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Impacts of plant density and fertilization on harvest and quality of maize hybrids for bioethanol production

Serhii Bogomaz[1], Oleksandr Mazur[2*], Ruslan Kravets[3], Svitlana Lutkovska[4], Olena Mazur[5], Pavel Verheles[5], Alina Korobko[2], Yevhen Chepernaty[2]

[1] Department of Agriculture, Soil Science and Agrochemistry, Vinnytsia National Agrarian University 3 Soniachna Str., 21008, Vinnytsia, Ukraine
[2] Department of Crop Production and Horticulture, Vinnytsia National Agrarian University 3 Soniachna Str., 21008, Vinnytsia, Ukraine
[3] Department of Ukrainian and Foreign Languages, Vinnytsia National Agrarian University 3 Soniachna Str., 21008, Vinnytsia, Ukraine
[4] Vinnytsia National Agrarian University 3 Soniachna Str., 21008, Vinnytsia, Ukraine
[5] Department of Botany, Genetics and Plant Protection, Vinnytsia National Agrarian University 3 Soniachna Str., 21008, Vinnytsia, Ukraine
* Corresponding author's email: selection@vsau.vin.ua

ABSTRACT

The article describes the research results on impacts of plant density, fertilization, and hybrid characteristics of maize on yield level, starch content and yield, bioethanol yield, as well as protein content. The evidence demonstrated that the production levels of starch, bioethanol and protein are chiefly dictated by total grain yield observed across the experimental conditions, with the starch and protein concentrations within the maize kernels playing a significantly smaller role. Research findings demonstrated that peak crop production was achieved when agricultural methods were employed to their completest extent and aimed at optimizing macro- and micronutrient nutrition (Ecoline boron, Ecoline zinc, zinc sulfate against the $N_{100}P_{31}$ background), combined with optimized plant density and alignment between plants/ha as well as available resources. Particularly, the hybrid DKS 3795 produced 8.8 t/ha and DKS 3972 – 10.1 t/ha at a plant density with 70 thsd. plants/ha, while DKS 4351 achieved 9.4 t/ha at a density with 60 thsd. plants/ha. The highest starch content occurred during the control treatment (without fertilization), which tended to increase with higher plant density. However, the maximum starch yield was recorded in the treatment where maize nutrition was optimized with macro- and micronutrients due to increased grain yield. Specifically, starch yield reached 6.3 t/ha for DKS 3795 (FAO 280) at a density of 70 thsd. plants/ha, 7.3 t/ha for DKS 3972 (FAO 300), and 6.8 t/ha for DKS 4351 (FAO 350) at a density with 60 thsd. plants/ha. Under this fertilization system, the highest bioethanol yield was noticed: at 70 thsd. plants/ha for DKS 3795 – 3.5 thsd. l/ha and DKS 3972 – 4.1 thsd. l/ha; at 60 thsd. plants/ha for DKS 4351 – 3.7 thsd. l/ha. These values exceeded the control treatment by 1.5 for DKS 3795, 2.0 for DKS 3972, and 1. thsd. l/ha for DKS 4351, respectively. The level of protein exhibited a consistent downward inclination as the number of plants/ha reached 60 to 80 thsd.: a reduction of 0.2–0.3% was observed for DKS 3795 (corresponding to FAO 280 maturity group), a 0.2-0.3% drop for DKS 3972 (FAO 300), and reduction ranging 0.3–0.5% for DKS 4351 (FAO 350).

Keywords: maize, hybrid, yield, starch, bioethanol, protein, plant density.

INTRODUCTION

Maize is classified as a high-yielding, multipurpose crop. Its grain is rich in starch (65–70%), protein (9–12%), and oil (4–8%). It is a first-rate preceding crop for legumes and spring cereals. However, achieving high yields and appropriate product quality requires attention to optimal applications of mineral fertilizers and micronutrients, growth stimulants, and high-quality seeds (Shevchenko et al., 2020; Branitskyi et al., 2022).

Maize requires high rates of nitrogen fertilizers, which causes great pressure on soils because of substantial demands for macronutrients, particularly nitrogen (Drulis et al., 2022; Mostovenko et al., 2022; Pantsyreva et al., 2023). The intensification of maize cultivation technologies is primarily associated with applying elevated nitrogen rates. Therefore, refining how nitrogen is applied in farming operations offers a dual benefit: boosting the yield of cultivated plants while simultaneously enhancing the ecological health of agricultural settings, assuming that the quantities of fertilizer utilized remain below the thresholds that could create ecological harm (Asibi et al., 2019; Myronova et al., 2023).

The need for phosphorus fertilization is also significant, although lower compared to nitrogen demand. The greatest phosphorus requirement occurs at the 4–6 leaf stage, while building female and male inflorescences. Nutrient deficiency in this period causes poorly developed ears and, consequently, reduced market quality. Adequate phosphorus supply enhances root system development, surges increasing of ears, and accelerates grain maturation (Zhmura and Andriienko, 2020; Yatsenko et al., 2023).

Potassium demand begins at the early stages of seed germination. Another critical period is the completion of flowering. Potassium deficiency slows plant change and progress, showing reduced plant height, vegetative biomass, and grain yield (Miliutenko, 2014; Vdovenko et al., 2024).

Maize requires substantially higher amounts of mineral fertilizers compared to other cereal crops. In addition to soil-applied fertilizers, obtaining high yields of appropriate quality also necessitates foliar fertilization with micronutrients (Pashchenko et al., 2009; Mazur et al., 2024).

Thus, in modern crop production technologies, applying micronutrient fertilizers is an integral component ensuring balanced maize nutrition. Along with pre-sowing seed treatment using micronutrient complexes to provide an initial nutrient reserve at early growth phases, foliar application during critical growth phases throughout the growing season is essential (Moldovan and Sobchuk, 2018; Korobko et al., 2024).

