Vol. 10 No. 5, 2024
DOI: https://doi.org/10.30525/2256-0742/2024-10-5-293-304

ENERGY AND ECONOMIC EFFICIENCY OF BIOETHANOL PRODUCTION DEPENDING ON THE QUALITY OF CORN GRAIN

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Abstract. The present article expounds upon the findings of research conducted on the energy and economic efficiency of bioethanol production, with the quality of corn grain taken as the primary variable. The research was conducted at the experimental field of Vinnitsa National Agrarian University in the conditions of the state enterprise "Kordelivske" of the Institute of Potato Growing of the National Academy of Agrarian Sciences of Ukraine in 2015-2017. The cultivation techniques incorporated elements that are widely accepted for the growing zone, with the exception of the factors under study. The elements of the yield structure, including the productivity of maize hybrids, were determined in accordance with established methods. The harvesting and accounting of the crop was conducted manually at each experimental site, followed by weighing and conversion to standard grain moisture. The yield of bioethanol from grain was calculated as the amount of ethanol obtained from a ton of carbohydrates in terms of starch, i.e., the ethanol yield. The purpose of the article is to assess the energy and economic efficiency of bioethanol production depending on the quality of corn grain. The results of studies of the influence of foliar fertilisation with a bacterial preparation based on beneficial symbiotic and associative microorganisms Biomag, microfertilisers "ROSTOK" corn, Ecolist Mono Zinc, carried out in the phase of 5-7 and 10-12 leaves of corn, on the level of pre-harvest grain moisture, the number of rows of grains are presented, number of grains in a row, weight of 1000 grains, starch content in grain, productivity and bioethanol yield in hybrids of early maturing group Kharkiv 195 MV (FAO 190) and DKS 2971 (FAO 200), medium early group DKS 3795 (FAO 250) and DKS 3871 (FAO 2480) and medium maturing group DK 315 (FAO 310) and DK 440 (FAO 350) in agro-ecological conditions of the Forest-Steppe of Right-Bank Ukraine. The research is grounded in an evaluation of the efficacy of optimising the supply of plant nutrients through foliar fertilisation in the formation of grain yield and quality. Additionally, it explores the potential for grain processing into bioethanol, contingent on the augmentation of grain yield and the attainment of acceptable quality. Corn is the most productive source of purified bioethanol from biomass feedstocks, and the price of 1 ton of bioethanol is higher than that of sugar beet, creating a favourable environment for the production of this type of biofuel. From an economic perspective, bioethanol production from corn is one of the most efficient options for bioethanol production in Ukraine. It has been established that the production of bioethanol from maize grain is an innovative technology: it improves the ecological situation and reduces harmful effects on the human body and the environment. The use of maize as a raw material partially resolves the existing conflict of interest associated with the use of food resources for bioethanol production. In turn, the opening of maize processing plants for bioethanol, with the production of biomethane and organic fertilisers, is a very profitable business.

Keywords: maize, bioethanol, nutrients, trace elements, pre-harvest moisture starch, yield, foliar feeding.

JEL Classification: O13**,** Q16, Q42

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1. Introduction

In the contemporary context, the prospect of generating alternative forms of energy from renewable raw materials has become a matter of pressing concern. The production of bioethanol from sugar- and starch-containing raw materials, as well as lignocellulosic biomass, is of considerable significance (Bušić et al., 2018; Saha et al., 2022; Adiya et al., 2022).

It is imperative to explore alternative fuel sources, given the significantly slower natural recovery rate of fossil resources through the carbon cycle in comparison to their current rate of exploitation (Honcharuk et al., 2023). Theoretically, biofuels have the potential to eventually substitute for fossil fuels, including oil and gas (Kaletnik et al., 2020; Kumar et al., 2020).

Ukraine is a powerful agrarian country with the capacity to produce a significant amount of plant products for food, fodder, and energy purposes (Lohosha R. et al., 2023). The potential of its biomass available for energy use is estimated at 27 million tons of conventional fuel per year (Kaletnik et al., 2021). A total of 575 bioethanol plants are in operation worldwide, with a combined production capacity of 80.631 million tons. The global oil saved from bioethanol is 50 million tons. Nevertheless, despite the implementation of numerous regulations pertaining to bioethanol production, Ukraine has yet to establish a definitive state policy on energy security and the market for alternative fuels.

Until 2010, Ukraine was a major producer of food alcohol. The total annual capacity of distilleries was around 500-700 million litres. Unfortunately, a large number of these enterprises are operating at full capacity or are completely idle. As of 2022, there are about 5 bioethanol plants operating at full capacity in Ukraine, using different raw materials and selling their products to Europe (Haiduk, 2022). With 40 million tonnes of maize in Ukraine, there could be a surplus of 17 million tonnes. At present, the country processes 5 million tonnes of maize into alcohol, which is very little because processing into bioethanol does not require high quality grain (Palamarchuk et al., 2021).

2. Literature Review

Bioethanol has recently become a key element of energy policy aimed at meeting growing energy demand and ensuring sustainable economic development. The main world producers of bioethanol in 2020 were the United States and Brazil. Their combined production accounted for 84% of the total. China, India and Canada also have relatively large market shares, with 3%, 2% and 2% respectively. The EU is also a significant producer, led by France, Germany and Hungary. (Analysis of the bioethanol market in Ukraine and the world, 2023).

In Brazil, 60% of fuel has been replaced by locally produced ethanol since the 1970s, and there is a law requiring that at least 20% ethanol be added to petrol. The development of bioethanol production in Brazil was dictated by the need to support sugar producers, who were in a difficult position due to quotas on the supply of their products in a number of countries, including the EU. The EU directives also establish the standard for bioethanol in automotive fuel at 10%, given its capacity to reduce emissions of harmful aerosol particles by 50% and carbon monoxide by 30%. It is a common practice for all gasoline sold in the EU to contain 10% ethanol.

If Ukraine mandates a 7% bioethanol content in fuel next year, the bioethanol market will open up three times, and the deregulation of 100,000 tonnes of exports will increase the potential fivefold.

