 4351 by 4.23 (45.2%), 4.0 (44.0%), 3.42 t/ha (40.6%), respectively. Thus, the highest yields were recorded in maize hybrids DCS 3795 and DCS 3972 at a density of 70 thousand plants/ha, and in hybrid DCS 4351 at a density of 60 thousand plants/ha.
4. In conclusion, this variant provides the highest yield and is promising in terms of maximum starch yield and subsequent bioethanol production for biofuel production and should be studied in our future research.

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