Applying nutrients directly onto the leaves represents a highly impactful method for managing the nutritional requirements of crops concerning major and trace elements, owing to their immediate accessibility and improved nutrient absorption effectiveness. Foliar feeding accelerates the incorporation of nutrients into organic compound synthesis and metabolic processes (Tsykov, 2017; Tkachuk and Verhelis, 2021; Mazur et al., 2023).

Maize belongs to common representative cereal crops; however, its defining characteristics stem from the prevailing ecological conditions and specific genotype (Liubych, 2020).

Central to assessing the excellence of maize kernels are the levels of protein, starch, and lipids. The proportional relationship among these elements dictates the appropriate end-use application for the grain – food, technical, or feed purposes. Protein determines both the nutritional and feed value of grain, influencing the quality of processed products and feed for livestock. Starch is the primary source of energy and is crucial for starch product manufacturing, bioethanol production, and food industry applications. Oil is important for feed use, as it forms the energy value of grain and affects the technological parameters relevant to processing (Garcia and Shultz, 2021; Myronova et al., 2023).

A confluence of factors determines the resultant quality of maize kernels, encompassing various hybrids' inherent biological traits, the employed farming methodologies, prevailing climatic conditions, specifically temperature and moisture, experienced throughout the crop development cycle.

According to numerous researchers' findings, under optimal growing conditions and depending on edaphic-climatic factors and hybrid characteristics, the chemical composition of maize grain may contain on average 11–14% protein, 60–85% starch, and 4.1–5.5% oil (Zhemoida et al., 2020; Palamarchuk et al., 2021; Mazur et al., 2024).

Adding oil enhances the energy density of grains, a key factor for suitability in animal feed applications, also influences technological properties during processing (Garcia and Shultz, 2021).

Research has established a direct correlation between protein accumulation and use of diverse rates of UAN-32 (urea–ammonium nitrate solution): increasing fertilizer rates leads to higher protein content. The peak 11.0% protein level was observed when applying 300 kg/ha of UAN-32, marking a 3% increase versus the untreated group that corresponded to varietal characteristics (8.8%). Applying UAN-32 at 250 and 300 kg per hectare levels led to grain oil concentrations 6.0–7.0%. Conversely, the control group and the treated plot (150 kg/ha lower rate) exhibited a 5% oil content.

The measured starch levels within the grain spanned from 65.0 to 70.0 percent, indicating a deficit of 5.3–12.0% when compared to established varietal specifications (Honcharuk et al., 2023; Bidnyna, 2025). This starch accumulation reduction is frequently attributable to ecological stresses, covering inadequate rainfall, elevated temperatures, and nutrient limitations.

Implementing humic preparations demonstrated to significantly mitigate the damaging effects stemming from these unfavorable conditions (Palamarchuk et al., 2024). Maximal starch concentration was achieved when the carbamide-ammonium mixture was applied at its highest rate, specifically 300 kg/ha of CAM-32, reaching 107.7% versus the untreated sample. Conversely, lowering the CAM-32 dosage to the 50–100 kg/ha range resulted in a less pronounced reduction in starch content (Palamarchuk and Telekalo, 2018).

The quantity of bioethanol obtainable is mainly contingent upon the starch levels present in the grain influenced by maturity group, hybrid subtype, and cultivation practices.

Worldwide, the spotlight on bioethanol generation is intensifying, consequently driving up the need for corn grain, recognized as a highly effective feedstock owing to its substantial carbohydrate proportion (ranging from 68% to 85%) (Tytko and Kalinichenko, 2010; and Kaletnik et al., 2020). Transitioning to the utilization of bioethanol contributes to environmental improvement and mitigates the severity of climate transformation, an issue moderately stemming from an excessive dependence on traditional energy sources (Rybalka et al., 2013; Kaletnik et al., 2020).

The aim of the research was to establish the relationships governing grain yield formation, starch content and yield, bioethanol output, protein content and yield, depending on fertilization practices, foliar feeding, and plant density.

MATERIALS AND METHODS

As outlined in the research guidelines, a trial involving three distinct factors was carried out on the private agricultural holding known as FLORA A.A. (Kryzhopil). The experimental design is presented in Table 1.

The year 2023 presented highly conducive hydrothermal circumstances for the flourishing and advancement of corn. Substantial rainfall registered during the spring months ensured a considerable recharging of water supplies, and subsequent seasonal downpours sustained vigorous growth for this cultivated plant. Conversely, in 2024, the hydrothermal environment proved less than ideal for the development of maize. This adverse situation stemmed from elevated temperatures observed across the entirety of the growing period, with figures reaching 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 concluding with 14.8 °C in September. Seventeen degrees Celsius marked the mean temperature. This figure represents an ascent of 2.5 °C above the established long-term mean, and furthermore, surpasses the 2023 temperature reading by 0.8 °C. Moreover, it warrants mention that throughout the majority of the cultivation period in 2024, rainfall totals fell below the typical long-term norm for numerous preceding years. Specifically, regarding precipitation amounts: April saw a deficit of 13.2 mm below the historical mean. July registered a shortfall of 30.8 mm less than the average, and August experienced an even greater reduction, being 40.4 mm below the norm. Cumulatively, throughout the entire growing season, the total precipitation was 64.5 mm below the long-term average accumulation, and 72.5 mm less than what was recorded in 2023.