Currently, ethanol as a fuel source has a positive impact on rural areas and contributes to improving the environment and strengthening US energy security. Bioethanol produced from corn and wheat is a first-generation biofuel as it uses only hexose sugars, which are subject to fermentation (Mohanty & Swain, 2019).

In 2019, global bioethanol production was around 30 billion gallons, with the main producers being the US, Brazil, China and the EU, and the main feedstocks being sugarcane and corn (Letti et al., 2019).

According to the State Statistics Committee of Ukraine, 70 million tonnes of grain were harvested in 2022, including 35.8 million tonnes of maize. Ukraine ranks 5th in the world in maize production, but unfortunately it trades in raw materials rather than products and does not supply even 1% of its own biofuels.

Argentina harvests 37 million tonnes of maize and produces 900,000 tonnes of bioethanol, while Ukraine produces only 80,000 tonnes. Poland harvests 4.5 million tonnes of maize per year and produces 800 tonnes of bioethanol.

Among biofuels, bioethanol from maize has great potential due to its high starch content, higher hybrid yields, substrate availability and technological know-how (Banerjee et al., 2019). Unlike the alcohol from which alcoholic drinks are made, fuel ethanol (octane number 105) contains no water (it is at least 99% ethyl alcohol) and is produced by shortened distillation (two distillation columns instead of five), so it contains methanol and oils (Holub et al., 2017; Burlaka et al., 2019). In addition to bioethanol, the production process also produces a valuable feed additive – bard (or bran, i.e., a high-protein supplement fed to animals) and carbon dioxide (Haiduk, 2022).

Corn is a leading agricultural crop that provides the bulk of the gross volume of grain in Ukraine and makes it possible to obtain biofuels (Kurambhatti et al., 2018;

Dudka et al., 2020) of the first and second generations (Heletukha, 2020).

In 2019, the area dedicated to corn cultivation in Ukraine amounted to 4.9 million hectares, constituting 17.5% of the total cropping area. By 2021, this figure had increased to 5.5 million hectares. However, in 2022, the area was significantly reduced to 4.267 million hectares due to the aggression of Russia (Palamarchuk et al., 2018). The potential yield from these cropping areas is estimated at 25 million tons of corn grain.

In Europe, approximately 50% of the total volume of biofuel is derived from corn grain. Conversely, the share of advanced bioethanol (from lignocellulosic and analogous raw materials) is a mere 8% (Heletukha & Zheliezna, 2023). A significant number of developed countries, including the USA, Brazil, France, Germany, India, China, and others, utilise corn as a primary raw material for bioethanol production (Chen et al., 2018; Lin et al., 2021; Han et al., 2022; Wang et al., 2023). In certain nations, the production of bioethanol is regarded as a pivotal factor in ensuring national energy security.

According to the FAO and OECD, global bioethanol production has exceeded 100 billion litres (80 million tonnes) (Holub et al., 2017), with 575 plants involved in bioethanol production worldwide.

The advantage of maize as a feedstock for bioethanol production is that it is widely available and requires little nitrogen to produce high yields (Wang et al., 2023; Lin et al., 2023). The average yield of bioethanol (100% ethanol) from different crops is as follows: maize 370-470 l/t, barley – 240-380 l/t, wheat – 340-445 l/t (Palamarchuk et al., 2018), rye and winter triticale – 280-428 l/t, millet – 390 l/t, sorghum – 464 l/t, potato – 90-140 l/t, sugar beet – 100 l/t (Marchenko & Kit, 2018).

The main criterion for raw material selection is accessibility and availability for processing 365 days a year. The cost of feedstock accounts for 70-80% of the cost of ethanol and the availability of feedstock determines the profitability of production. As corn can be left undried for processing, this can reduce the price of the raw material (Haiduk, 2022).

The production of 1.0 t of bioethanol necessitates the cultivation of 0.64 ha of wheat or 0.47 ha of corn (Kaletnik et al., 2021). It should be noted that 1 liter of bioethanol equates to 0.79 kg.

Maize, as a typical representative of plants having C4 type of photosynthesis, has a high yield due to higher photosynthetic activity compared to C3 plants (Heletukha et al., 2020). In a relatively brief period, corn has been shown to yield a greater quantity of organic matter in comparison to other crops (Kumar et al., 2020). According to the National Corn Growers Association of the USA, the maximum yield of corn grain of approximately 38.7 t/ha (616.2 bushels/acre) was obtained in Virginia in 2019 (Heletukha et al., 2020).

In terms of farming technology, corn cleans the soil well from weeds, it is more cost-effective and is a good preceding crop in crop rotation for most crops. As for carbon dioxide absorption and oxygen release, corn ranks first among all cultivated plants and is even more efficient than a forest in the same area (Kaletnik et al., 2021). Growing corn for grain makes it possible to optimize the use of agricultural machinery due to later sowing and harvesting terms.

The formation of corn grain of a quality suitable for processing into bioethanol is influenced by a number of factors. These include technological factors (Kaminskyi & Asanishvili, 2020), growing conditions, and the selection of hybrids that is appropriate to specific soil and climatic zone characteristics (Palamarchuk et al., 2021), as well as the characteristics of plant growth and development (Chen X. et al., 2013). The pivotal factor that enhances the yield and optimises the quality of corn grain (starch accumulation) is the effective provision of macro- and microelements to plants in science-based fertilisation systems (Galindo et al., 2022). Grain starch is constituted by an average of 20-25% amylose (a linear glucose polymer) and 70-75% amylopectin (a branched glucose polymer) (Palamarchuk et al., 2021).

Spraying maize plants with microfertilisers can be an effective way of providing plants with trace elements during the growing season, ensuring a 5-20% increase in yield (Dudka et al., 2020). Foliar nutrition is particularly effective in years characterised by adverse weather conditions (Moldovan & Sobchuk, 2018).

