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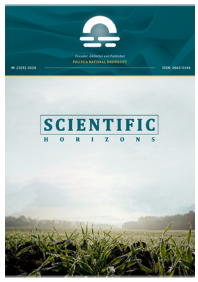

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Prospects for maize processing for the development of bioeconomy and decarbonisation in Ukraine

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Abstract. Under the terms of the European Green Deal, including the transition to a green economy, decarbonisation, and a sustainable model of inclusive growth, Ukraine has committed itself to achieving climate neutrality by 2060. The military challenges caused by Russia's full-scale invasion of Ukraine require an in-depth

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investigation and substantiation of mechanisms for developing promising areas of deep processing of domestic agricultural raw materials to ensure food security, domestic market development, and post-war economic recovery. The purpose of this study was to analyse and assess the potential for processing Ukrainian maize in the context of bioeconomy development, specifically to produce starch, bioplastics, and bioethanol. The study was conducted using a systematic approach with extrapolation methods, exponential smoothing, and confidence interval construction to assess the forecast. It was proved that Ukraine has all the opportunities to increase the production of a wider product line of deeply processed maize products. Realising the potential of maize processing as a biological and energy feedstock in the Ukrainian economy for post-war recovery depends on the creation of an innovative bioeconomy infrastructure, through strengthening strategic partnerships between agricultural producers, research institutions and public authorities, cluster development and export promotion. The practical value of this study lies in the developed recommendations for the implementation of maize processing opportunities for the development of the bioeconomy and acceleration of decarbonisation in Ukraine

Keywords: sustainable development; Green Deal; carbon footprint; deep processing of agricultural raw materials; added value; green energy

INTRODUCTION

One of today's global challenges that directly affects everyone's life is climate change, caused by the growth of greenhouse gas emissions from economic activity. Reduction of carbon dioxide emissions and mitigation of climate change can be achieved through decarbonisation and the development of the bioeconomy. Maize, as a versatile crop, can play a key role in both areas, as its processing into biofuels, bioplastics, animal feed, and biochemicals will contribute to greenhouse gas emissions reduction, sustainable economic development, and energy security. This demonstrates the relevance of researching sustainable practices, technological innovations, and balanced policies for deep processing of one of the most common and important crops – maize.

M.M. Miralles-Quirós *et al.* (2022) investigated the reasons for the increase in the greenhouse effect due to the accumulation of carbon dioxide, methane, nitrogen oxide, and fluorinated gases as a result of economic activity, which lead to global warming. Due to human activity, the temperature of Earth has risen by more than 1°C in 120 years. Global warming caused by human activity is increasing at a rate of 0.2°C per decade. If the situation is not remedied, in less than 50 years, humanity will reach a temperature increase of 2°C compared to pre-industrial levels. This rise in global temperatures is threatening life on Earth. J. Rosenboom *et al.* (2022) concluded that the bioeconomy, including biomass production and use, is essential for decarbonising the energy system and replacing fossil and energy-intensive materials through scenario planning for Austria with a reduction in greenhouse gas emissions of up to about 20% of the Kyoto Protocol baseline (United Nations Framework Convention on Climate Change, 1998). The scenarios were developed using an optimisation model that integrates the energy sector, land use, and biomass flows.

According to A.G. Rodríguez *et al.* (2019), the bioeconomy is based on biological resources and is a real alternative for decarbonising fossil fuels in the economy, which plays a fundamental role in the fight against climate change. Prospects for the use of bioeconomic technologies to achieve decarbonisation are being identified in many sectors of the economy. P. Kumar and M. Richardson (2017) compared the energy efficiency and environmental impact of different maize processing technologies for food and biofuel production and identified the economic and environmental impacts of using these resources. Based on the analysis and assessment of the impact of many factors, including energy, soil conditions, soil nutrients, and carbon storage, required for maize production and its conversion into biofuels, scientists have proven the prospects for developing maize production and processing as an energy crop for the future of renewable energy. J. Streimikis and T. Baležentis (2020) emphasise the significance of strong partnerships between international and national stakeholders, agricultural and research institutions, as well as civil society organisations, which play a key role in supporting the achievement of the Sustainable Development Goals.

The studies of Ukrainian researchers deserve special attention. Specifically, T. Kvasha and L. Musina (2015) analysed approaches to the development of a system of green growth indicators in Ukraine. I. Kravchenko *et al.* (2021) covered the theoretical aspects of greenhouse gas emissions taxation, summarised and systematised the experience of combining environmental taxation with the system of CO_2 emissions trading in European countries. O. Ryabchyn *et al.* (2021) define the concept of "greenness" as a synergy between reducing greenhouse gas emissions and caring for the environment, which is relevant for Ukraine. L.A. Horoshkova and E.V. Khlobistov (2020) identified the conditions for ensuring sustainable development in terms of emissions of harmful substances and waste generation, modelling the factors influencing these parameters and the overall environmental situation in Ukraine. In this context, the search for and implementation of effective technologies for deep processing of maize is relevant and promising for the development of the bioeconomy and accelerating Ukraine's decarbonisation within the framework of the European Green Deal and performance of its commitments. This involves not only setting targets and measures to reduce CO_2 emissions, but also devising and implementing a strategy for developing a resource efficient economy.