The conditions of 2025 proved to be more favorable in terms of the hydrothermal regime for

Table 1. Experimental scheme

Hybrid (factor A)	Fertilization (factor C)	Plant density, thsd/ha (factor B)
DKS 3795 DKS 3972 DKS 4351	Control (no fertilizer)	60, 70, 80
	$N_{100}P_{31}$ (background)	
	Background + zinc sulfate (8 kg/ha before cultivation)	
	Background + Ecoline zinc (1 l/ha at microstage BBCH 14–15	
	Background + zinc sulfate (8 kg/ha before cultivation) + Ecoline boron (1 l/ha at microstage BBCH 61-63	
	Background + zinc sulfate (8 kg/ha before cultivation) + Ecoline zinc (1 l/ha at microstage BBCH 14-15) + Ecoline boron (1 l/ha at microstage BBCH 61-63)	

crop cultivation compared with the conditions of 2024. However, precipitation was unevenly distributed. In some months a deficit of rainfall was observed, particularly in June, when precipitation was 11.1 mm lower, and in July, when it was 12.2 mm lower than the long-term average. In contrast, in August precipitation exceeded the long-term average by 59 mm, and in September by 76.4 mm. Overall, during the 2025 growing season, total precipitation exceeded the long-term average annual indicators by 134.5 mm. A higher temperature regime was recorded in May – 15.2 °C, June – 21.8 °C, July – 20.5 °C, August – 20.7 °C, and September – 15.7 °C. These values exceeded the long-term average temperatures by 1.2 °C, 4.8 °C, 2.5 °C, 3.7 °C and 2.3 °C.

On the basis of current taxonomies, the earth in the study area falls under the category of podzolized, warm, shallowly frozen, medium loamy chernozem. The terrain is level. The pH of the soil solution in a salt extract registers near neutral readings, specifically between 6.8 and 7.1. Exchangeable bases hover around 33 to 39 milliequivalents per 100 grams of soil, with calcium being the dominant cation. Absorbed sodium levels are quite minimal, making up only 0.5-1.5% of the total exchange capacity. Texturally, the soil consists of clay and loam, exhibiting a fine granular structure. This composition lends itself well to tillage, promotes excellent aeration and water retention capabilities, enabling the soil to hold substantial amounts of moisture. Horizon A exhibits a total nitrogen concentration ranging from 0.23% to 0.26%, translating to an overall stock of 20 to 30 t/ha. The nitrogen available for easy hydrolysis is in the amount of 60 to 110 milligrams per kilogram of soil, while the nitrified nitrogen content stands between 30 and 40 mg/kg of soil. These measurements suggest that the soil possesses an ample supply of total nitrogen. Conversely, chernozem soils typically feature modest concentrations of readily available phosphorus, measuring 15–20 mg/kg of soil, despite having a substantial total phosphorus presence of 0.18–0.24%. Regarding potassium, the exchangeable form in these soils is quite abundant, registering 300–350 mg/kg of soil. Overall, considering its fertility profile, texture, and physicochemical characteristics, the soil within the research area presents favorable conditions for agricultural production.

The application of $N_{100}P_{31}$ of active ingredient per hectare was achieved by applying urea – 203 kg/ha and ammonium phosphate (ammophos) – 60 kg/ha in physical weight. Urea was applied during pre-sowing cultivation, while ammophos was applied in rows at sowing.

Urea (carbamide) is a fertilizer containing the amide form of nitrogen. It is the most concentrated of all nitrogen fertilizers (N – 46%) and is produced in granular form.

Ammophos 12:52 is a mineral fertilizer that contains two main macronutrients – nitrogen (N) and phosphorus (P).

To eliminate zinc deficiency, foliar feeding of crops−especially those highly sensitive to zinc supply−was carried out using Ecoline zinc at a rate of 1 liter/ha at the microstage BBCH 14–15 by means of foliar application.

Ecoline boron is a highly concentrated liquid boron micronutrient fertilizer. It is designed to eliminate symptoms of boron deficiency and for foliar feeding of crops, particularly those highly demanding in terms of boron supply. It contains boron in the form of an organic complex with monoethanolamine and was applied as foliar feeding at a rate of 1 l/ha at the microstage BBCH 61–63.

The study plots were placed according to a random arrangement, with four instances of each treatment or unit being present. The accounting plot area was 50 m² (Vovkodav, 2001). Floral timing was documented by adhering to the standardized procedure previously set forth (Vovkodav, 2001). The calculation of maize harvest, considering utilized cultivation acreage, was performed following the established protocol for state-level agricultural crop performance assessment (cereals, groat crops, and legumes) (Vovkodav, 2001) and the specific methodology developed for maize (Lebid et al., 2008).

The chemical quality parameters of grain were calculated in "Laboratory for Monitoring Quality and Safety of Feed and Raw Materials", NAAS.

The analysis for total nitrogen, leading to crude protein calculation, was executed following the Kjeldahl methodology (DSTU ISO 5983:2003). The quantification of starch levels adhered to the standards set forth in DSTU 46.045:2003.

The bioethanol yield from grain was calculated as the ethanol yield. Ethanol yield refers to the amount of ethanol obtained from one ton of carbohydrates expressed in terms of starch. The theoretical yield is calculated based on the alcoholic fermentation equation: $C_6H_{12}O_6 = 2C_2H_5OH + 2CO_2$. From 100 kg of hexoses, 51.14 kg of anhydrous ethanol and 48.86 kg of carbon dioxide are produced. Given the relative density of ethanol (d^4_{20} = 0.78927), its theoretical yield is 64.79 liters (Blium et al., 2010).

The results obtained in this study underwent analytical scrutiny, utilizing a dual method involving both analysis of variance (ANOVA) and a correlation-regression frame.

To ascertain the average values (x) along with their associated standard errors (± Sx), a small sample technique was employed. All numerical data presented in the tables are formatted as x ± Sx (mean ± standard error). Student's t-test was utilized for the statistical appraisal of any observed disparities. A divergence was deemed statistically important if the empirically derived reliability criterion for the difference (the experimental value) met or surpassed the established benchmark value for Student's t-test. Statistical importance for the mean values was established when $^*P < 0.05$ (Moiseychenko and Yeshchenko, 1994).