3. Materials and Methods

The research was conducted at the experimental field of the Department of Plant Breeding and Horticulture of Vinnytsia National Agrarian University in the conditions of the state enterprise "Kordelivske" of the Institute of Potato Growing of the National Academy of Sciences of Ukraine in 2015-2017.

The soils were deep medium loamy chernozems on loess. According to the results of the last comprehensive agrochemical analysis, the humus content was 4.60%. Soil reaction was pH (saline) 5.7; weighted average: hydrolytic acidity – 40 mg-eq per 1 kg of soil; number of absorbed bases – 158 mg-eq per 1 kg of soil; degree of saturation with bases -82.3%.

The climate of the study area was moderately warm. In 2015, in the second half of July – first half of August, the maize grain crop was formed under the influence of unusually high temperatures, which remained at the level of +23...+25 °C at night and reached a maximum of +34...+37 °C during the day. In 2016, the rapid increase in heat and dry weather contributed to soil desiccation; fluctuations in average daytime temperatures and a decrease in nighttime temperatures to +4...+7 °C had a somewhat negative effect on maize development; hot weather was observed. In 2017, the weather was moderately warm with significant precipitation.

Farming techniques included those generally accepted for the growing area, with the exception of the factors studied.

The determination of the elements of the crop structure (10 cobs in each replicate), including the productivity of maize hybrids, was carried out using generally accepted methods (Lebid et al., 2008; Moldovan & Sobchuk, 2018).

Grain moisture content was determined using an automatic moisture meter "Wile – 55".

Starch content in corn grain per completely dry matter was determined with an accuracy of 0.01% according to the formula:

$$S(\%) = \frac{a \times C \times 100}{100 - w};$$

where: S – starch content, %;

a – average indicator of the sugar meter; C is the Evers coefficient (1.898) (depends on the type of starch);

w – hygroscopic water, % (DSTU 4863:2007).

The harvesting and subsequent recording of the harvest were performed manually at each experimental site. These were then followed by the weighing of the harvested material and its conversion to standard grain moisture (Lebid et al., 2008).

Bioethanol yield from grain was calculated as ethanol yield – the amount of ethanol obtained from a tonne of carbohydrates in terms of starch. The theoretical yield is calculated using the alcoholic fermentation equation: $C_6H_{12}O_6=2C_2H_5OH+2COA_2$. 100 kg of hexose forms 51.14 kg of anhydrous ethanol and 48.86 kg of carbon dioxin. At the relative density of ethanol $d^4_{20}=0,78927$, its theoretical output is 64.79 liters (Blium et al., 2010).

4. Results and Discussion

With the increasing production of bioethanol worldwide and in Europe and its use as an alternative fuel, mainly in the transport sector, it is necessary to analyse and optimise the economic aspects of this process in order to reduce production costs and increase the competitiveness of biofuels compared to fossil fuels. In this context, the choice of affordable and suitable feedstock is crucial, as its cost represents the majority of the total production cost.

In 2018, the selling price of bioethanol in Ukraine was 0.61 EUR/l, and in Europe – 0.96 EUR/l. The cost of processing corn and producing 1 litre of alcohol is 3.71 USD. Accordingly, 1 dal equals 10 litres of alcohol (Zhelezna et al., 2018).

The primary countries responsible for the production of bioethanol are the United States, Brazil, France, Germany, Spain, China, and Canada. The estimated yields of various crops and the potential bioethanol yields from biological feedstocks are presented in Table 1.

As demonstrated in Table 1, corn is one of the primary crops in bioethanol production, both in Ukraine and on a global scale. Specifically, in the US, approximately 40% of the corn crop (130 million tons per year) is processed to produce corn ethanol. The yield of bioethanol from 1 ton of corn grain ranges from 400 to 500 liters.

From the standpoint of self-sufficiency in energy resources, Ukraine is an energy-deficient country, with a fuel consumption of approximately 200 million tons, of which a mere 53% is produced domestically. Consequently, it is imperative for Ukraine to explore alternative energy sources, with a concurrent decline in the utilisation of fossil fuels, primarily through agricultural products (Yawson et al., 2020).

In the context of military operations and the refusal to supply energy from Belarus and Russia, the most effective solution is to use the existing agricultural potential of grain crops for phytoenergy. Corn plays an important role in phytoenergy for bioethanol production (Table 2), as in the world practice, including in Ukraine, corn is used as a universal crop – for livestock feed, for food and technical needs – production of cereals and flour, food starch and vegetable oil, honey and sugar, dextrin and ethyl alcohol, etc.

Table 1
Estimated yields of different crops and possible bioethanol output from biomass

Culture (bio-raw materials)	Average yield, t/ha	Ethanol yield	
		From 1 ton of raw materials, l/t	Per 1 hectare, l/ha
Sugar beet	90,0	100	9000
Jerusalem artichoke	30,0	87	2610
Corn for grain	7,0	416	2912
Wheat	5,0	395	1975
Barley	5,8	370	2150
Sugar cane	65,0	70	4550
Cassava	12,0	180	2160

Source: Facts on health and the environment. Biofuel yields for different feedstocks

Table 2
Feedstock for bioethanol production in Ukraine

Raw materials	Demand for production of 220 thousand tonnes of bioethanol	Average production in Ukraine per year (2012-2022), thousand tonnes
Molasses	946	551,7
Sugar beet (in sugar production using molasses as a waste product)	23650	13972
Corn	660	22500

Source: compiled by the authors

The potential for producing bioethanol from maize grain: by processing 10 million tonnes of maize alone, Ukraine can produce at least 4 million tonnes of this biofuel. Over the past half century, the area under maize has increased by 1.6 times, the yield by 3 times and the gross grain harvest by 4.8 times.

An important component of the efficient use of maize grain for bioethanol production is the economic justification of its production from different types of biomass (Table 3).

Corn provides the highest yield of purified bioethanol from biomass feedstocks, and the selling price of 1 tonne of bioethanol is higher than that of sugar beet, which creates conditions for the production of this type of biofuel. From an economic point of view, bioethanol production from maize is one of the most efficient options for bioethanol production in Ukraine.