RESULTS AND DISCUSSION

For successful cultivation, hybrid corn varieties necessitate particular environmental conditions throughout their growth cycle. Initial phases of development correspond to the emergence of 3 to 5 leaves, the maize root structure is still rudimentary, and the expanse of its foliage is restricted; as a result, the required area for resource acquisition is modest. However, as the vegetation reaches full maturity and advances through later phases of its lifecycle, its foliage increases in surface area, thereby necessitating greater inputs of nutritional sustenance, water, and the necessary light energy for photosynthesis. Consequently, the uptake of these vital components intensifies. Should the planting density prove excessive, a harmful struggle for resources can develop among adjacent plants, hindering the development and ripening of all involved, ultimately resulting in a lowered yield. This negative consequence, arising from the competition for surrounding environmental factors, becomes more obvious as plants are situated closely together, resulting in actual physical interfacing (Wade and Douglas, 1990).

Maize hybrids' yield largely depends on plant density, as this factor determines competition among plants for light, moisture, and nutrients. Under sparse stands, plants have more space and compete less for vital factors. This typically results in increasing the size and number of ears per plant. Nonetheless, the aggregate count of flora within a specified space diminishes, resulting in lower gross output even when individual specimens exhibit strong productivity. Fine-tuning the spacing between plants guarantees a balance where the quantity of vegetation per surface area aligns with the accessible supplies. Plants are adequately supplied with light, moisture, and nutrients, which promotes maximum yield per unit area. Detection of optimal sowing density requires experimental results regarding hybrid responses to plant density changes under specific environmental conditions (Kutsenko et al., 2023; Bogomaz et al., 2025).

The final harvest quantity stems from a combination of influences exerted by biotic and abiotic facets of the surroundings, further coupled with suitability of cultivation methods implemented to foster ideal circumstances for maize progression and maturation.

Figures 1, 2 and 3 illustrate graphically the anticipated average yield spanning years 2023 through 2025 for various maize hybrids, contingent upon fertilizer application rates, population density.

A direct consequence was that the trial group incorporating the most sophisticated technological tools registered the greatest output, particularly when the combination of Ecoline boron and Ecoline zinc, alongside zinc sulfate, was applied over a foundation of $N_{100}P_{31}$.

Plant density increased from 60000 to 80000 units/ha; resultant yield displayed the subsequent pattern of change: DKS 3795 – 8.4; 8.8; 8.6 t/ha; DKS 3972 – 9.4; 10.1; 9.6 t/ha; DKS 4351 – 9.4; 9.2; 8.6 t/ha.

This exceeded control treatments by: DKS 3795 – 3.6; 3.9; 3.9 t/ha; DKS 3972 – 4.3; 5.0; 4.5 t/ha; DKS 4351 – 4.3; 4.2; 3.7 t/ha

For the DKS 3795 hybrid, the 8.8 t/ha peak productivity was achieved when the plant population reached 70 thousand per hectare. Similarly, hybrid DKS 3972 delivered its 10.1 t/ha maximum yield at the similar 70000 plants/ha density. In turn, the DKS 4351 hybrid verified its best performance, yielding 9.4 t/ha, at a lower density, specifically 60000 plants/ha.

A decline of harvested yield was observed across both higher (80,000 plants/ha) and lower (60000 plants/ha) planting densities, specifically when utilizing the early and mid-early DKS 3795 and DKS 3972 maize hybrids.

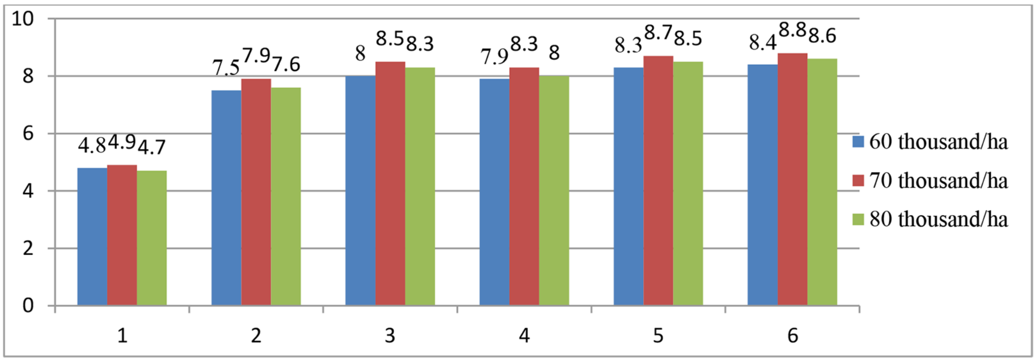

Figure 1. Impact of plant population levels and fertilizer rates on the cultivar DKS 3795 yield attributes across the years 2023 to 2025: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sUlfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

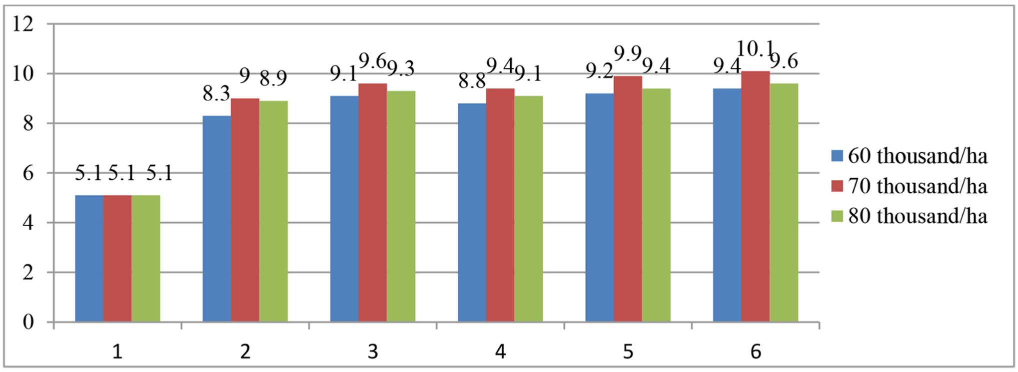

Figure 2. Impact of plant population levels and fertilizer rates on the cultivar DKS 3972 yield attributes across the years 2023 to 2025: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 –background + zinc sulfate + Ecoline zinc + Ecoline boron.

In a comparable fashion, for the DKS 4351 hybrid variety, elevating plants to either seventy thousand or eighty thousand per hectare led to a decline in yield.