According to the research results, the influence of maturity group, biological characteristics of hybrids and foliar nutrition on the formation of elements of the plant structure was established (Table 4).

Grain moisture content has changed significantly over the years of research, in particular, in 2015 it averaged 21.87% in the studied hybrids, in 2016 – 24.65%, and in 2017 – 27.35%, which is due to different amounts of precipitation during the maize growing season and especially during the grain ripening period "September-October" (Table 4).

The maturity group of hybrids (factor A) also influenced the pre-harvest grain moisture content of the studied corn hybrids, in particular in the group of early hybrids. Over the course of three years of research, the mean values were as follows: 21.88% for the early hybrids, 24.42% for the mid-early hybrids, and 27.57% for the mid-early hybrids. Furthermore, the growth of grain moisture content in hybrids with an extended growing season was 2.54-5.69%, in comparison to the early ripening group.

Biological features of hybrids (factor B) provided different values of pre-harvest grain moisture content, in particular, Kharkiv 195 MV – 21.81%, DKS 2971 – 21.95%, DKS 3795 – 24.72%, DKS 3871 – 24.13%, DK 315 – 26 .88%, and DK 440 – 28.26%. Consequently, it is feasible to exert an influence on grain moisture indicators during the harvesting period by selecting hybrids even within the same maturity group.

The application of foliar nutrition with the bacterial agent Biomag, micro-fertilizers Ecolist Mono Zinc, and "Rostok" corn resulted in an enhancement of the rate of grain moisture content. Specifically, a single foliar nutrition in the phase of 5-7 corn leaves increased the grain moisture content of the studied corn hybrids by 1.59% (24.49%), and a double foliar nutrition in the phase of 5-7 and 10-12 corn leaves increased it by 2.21% (25, 11%), compared to the control variant (without feeding) – 22.89%.

Consequently, foliar nutrition has been demonstrated to enhance the level of pre-harvest grain moisture content by 1.59-2.21%, in comparison to the control variant (i.e., without feeding).

The number of kernel rows in the maize hybrids studied ranged from 13.7 to 16.6. This characteristic is genetically determined, but at the same time it has changed over the years of research, in particular in 2015 it was 14.38 units on average in the studied maize hybrids, 15.30 in 2016 and 14.86 in 2017.

The maturity group of hybrids was found to be a contributing factor to alterations in the number of kernel rows. Specifically, an average of 13.88 was observed in the group of early hybrids, 14.45 in the mid-early group, and 16.21 in the mid group.

Table 3
Economics of bioethanol production from different types of biomass

Bioenergy culture	Yields t/ha	Bioethanol yield, t/ha	Yield of purified bioethanol per 1 t. of product, t.	Sales price 1 tonne of bioethanol (including VAT), UAH.
Jerusalem artichoke	30	1,76	0,098	31913,3
Corn	7	1,38	0,230	12122,8
Sugar beet	50	4,015	0,080	5783,7

Source: based on the data (Sigayov, 2012)

Furthermore, a discrepancy in the number of kernel rows was identified within the hybrids that were the focus of this study. The mid-hybrid DK 440 exhibited the highest number of kernel rows (16.6), followed by DK 315 (16.06), DKS 3871 (14.22), DKS 3795 (14.68), DKS 2971 (13.75), and Kharkiv 195 MV (14.01).

The application of a single foliar nutrition with a bacterial agent and microfertilisers resulted in 14.80 rows of kernels, a double one – 14.92, while in the control variant this indicator was 14.68. Thus, due to the optimisation of plant nutrition, the foliar nutrition provides a 0.12-0.24-fold increase in the number of kernel rows compared to the control variant (no nutrition).

On average, over the three years of research, the number of grains per row in the early group of maize hybrids was 39.44, the mid-early group – 40.82, and the middle group – 43.23.

Table 4
Effect of foliar nutrition on the formation of productivity elements of maize hybrids, (average for 2015-2017 ±Sx)

Maturity group (A)	Hybrid (B)	Foliar nutrition (C)	Number of feedings (D)	Elements of productivity			
				Grain moisture, %	Number of kernel rows, units	Number of kernels per row, pcs	Weight of 1,000 grains, g
1	2	3	4	5	6	7	8
Early group	Kharkiv 195 MB	Control***	-	20.1±3.1	13.7±0.5	36.6±0.5	233.2±11.5
Early group	Kharkiv 195 MB	Biomag	I*	21.8±3.4	13.8±0.6	37.6±0.3	234.7±10.0
Early group	Kharkiv 195 MB	Biomag	II*	22.2±3.4	14.0±0.6	38.2±0.8	246.7±6.4
Early group	Kharkiv 195 MB	"Rostok" corn	I*	21.1±3.3	13.7±0.5	37.4±0.4	239,.±10.0
Early group	Kharkiv 195 MB	"Rostok" corn	II*	21.9±2.8	13.8±0.6	39.1±1.1	247.7±5.1
Early group	Kharkiv 195 MB	Ecolist Mono Zink	I*	21.9±3.3	14.0±0.7	38.0±0.8	250.2±4.6
Early group	Kharkiv 195 MB	Ecolist Mono Zink	II*	22.4±3.3	14.4±0.6	38.9±1.2	254.9±5.5
Early group	Kharkiv 195 MB	Biomag + "Rostok" corn	I*	21.7±3.2	13.8±0.5	37.6±0.5	239.9±8.6
Early group	Kharkiv 195 MB	Biomag + "Rostok" corn	II*	22.1±3.1	14.3±0.6	38.1±0.5	246.3±3.7
Early group	Kharkiv 195 MB	Biomag + Ecolist Mono Zink	I*	22.1±3.3	14.1±0.6	37.8±0.6	254.9±5.0
Early group	Kharkiv 195 MB	Biomag + Ecolist Mono Zink	II*	22.6±3.4	14.6±0.5	38.5±0.9	259.5±4.5
Early group	DKS 2971	Control	-	20.8±2.4	13.6±0.5	38.6±1.0	249.2±10.0
Early group	DKS 2971	Biomag	I*	21.3±3.0	13.7±0.5	40.6±1.1	261.0±11.2
Early group	DKS 2971	Biomag	II*	21.8±3.0	13.7±0.5	41.1±1.3	268.0±10.7
Early group	DKS 2971	"Rostok" corn	I*	22.0±2.9	13.7±0.5	40.2±1.1	264.6±12.2
Early group	DKS 2971	"Rostok" corn	II*	22.3±3.1	13.9±0.6	41.8±1.4	270.6±9.5
Early group	DKS 2971	Ecolist Mono Zink	I*	22.3±3.4	13.7±0.5	41.5±1.4	266.2±12.8
Early group	DKS 2971	Ecolist Mono Zink	II*	22.6±3.2	13.7±0.5	42.2±1.6	270.4±11.8
Early group	DKS 2971	Biomag + "Rostok" corn	I*	21.6±3.2	13.7±0.4	40.5±1.3	264.8±11.6
Early group	DKS 2971	Biomag + "Rostok" corn	II*	21.9±3.2	14.0±0.5	40.8±1.6	268.9±7.9
Early group	DKS 2971	Biomag + Ecolist Mono Zink	I*	22.2±3.4	13.8±0.5	41.2±1.2	269.9±12.6
Early group	DKS 2971	Biomag + Ecolist Mono Zink	II*	22.6±3.3	13.9±0.4	41.3±1.2	274.0±11.9
Mid-early group	DKS 3795	Control	-	23.1±2.6	14.6±0.1	38.0±0.7	263.6±11.9
Mid-early group	DKS 3795	Biomag	I*	23.7±2.6	14.6±0.1	38.9±0.5	267.8±8.0
Mid-early group	DKS 3795	Biomag	II*	24.4±2.3	14.7±0.2	40.2±1.5	285.7±4.1
Mid-early group	DKS 3795	"Rostok" corn	I*	24.2±2.3	14.6±0.1	38.9±0.1	270.7±6.5
Mid-early group	DKS 3795	"Rostok" corn	II*	24.9±2.3	14.6±0,1	39.3±0.1	281.5±6.5
Mid-early group	DKS 3795	Ecolist Mono Zink	I*	24.5±3.0	14.6±0.1	40.0±1.1	278.7±13.1
Mid-early group	DKS 3795	Ecolist Mono Zink	II*	25.0±2.9	14.6±0.1	41.2±1.5	290.2±9.6
Mid-early group	DKS 3795	Biomag + "Rostok" corn	I*	24.5±2.2	14.8±0.1	38.7±0.4	273.9±6.6
Mid-early group	DKS 3795	Biomag + "Rostok" corn	II*	25.2±1.6	14.9±0.1	39.4±0.2	283.8±6.4
Mid-early group	DKS 3795	Biomag + Ecolist Mono Zink	I*	25.7±2.7	14.7±0.1	39.8±1.0	287.2±9.6
Mid-early group	DKS 3795	Biomag + Ecolist Mono Zink	II*	26.6±2.5	14.6±0.1	40.5±0.8	293.3±9.1
Mid-early group	DKS 3871	Control	-	22.2±3.6	14.1±0.5	39.7±1.5	275.6±11.1
Mid-early group	DKS 3871	Biomag	I*	23.2±3.7	14.1±0.5	42.1±1.7	277.1±11.1
Mid-early group	DKS 3871	Biomag	II*	23.5±3.7	14.2±0.5	42.7±1.6	287.3±13.7
Mid-early group	DKS 3871	"Rostok" corn	I*	23.4±3.8	14.1±0.5	41.7±1.7	281.2±11.5
Mid-early group	DKS 3871	"Rostok" corn	II*	25.0±3.8	14.1±0.5	42.9±1.8	288.6±11.8
Mid-early group	DKS 3871	Ecolist Mono Zink	I*	24.7±4.5	14.2±0.5	42.3±2.1	281.2±10.2
Mid-early group	DKS 3871	Ecolist Mono Zink	II*	26.0±4.0	14.6±0.4	42.8±2.0	292.4±13.0
Mid-early group	DKS 3871	Biomag + "Rostok" corn	I*	23.4±4.1	14.1±0.5	41.9±1.9	282.0±11.5
Mid-early group	DKS 3871	Biomag + "Rostok" corn	II*	23.8±4.2	14.1±0.5	42.3±1.8	286.6±10.8
Mid-early group	DKS 3871	Biomag + Ecolist Mono Zink	I*	24.9±4.1	14.3±0.6	42.3±2.1	291.0±10.8
Mid-early group	DKS 3871	Biomag + Ecolist Mono Zink	II*	25.3±4.1	14.4±0.6	42.6±2.1	298.7±11.3

(End of Table 4)

1	2	3	4	5	6	7	8
Mid group	DK 315	Control	-	25.0±2.3	15.9±0.7	40.9±0.1	266.6±15.8
		Biomag	I*	25.9±2.2	16.0±0.7	41.5±0.3	280.5±18.1
			II*	27.1±2.3	16.1±0.7	42.8±0.4	283.1±16.3
		"Rostok" corn	I*	26.5±2.1	16.0±0.8	42.5±0.3	273.2±15.5
			II*	27.1±1.9	16.1±0.6	43.2±0.3	281.4±13.8
		Ecolist Mono Zink	I*	26.8±2.7	16.3±0.6	41.7±0.2	275.3±10.9
			II*	27.4±2.7	16.4±0.5	42.2±0.4	283.1±8.4
		Biomag + "Rostok" corn	I*	27.2±2.0	16.0±0.8	42.4±0.4	273.7±12.9
			II*	27.1±2.3	16.1±0.8	42.7±0.5	282.7±13.3
		Biomag + Ecolist Mono Zink	I*	27.2±3.0	15.9±0.7	42.1±0.2	288.5±12.3
			II*	28.4±2.2	15.9±0.7	43.0±0.2	295.0±11.8
	DK 440	Control	-	26.2±1.6	16.2±0.6	42.4±0.7	269.3±10.5
		Biomag	I*	26.6±1.4	16.2±0.6	44.8±0.9	278.4±14.0
			II*	28.6±1.3	16.3±0.6	45.2±0.9	285.5±14.6
		"Rostok" corn	I*	28.4±1.4	16.4±0.7	44.1±0.7	274.6±5.4
			II*	29.3±1.0	16.6±0.7	44.8±0.7	280.4±4.8
		Ecolist Mono Zink	I*	28.6±1.9	16.4±0.7	43.6±0.7	285.9±4.6
			II*	28.5±3.0	16.2±0.6	44.1±0.8	292.0±6.2
		Biomag + "Rostok" corn	I*	29.3±1.3	16.5±0.3	43.4±0.8	277.3±5.1
			II*	28.9±1.5	16.6±0.2	44.3±1.1	283.1±6.5
		Biomag + Ecolist Mono Zink	I*	27.8±2.9	16.2±0.6	44.2±0.8	293.5±7.1
			II*	28.6±2.5	16.2±0.6	45.3±0.7	296.3±6.0