As a result, where moisture content varies, in the Right-Bank Forest-Steppe ecological zone, the key to maximizing maize output was the precise calibration of nutrient application. More precisely, combining essential macro- and micronutrients through the concurrent deployment of Ecoline boron and Ecoline zinc, besides zinc sulfate, layered over an initial fertilization regimen of $N_{100}P_{31}$, allowed for harvests reaching 8.8 t/ha for DKS 3795 and 10.1 t/ha for DKS 3972, both sown at 70000 plants/ha, while the DKS 4351 variety produced 9.4 t/ha when planted at 60000 per hectare.

Numerous elements contribute to shaping the characteristics of maize grain quality, such as soil conditions, the equilibrium between hydration level and thermal conditions, as well as agricultural methods employed. In pursuit of higher harvests and enhanced grain attributes, it becomes essential to ascertain how various farming techniques impact the stages of growth and maturation, thus allowing for defining fit methods to manage them (Vlashchuk et al., 2017).

Consequently, boosting both the yield and the grade of maize kernels necessitates the careful choosing of hybrid varieties tailored to distinct soil and climate regions, paying close attention to their inherent biological needs, alongside the creation of efficient farming techniques designed to maximize the vital physiological functions within the plants throughout their growth cycle.

The obtained investigative findings indicate amount changes in starch present were the result of differences stemming from the hybrid's genetic makeup, the point in the growth cycle attained, how closely plants were spaced, and the nutrients provided through fertilization (Figures 4–6).

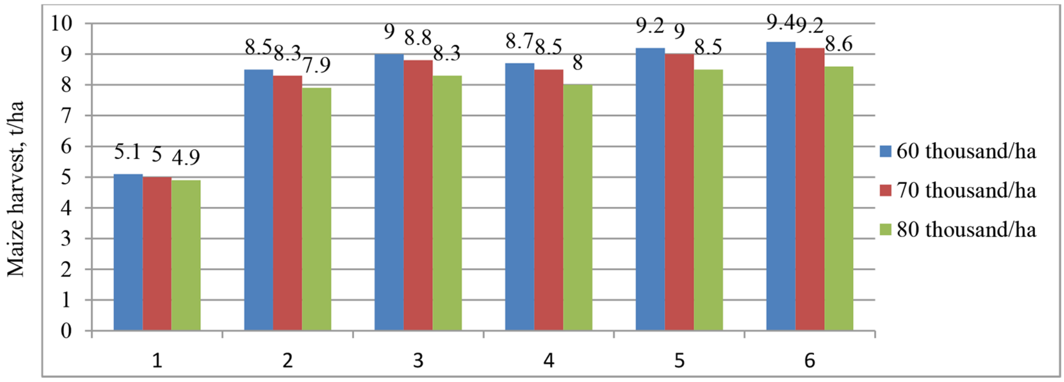

Figure 3. Impact of plant population levels and fertilizer rates on the cultivar DKS 4351 yield attributes across the years 2023 to 2025: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

A slight rise in starch occurred with extended growth durations, alongside denser planting arrangements and greater fertilizer application.

In maize hybrid DKS 3795 (FAO 280), starch content ranged from 71.4 to 73.0%; in DKS 3972 (FAO 300) from 71.9 to 73.0%; and in DKS 4351 (FAO 350) from 72.0 to 73.4%.

Conversely, the quantity of starch generated showed a tighter link to grain harvest obtained within each distinct test setup. The lowest level of starch creation was in the control group (that is, where no sort of fertilizer was administered). In hybrid DKS 3795 (FAO 280), starch yield ranged from 3.4 to 3.5 t/ha; in DKS 3972 (FAO 300) it was 3.7 t/ha; in DKS 4351 (FAO 350) from 3.6 to 3.7 t/ha.

Raising the plants/ha, specifically moving from 60000 to 80000, resulted in a modest boost in the starch level: in DKS 3795 (FAO 280) by 0.2–0.8%, with starch yield increasing by 0.1–0.4 t/ha; in DKS 3972 (FAO 300) by 0.2–0.6%, with starch yield increasing by 0.4–0.6 t/ha; in DKS 4351 (FAO 350) by 0.2–0.4%. Yet, as the plant density and fertilization level were pushed higher, the resulting starch output saw a drop of between 0.1 and 0.5 t/ha.

The largest starch output appeared in the experimental group where maize crop nutrition was made optimal by supplementing with macro- and micronutrients via joint using Ecoline boron, Ecoline zinc, zinc sulfate, all applied over a base of mineral fertilizers dosed at $N_{100}P_{31}$: in hybrid DKS 3795 (FAO 280) at 70000 plants/ha – 6.3 t/ha; in DKS 3972 (FAO 300) – 7.3 t/ha; in DKS 4351 (FAO 350) at 60000 plants/ha – 6.8 t/ha. Yet, a comparison against the control group revealed that starch yields were diminished: specifically by 0.4% for DKS 3795, by 0.8% for DKS 3972, and by 0.5% for DKS 4351. A similar pattern of starch content formation depending on macro- and micronutrient application in dense and sparse stands was noticed.