Note: I* – single application of the product in the phase of 5-7 leaves of corn;
II* – double application of the preparation in the phase of 5-7 and 10-12 leaves of corn;
Control*** – without feeding.

The use of hybrids with a longer vegetation period increases the number of grains per row by 2.41-3.79 pcs. compared to early forms.

In the hybrids under consideration, the mean number of kernels per row was as follows: Kharkiv 195 MV – 37.98 pcs., DKS 2971 – 40.90 pcs., DKS 3795 – 39.53 pcs., DKS 3871 – 42.12 pcs., DK 315 – 42.26 pcs., and DK 440 – 44.21 pcs.

The mean number of kernels per row in the control variant (i.e., without feeding) was 39.36. When single foliar nutrition was applied, the average increased to 40.98 pcs., and under double feeding, it increased to 41.71 pcs.

The increase in the number of kernels per row due to foliar nutrition was 1.62-2.35 pcs., compared to the control variant.

The weight of 1,000 grains in the group of early hybrids was on average 257.50 g, in the group of medium early – 282.78 g and in the group of medium – 271.73 pcs. Among the hybrids the weight of 1,000 grains was as follows Kharkiv 195 MV – 247.57 g, DKS 2971 – 267.44 g, DKS 3795 – 280.76 g, DKS 3871 – 284.79 g, DK 315 – 280.52 g and DK 440 – 262.94 g. Application of foliar nutrition had an ambiguous effect on the weight of 1,000 grains, in particular, one foliar nutrition provided 278.58 g of 1,000 grain weight, double – 263.58 g, while in the control variant it was 266.57 g.

The characteristics of yield, content, and output of starch and bioethanol in the studied corn hybrids depending on foliar nutrition are given in Table 5.

The average grain yield of the investigated hybrids was 9.17 t/ha in 2015, 10.88 t/ha in 2016 and 10.29 t/ha in 2017. Within the maturity groups, the productivity of early hybrids was 8.44 t/ha, medium early – 10.02 t/ha and medium – 11.87 t/ha.

The most productive hybrids were those with a long growing season, e.g., DK 440 – 12.31 t/ha, DK 315 – 11.43 t/ha, while the productivity of medium-early hybrids was as follows DKS 3871 – 10.30 t/ha and DKS 3795 – 9.75 t/ha, and that of early hybrids was DKS 2971 – 9.01 t/ha and Kharkiv 195 MV – 7.88 t/ha.

The application of foliar nutrition increased the yield of the maize hybrids studied by 0.87-1.40 t/ha compared to the control. Single application of foliar nutrition gave an average yield of 9.95 t/ha, double application 10.48 t/ha compared to 9.08 t/ha in the control.

The starch content varied according to the hydrothermal conditions of the year. The year 2016 was the most favourable in terms of temperature and humidity indices, the average starch content in the hybrids studied was 75.20%, while in 2015 it was 72.04% and in 2017 it was 74.85%.

In the group of early maize hybrids, the starch content averaged 72.64% over three years, medium early – 74.48%, and medium – 74.97%. Thus, the use of hybrids with a long growing season provides an increase in starch content by 1.84-2.33% compared to the group of early hybrids.

Within the hybrids there was also a difference in the amount of accumulated starch, so that the highest

Table 5

Grain yield, starch and bioethanol content and yield in maize hybrids depending on foliar feeding, (average for 2015-2017 ±Sx)