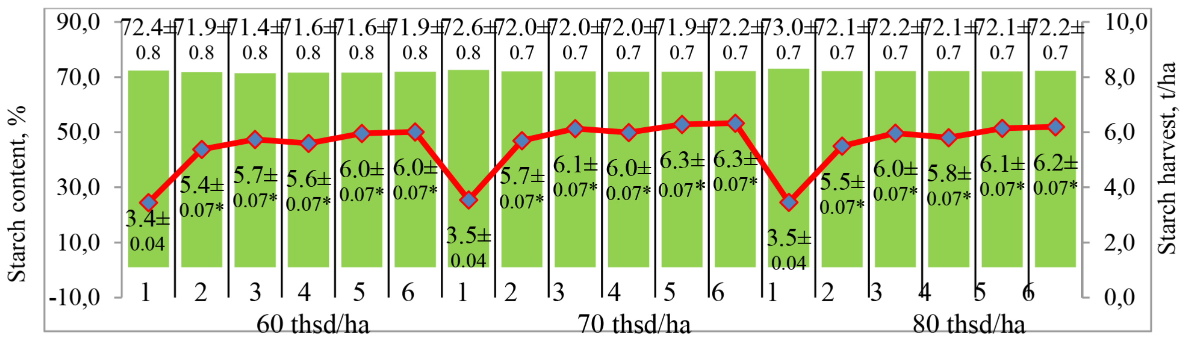

Figure 4. Starch quantity and harvest outcome in maize hybrid DKS 3795 as functions of plant population and nutrient application: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

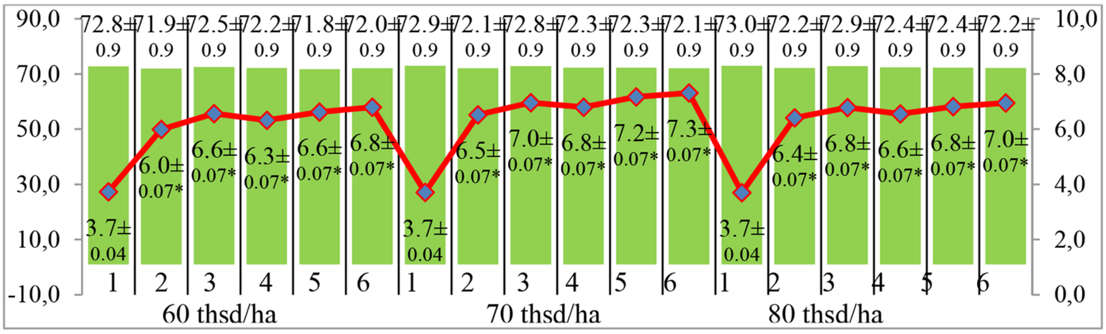

Figure 5. Starch quantity and harvest outcome in maize hybrid DKS 3972 as functions of plant population and nutrient application: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

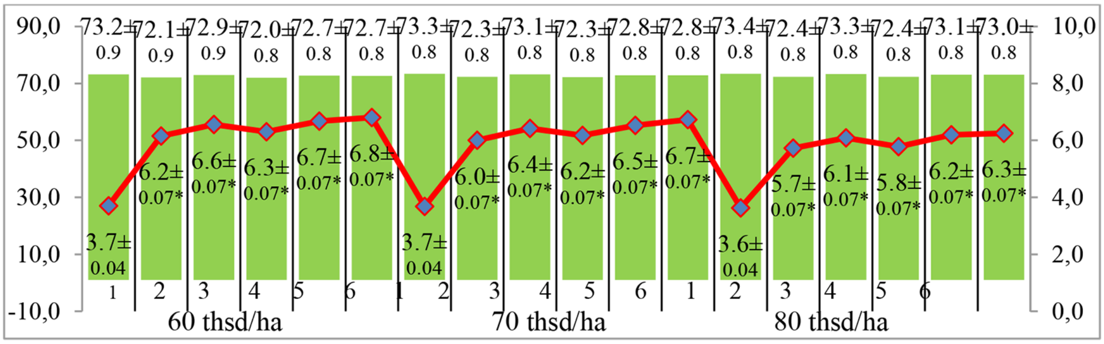

Figure 6. Starch quantity and harvest outcome in maize DKS 4351, investigated relative to functions of plant population and nutrient application: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

For bioethanol production, particular attention is paid to the starch content in grain, whereas the significance of protein levels for dietary applications takes precedence. The kernels of maize constitute a major feedstock in the manufacturing of bioethanol. Simultaneously, residues left over from harvesting this crop offer potential for creating solid biofuels. Maize stalks possess a significant energy content, hovering around 12.5 megajoules per kilogram, surpassing the energy density of limbs from fruit-bearing trees by a margin of eighteen to twenty percent. When set against alternative crops employed in creating bioethanol, maize grain boasts a notably elevated starch concentration, consequently delivering the greatest output of bioethanol achievable from a given tract of land (Polishkevych, 2011).

Table 2 displays the bioethanol output achievable per land unit, which varies considering the fertilization level and plant population.

Accordingly, the experimental setup showed the peak bioethanol output that featured the most intensive maize cropping methods, specifically where Ecoline boron, Ecoline zinc, zinc sulfate were administered concurrently, all built upon a base fertilization rate of $N_{100}P_{31}$. As the concentration of plants/ha was raised from sixty thousand to eighty thousand, the resulting bioethanol productivity across the maize varieties displayed the subsequent pattern: DKS 3795 – 3.3; 3.5; 3.4 thsd. l/ha; DKS 3972 – 3.7; 4.1; 3.8 thsd. l/ha; and DKS 4351 – 3.7; 3.7; 3.4 thsd. l/ha. This exceeded the control treatment by 1.4; 1.5; 1.5 thsd. l/ha in DKS 3795; by 1.6; 2.0; 1.7 thsd. l/ha in DKS 3972; and by 1.7; 1.7; 1.4 thsd. l/ha in DKS 4351.

A correlation linking the observed protein levels with the thermal environment conditions experienced throughout the maize plant's growth cycle was discovered. Maize kernels exhibited a tendency to accrue greater amounts of protein when exposed both to increased temperatures and a slight deficit in moisture.

Consequently, the circumstances involving hydrothermal factors throughout 2024 were

Table 2. The ethanol output from biomass, measured in thousands of liters per hectare, determined as nutrient application and plant population (average for 2023–2025)

Hybrid (factor A)	Fertilization (factor C)	Plant density, thsd/ha (factor B)		
		60	70	80
DKS 3795 (FAO 250)	No fertilizers (control sample)	1.9	2.0	1.9
	$N_{100}P_{31}$ (background)	3.0	3.1	3.0
	Background + zinc sulfate	3.2	3.4	3.3
	Background + Ecoline zinc	3.1	3.3	3.2
	Background + zinc sulfate + Ecoline boron	3.3	3.5	3.4
	Background + zinc sulfate + Ecoline zinc + Ecoline boron	3.3	3.5	3.4
DKS 3972 (FAO 300)	No fertilizers (control sample)	2.1	2.1	2.1
	$N_{100}P_{31}$ (background)	3.3	3.6	3.5
	Background + zinc sulfate	3.6	3.8	3.7
	Background + Ecoline zinc	3.5	3.7	3.6
	Background + zinc sulfate + Ecoline boron	3.6	3.9	3.8
	Background + zinc sulfate + Ecoline zinc + Ecoline boron	3.7	4.1	3.8
DKS 4351 (FAO 350)	No fertilizers (control sample)	2.0	2.0	2.0
	$N_{100}P_{31}$ (background)	3.4	3.3	3.2
	Background + zinc sulfate	3.6	3.5	3.4
	Background + Ecoline zinc	3.5	3.4	3.2
	Background + zinc sulfate + Ecoline boron	3.7	3.6	3.4
	Background + zinc sulfate + Ecoline zinc + Ecoline boron	3.7	3.7	3.4
LSD_{05}: A – 0.03 B – 0.03; C – 0.5; AB – 0.6; AC – 0.1; BC – 0.1; ABC – 0.17				

conducive to elevated protein levels development. There exists a recognized negative relationship linking the protein and starch found within maize kernels; specifically, as one constituent rises, the other correspondingly diminishes (Palamarchuk and Kolisnyk, 2022).

The study findings substantiate this correlation; precisely, as the protein rises, the rate at which carbohydrates, namely starch, accumulate within the grain decreases. Fluctuations were observed in protein quantities of grain among different maize hybrids. For hybrid DKS 3795 (FAO 280 sector), the protein concentration spanned from 8.79% up to 9.91%. In the case of DKS 3972 (FAO 300 category), this varied between 8.67% and 9.85 %. Meanwhile, DKS 4351 (FAO 350 group) exhibited a range from 8.69% to 10.2%. The variations depended upon the precise quantities of nutrients and proximity of the vegetation. (Figures 7–9).

The minimum protein level was in unfertilized control groups: for the DKS 3795 variety (FAO 280), this ranged between 8.79% and 9.09%; for DKS 3972 (FAO 300), it ranged from 8.67% to 8.94%; and for DKS 4351, it fell between 8.69% and 9.22%. These figures correlated with a lower stand density (reduced from 80000 to 60000 plants/ha). Enhanced feeding with primary nutrients led to a rise in protein levels across different maize varieties.

Specifically, for DKS 3795 (FAO 280), the protein moved from 9.56% to 9.83%; for DKS 3972 (FAO 300), it climbed from 9.49% to 9.68%; and DKS 4351 saw an increase from 9.68% to 10.05%. These gains were observed when planting density was lowered (from 80000 down to 60000 plants/ha). Consequently, when pitted against the initial baseline, the protein concentration saw increments of 0.77 and 0.74% for DKS 3795 (FAO 280), while DKS 3972 (FAO 300) registered increases of 0.82 and 0.74%, as for latter two instances, the jumps were 0.99 and 0.83%.

The experimental cohort benefiting from most complete dietary modifications concerning the maize cultivars, encompassing both primary and trace elements, unveiled the utmost surge in protein concentration. This superior outcome resulted from the simultaneous use of Ecoline boron, Ecoline zinc, zinc sulfate, all applied atop a

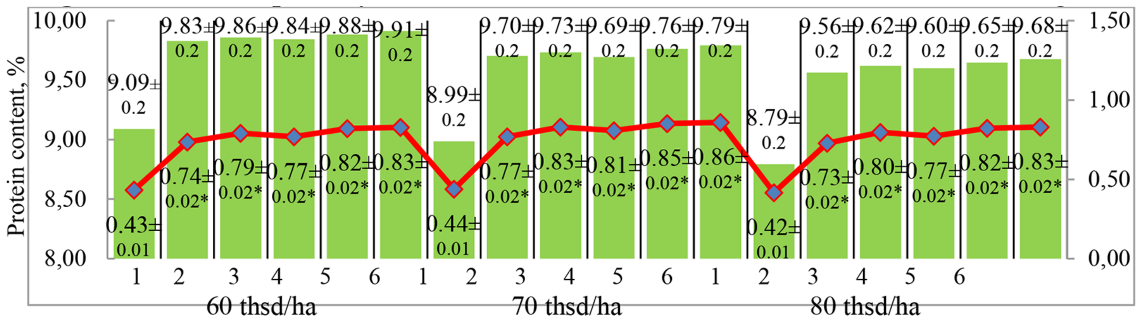

Figure 7. Protein quantity and harvest outcome in maize DKS 3795, investigated relative to functions of plant population and nutrient application: * 1 – no fertilizers (control); 2 – N_{100}, P_{31} (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

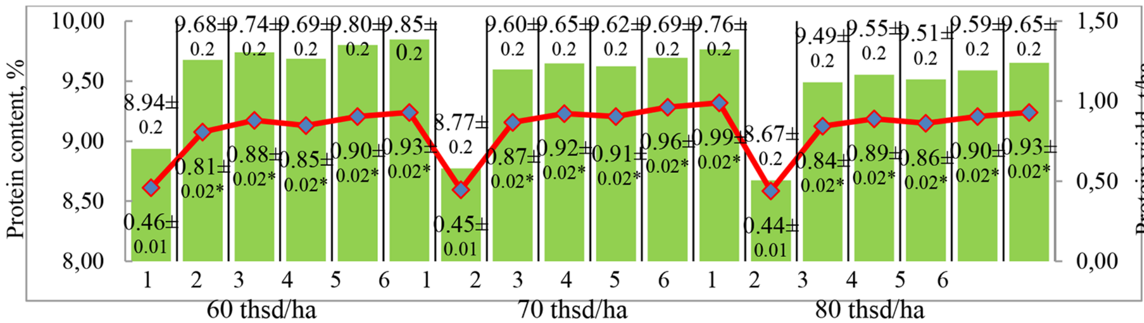

Figure 8. Protein quantity and harvest outcome in maize DKS 3972, investigated relative to functions of plant population and nutrient application: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