Maturity group (A)	Hybrid (B)	Foliar nutrition (C)	Number of feedings (D)	Indicators			
				Yield, t/ha	Starch content	Starch output, t/ha	Bioethanol ooutput, thousand l/ha
1	2	3	4	5	6	7	8
Early group	Kharkiv 195 MB	Control***	-	7.00±0.68	72.45±0.4	5.075±0.514	2.781±0.282
		Biomag	I*	7.31±0.70	72.49±1.3	5.305±0.595	2.906±0.326
			II*	7.91±0.70	72.97±1.4	5.778±0.613	3.166±0.336
		"Rostok" corn	I*	7.34±0.64	72.48±1.5	5.329±0.568	2.920±0.311
			II*	8.05±0.74	72.66±1.6	5.859±0.662	3.210±0.363
		Ecolist Mono Zink	I*	8.01±0.71	73.35±1.8	5.881±0.660	3.222±0.361
			II*	8.59±0.77	73.82±2.0	6.356±0.727	3.482±0.398
		Biomag + "Rostok" corn	I*	7.47±0.65	73.00±1.2	5.461±0.558	2.992±0.306
			II*	8.05±0.55	73.65±1.4	5.932±0.512	3.250±0.280
		Biomag + Ecolist Mono Zink	I*	8.18±0.60	73.77±1.1	6.039±0.534	3.309±0.293
			II*	8.75±0.65	74.07±1.1	6.486±0.580	3.554±0.318
	DKS 2971	Control	-	7.86±0.75	71.34±0.6	5.613±0.587	3.075±0.322
		Biomag	I*	8.71±0.87	71.36±1.6	6.224±0.748	3.410±0.410
			II*	9.11±0.97	71.86±1.6	6.555±0.833	3.591±0.456
		"Rostok" corn	I*	8.75±0.94	71.52±1.8	6.269±0.827	3.435±0.453
			II*	9.43±1.02	72.20±1.6	6.817±0.879	3.735±0.482
		Ecolist Mono Zink	I*	9.11±1.04	72.22±2.1	6.596±0.924	3.614±0.506
			II*	9.42±1.09	72.96±2.4	6.892±1.011	3.776±0.554
		Biomag + "Rostok" corn	I*	8.84±0.93	71.81±1.5	6.357±0.793	3.483±0.434
			II*	9.21±0.91	72.17±1.7	6.662±0.805	3.650±0.441
		Biomag + Ecolist Mono Zink	I*	9.22±1.01	72.70±2.1	6.712±0.911	3.677±0.499
			II*	9.44±0.96	73.19±2.5	6.922±0.921	3.793±0.505
Mid-early group	DKS 3795	Control	-	8.79±0.57	73.29±0.7	6.440±0.478	3.529±0.262
		Biomag	I*	9.14±0.41	73.72±2.0	6.743±0.470	3.694±0.258
			II*	10.15±0.41	74.21±2.3	7.538±0.527	4.130±0.289
		"Rostok" corn	I*	9.22±0.31	73.32±2.1	6.769±0.405	3.709±0.222
			II*	9.72±0.28	73.61±2.1	7.160±0.381	3.923±0.209
		Ecolist Mono Zink	I*	9.80±0.74	73.46±1.3	7.206±0.669	3.948±0.367
			II*	10.49±0.75	74.39±1.8	7.814±0.730	4.281±0.400
		Biomag + "Rostok" corn	I*	9.40±0.31	73.30±1.0	6.892±0.322	3.776±0.177
			II*	9.97±0.27	73.80±1.3	7.357±0.276	4.031±0.151
		Biomag + Ecolist Mono Zink	I*	10.12±0.62	74.13±1.3	7.507±0.588	4.113±0.322
			II*	10.42±0.53	74.60±1.7	7.779±0.569	4.262±0.312
	DKC 3871	Control	-	9.26±1.01	74.69±0.7	6.921±0.812	3.792±0.445
		Biomag	I*	9.91±1.13	74.63±1.1	7.404±0.944	4.056±0.517
			II*	10.52±1.27	74.75±1.1	7.872±1.053	4.313±0.577
		"Rostok" corn	I*	9.94±1.13	75.02±1.0	7.461±0.935	4.088±0.512
			II*	10.47±1.21	75.56±1.4	7.925±1.046	4.342±0.573
		Ecolist Mono Zink	I*	10.20±1.22	74.89±0.9	7.645±0.990	4.189±0.542
			II*	11.03±1.23	75.31±0.6	8.309±0.986	4.553±0.540
		Biomag + "Rostok" corn	I*	10.03±1.17	74.98±1.7	7.534±1.035	4.128±0.567
			II*	10.30±1.16	75.33±2.0	7.776±1.061	4.261±0.581
		Biomag + Ecolist Mono Zink	I*	10.59±1.28	75.55±1.2	8.011±1.086	4.389±0.595
			II*	11.03±1.34	76.05±1.3	8.399±1.147	4.602±0.628
Mid group	DK 315	Control	-	10.42±1.13	74.18±1.7	7.738±0.990	4.240±0.543
		Biomag	I*	11.16±1.19	74.18±2.3	8.299±1.122	4.547±0.614
			II*	11.70±1.24	74.55±2.2	8.738±1.162	4.787±0.637
		"Rostok" corn	I*	11.14±1.16	74.43±2.8	8.311±1.143	4.554±0.626
			II*	11.76±1.05	75.03±2.5	8.839±1.053	4.843±0.577
		Ecolist Mono Zink	I*	11.21±0.80	74.33±3.0	8.347±0.896	4.573±0.491
			II*	11.79±0.64	74.99±2.6	8.848±0.733	4.848±0.402
		Biomag + "Rostok" corn	I*	11.19±1.15	74.71±3.1	8.378±1.182	4.590±0.648
			II*	11.68±1.18	74.93±3.1	8.778±1.225	4.810±0.671
		Biomag + Ecolist Mono Zink	I*	11.59±1.05	75.21±2.8	8.732±1.084	4.784±0.594
			II*	12.10±1.07	75.35±2.7	9.133±1.100	5.004±0.603

(End of Table 5)

1	2	3	4	5	6	7	8
	DK 440	Control	-	11.15±1.00	74.47±0.7	8.305±0.826	4.551±0.453
		Biomag	I*	12.18±1.24	74.54±1.6	9.095±1.110	4.983±0.608
			II*	12.64±1.23	75.13±1.6	9.505±1.121	5.208±0.614
		"Rostok" corn	I*	11.94±0.89	75.06±2.5	8.976±0.950	4.918±0.520
			II*	12.51±0.89	75.78±1.8	9.491±0.887	5.200±0.486
		Ecolist Mono Zink	I*	12.31±0.90	74.76±1.6	9.218±0.855	5.050±0.468
			II*	12.57±0.95	75.58±2.0	9.510±0.953	5.210±0.522
		Biomag + "Rostok" corn	I*	11.89±0.64	75.00±2.7	8.929±0.787	4.892±0.431
			II*	12.51±0.69	75.20±2.8	9.420±0.848	5.161±0.465
		Biomag + Ecolist Mono Zink	I*	12.64±0.98	75.80±1.9	9.596±0.967	5.258±0.530
			II*	13.08±0.93	76.06±1.9	9.957±0.937	5.456±0.513

Note: I* – single application of the product in the phase of 5-7 leaves of corn;
II* – double application of the preparation in the phase of 5-7 and 10-12 leaves of corn;
Control*** – without feeding.

starch content, averaged over three years of research, was found in the hybrid DK 440 – 75.22%, while in other hybrids it was as follows DK 315 – 74.72%, DKS 3871 – 75.16%, DKS 3795 – 73.80%, DKS 2971 – 72.12% and Kharkiv 195 MV – 73.16%.