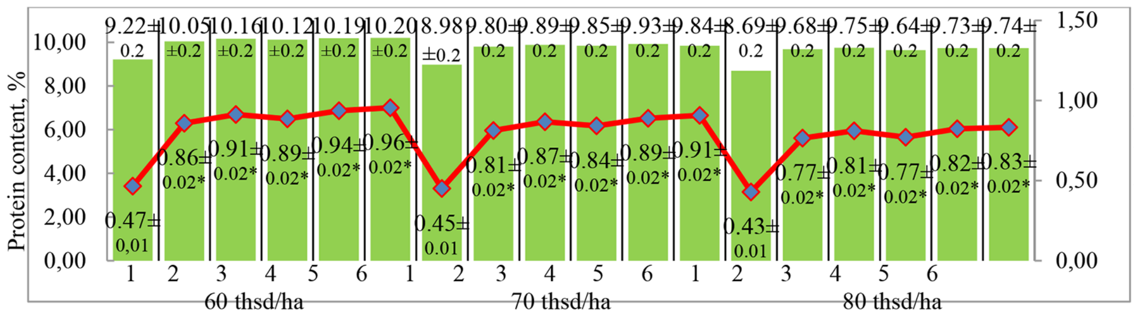

Figure 9. Protein quantity and harvest outcome in maize DKS 4351, investigated relative to functions of plant population and nutrient application: * 1 – no fertilizers (control); 2 – $N_{100}P_{31}$ (background); 3 – background + zinc sulfate; 4 – background + Ecoline zinc; 5 – background + zinc sulfate + Ecoline boron; 6 – background + zinc sulfate + Ecoline zinc + Ecoline boron

base dressing of mineral fertilizer at the $N_{100}P_{31}$ rate. The protein percentages across the maize varieties were measured within these ranges: DKS 3795 (FAO 280) registered between 9.68% and 9.91%; DKS 3972 (FAO 300) varied from 9.65% to 9.85%; DKS 4351 (FAO 350) showed results fluctuating between 9.74% and 10.2%. The findings corresponded to a lower stand density, specifically 60000 plants/ha, down from the initial 80,000. Consequently, with the unprocessed control, the protein yield saw enhancements of 0.89% and 0.82% for DKS 3795 (FAO 280), 0.98% and 0.91% for DKS 3972 (FAO 300), and 1.05% and 0.98% for DKS 4351 (FAO 350).

Protein extraction per surface area unit depended less on the mere protein concentration and much more heavily on the total volume of grain harvested. Maximal protein recovery manifested in the trial where a combination of Ecoline Boron, Ecoline zinc, zinc sulfate was administered over a substrate of mineral fertilizers precisely dosed as $N_{100}P_{31}$. Under these precise conditions, the harvested protein reached 0.86 t/ha for the DKS 3795 variety (FAO rating 280) and 0.99 t/ha for the DKS 3972 variety (FAO rating 300), both cultivated at a density of 70,000 plants/ha. Correspondingly, for the DKS 4351 hybrid (FAO rating 350), planted at 60,000 plants/ha, the protein output reached 0.96 t/ha. Relative to the non-treated baseline group, these results signified enhancements of 0.42, 0.54, and 0.49 t/ha.

Thus, protein levels exhibited a steady downward trend as the plant density rose from 60000 to 80000 units per ha. Specifically, hybrid DKS 3795 (FAO 280) saw a reduction of 0.2–0.3%, hybrid DKS 3972 (FAO 300) experienced a 0.2–0.3% drop, and hybrid DKS 4351 (FAO 350) displayed a decrease ranging from 0.3% to 0.5%.

CONCLUSIONS

The peak yield was attained when the technological measures designed to perfect the supply of essential macro- and micronutrients were maximized (specifically, integrating Ecoline boron, Ecoline zinc, zinc sulfate alongside an $N_{100}P_{31}$ base) and when plant population density was concurrently fine-tuned to reach an equilibrium between the number and resources accessible. To illustrate, maize hybrid DKS 3972 produced 10.1 t/ha, and DKS 3795 yielded 8.8 t/ha, both at a density of 70000 plants/ha. Meanwhile, hybrid DKS 4351 attained 9.4 t/ha as grown at a density of 60000 plants/ha.

Starch concentration reached its peak in the unfertilized control group, exhibiting a trend where higher densities led to elevated levels. Nonetheless, the greatest starch output per m^2 was achieved where macro- and micronutrients were optimally supplied, principally because of a superior grain harvest. Under this optimal nutrient regime, starch generation hit 6.3 t/ha for hybrid DKS 3795 (FAO 280) at 70000 plants/ha, 7.3 t/ha for hybrid DKS 3972 (FAO 300), and 6.8 t/ha for hybrid DKS 4351 (FAO 350) at 60000 plants/ha. This identical fertilization approach also led to the maximum bioethanol output. Adjusting plant population from 60000 to 80000 plants/ha triggered the bioethanol yield figures to shift: for DKS 3795, the yields were 3.3, 3.5, and 3.4 thsd. l/ha; for DKS 3972, they were 3.7, 4.1, and 3.8 thsd. l/ha; and for DKS 4351, they were 3.7, 3.7, and 3.4 thsd. l/ha. These increases, relative to unfertilized plots, in bioethanol production amounted to 1.4, 1.5, and 1.5 thsd. l/ha for hybrid DKS 3795; 1.6, 2.0, and 1.7 thsd. l/ha for hybrid DKS 3972; and 1.7, 1.7, and 1.4 thsd. l/ha for hybrid DKS 4351, correspondingly.

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