In the context of the study, the starch content of the hybrids was found to be 73.86% under single foliar nutrition, 74.33% under double foliar nutrition, and 73.40% in the control variant (without feeding). The application of foliar nutrition to corn with the bacterial agent Biomag and micro-fertilizers Ecolist Mono Zinc and "Rostok" resulted in an increase in the starch content of the grain by 0.46-0.92%, compared to the control.

The highest yield of starch recorded in the studied corn hybrids was 8.20 t/ha in 2016, while it was 6.61 t/ha in 2015 and 7.72 t/ha in 2017.

Within maturity groups, the optimal indices of starch yield were obtained in mid hybrids – 8.92 t/ha, while it was 7.48 t/ha in mid-early hybrids and 6.14 t/ha in early hybrids. Among the hybrids studied, the average starch yield was found in Kharkiv 195 MV – 5.77 t/ha, DKS 2971 – 6.51 t/ha, DKS 3795 – 7.20 t/ha, DKS 3871 – 7.75 t/ha, DK 315 – 8.56 t/ha, and DK 440 – 9.27 t/ha.

The use of foliar feeding increased the starch yield per unit area of the studied hybrids by 0.69-1.13 t/ha. At the same time, the starch yield in the control variant was 6.68 t/ha, with a single foliar feeding – 7.37 t/ha in the phase of 5-7 leaves, while with two foliar feeding (in the phase of 5-7 and 10-12 leaves) – 7.81 t/ha.

The average bioethanol yield was 3.37 thousand l/ha in the early hybrid group, 4.10 thousand l/ha in the medium early hybrids and 4.88 thousand l/ha in the medium hybrids. Among the hybrids, the bioethanol yield was as follows Kharkiv 195 MV – 3.16 thousand l/ha, DKS 2971 – 3.57 thousand l/ha, DKS 3795 – 3.95 thousand l/ha, DKS 3871 – 4.25 thousand l/ha, DK 315 – 4.69 thousand l/ha and DK 440 – 5.08 thousand l/ha.

Foliar feeding contributed to an increase in bioethanol yield of 0.38-0.62 thousand l/ha compared to the control (3.66 thousand l/ha). Single foliar feeding contributed 4.04 thousand l/ha to the bioethanol yield and double feeding contributed 4.28 thousand l/ha.

Of the 22 small bioethanol plants in Ukraine, seven are new private production facilities, while the rest are reconstructed old state-owned plants (Heletukha & Zhelezna, 2023). Ukrainian producers sell bioethanol to Europe at a profit, taking into account automotive logistics. There are currently 5 fully operational plants in Ukraine using different feedstocks and selling ethanol to Europe (Haiduk, 2022).

In 2022, the price of bioethanol in Rotterdam was 1,264 EUR, and the current price is 147 EUR, including VAT on corn and a gas price of 26 thousand UAH. The production cost of bioethanol, excluding taxes, is 435 EUR, which creates a very high profitability of its production. The cost of bioethanol consists of 75% of the cost of raw materials and 20% of energy. Given that corn does not need to be dried for processing, this can reduce the price of raw materials. Ukraine may have a surplus of 17 million tonnes of corn out of 40 million tonnes. Ukraine has quotas for the supply of bioethanol to the EU of 100,000 tonnes annually. Producers use only a quarter of them.

In Ukraine, it is promising to build modern bioethanol plants from scratch, as they can correctly calculate fuel consumption. It is also profitable to process the bard produced in the bioethanol production process into biomethane and organic fertiliser (digestate). The production of biomethane makes it possible to supply the company with electricity. For example, the cost of building and launching a corn-to-ethanol plant in Ukraine, plus biomethane and organic fertilisers, is 32 million EUR. In the first year, such a plant can process up to 170,000 tonnes of corn and produce 200 cubic metres of bioethanol, 42,000 cubic metres of biomethane, 800 cubic metres of organic fertiliser per day, as well as generate electricity and steam that can be used for its own needs. That is why bioethanol production in Ukraine has prospects, given the cost of the product when it is sold in Europe.

5. Conclusions

Bioethanol production in the world is carried out by highly developed countries and countries with sufficient reserves of renewable high-energy biomass, including Ukraine. Among the main bioenergy crops, scientists identify sugar beet, maize, Jerusalem artichoke, sorghum and others. Of these, maize is the most suitable for bioethanol production due to its high starch content (65-85%), hybrid yield potential (7-13 t/ha), substrate availability and technological know-how.

It has been found that the formation of elements of the structure of productivity, yield, starch content and bioethanol yield in maize is significantly influenced by the maturity group of hybrids, genetic characteristics of a particular hybrid, hydrothermal conditions of the year and the use of foliar fertiliser. The bioethanol yield in the group of early hybrids averaged 3.37 thousand litres per hectare, medium early – 4.10 thousand litres per hectare, and medium mature – 4.88 thousand litres per hectare. Among the hybrids, the bioethanol yield was distributed as follows: Kharkiv 195 MV – 3.16 thousand l/ha, DKS 2971 – 3.57 thousand l/ha, DKS 3795 – 3.95 thousand l/ha, DKS 3871 – 4.25 thousand l/ha, DK 315 – 4.69 thousand l/ha and DK 440 – 5.08 thousand l/ha.

The study found that the production of biofuels from maize seed shows signs of being an innovative technology. The use of maize grain as a raw material partially resolves the existing conflict of interest associated with the use of food resources for bioethanol production. The main advantages of the production and use of corn ethanol are improved environmental conditions, reduced harmful effects on the human body and reduced environmental pollution. In turn, the opening of corn ethanol plants for the production of biomethane and organic fertilisers is a very profitable business.

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Received on: 11th of October, 2024
Accepted on: 30th of November, 2024
Published on: 30th of December, 2024