Considering the above, the purpose of this study was to substantiate the possibilities of deep processing of maize for the development of the bioeconomy and acceleration of decarbonisation in Ukraine as a key principle of the green transition and sustainable development.

MATERIALS AND METHODS

The focus of this study was to identify opportunities to increase production capacity in Ukraine for processing maize into starch, bioplastics, and bioethanol. To formulate a strategic vision and measures for the development of the green economy in Ukraine, it is advisable to build a forecast until 2032. Accordingly, a statistical sample was made for the last 11 years, i.e., from 2013 to 2023. The information base for the construction of these series was the UN Comtrade Database service (2024), State Statistics Service of Ukraine (2024), Annual National Inventory Report… (2023), Designing the Bioeconomy for Deep Decarbonisation (2021), ESOMAR Pro-Consulting (Starch market in Ukraine, 2021), Latifundist (Bioethanol, 2023), the Office of Technological Development Planning Unitika Ltd (Polylactic Acid, 2022), Fortune Business Insights (Food Additives & Ingredients, 2024). Since most international databases and services that provide data on exports of goods sometimes lack data on international trade in physical terms, it is advisable to use data on exports of goods in physical terms.

The Minitab statistical data processing tool was used to build the autocorrelation function and perform structural analysis of time series. This tool was used to analyse the time series according to various evaluation criteria. Trends were identified, an autocorrelation function was built, time series were decomposed, and the presence of seasonal fluctuations was determined.

The results of the time series analysis of exports made it possible to identify the most suitable methods for forecasting until 2030. Considering the above, it is advisable to use extrapolation methods and exponential smoothing and confidence interval construction to assess the forecast. Since the use of the exponential smoothing method is widely used in forecasting time series in the economy and has its advantages. To make a forecast based on the extrapolation method using exponential smoothing and building a confidence interval, it is advisable to use MS Excel, as the versions since 2016 have the necessary built-in capabilities and tools for making forecasts.

RESULTS AND DISCUSSION

The prospects for the development of the bioeconomy and decarbonisation are widely discussed in the public and scientific space, both abroad and in Ukraine. Areas of development of the bioeconomy, which, according to the GBS 2018 Communiqué, can be defined as the production, consumption, and protection of biological resources, based on knowledge, scientific achievements, technologies, and innovations to inform sustainable economic development, related to the deep processing of agricultural raw materials (Bioeconomy Policy Part III, 2018). However, the use of agricultural raw materials covers a wider range of industrial production, and their deep processing not only provides relevant effects in the areas of food security, resource efficiency and environmental protection, but can also act as one of the engines of post-war industrial recovery. The global nature and significance of concerted urgent action to counteract the growth of greenhouse gas emissions and its consequences is emphasised in the Sustainable Development Goals (United Nations, 2015). Thus, *Climate change 2022* (2022) substantiated the close connection of Sustainable Development Goal 13, "Combat climate change", with all 16 other goals of the 2030 Agenda for Sustainable Development.

T. Ronzon *et al.* (2020) have developed a methodology for monitoring the contribution of the bioeconomy to jobs and growth in the European Union and its Member States and have proven the strategic significance of the EU bioeconomy in guaranteeing a secure food supply, acting as a buffer for employment and providing a significant potential for the transition to an innovative resource – an efficient and competitive economy. Proceeding from the findings of the US Department of Energy's National Laboratories' 2021 studies, which proved that biotechnology is a vital tool for reducing greenhouse gas emissions, the areas of intervention to achieve decarbonisation goals are the transport sector, industry, and agriculture (Fig. 1).

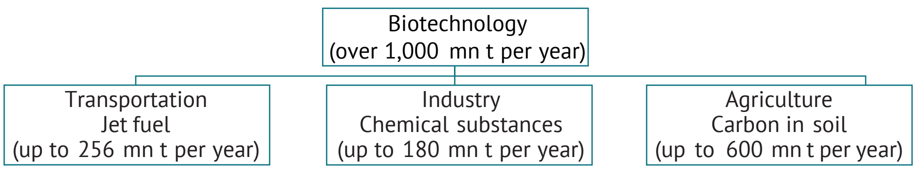

***Figure 1**. Potential greenhouse gas reduction effects of biotechnology in millions of metric tonnes per year*
***Source:** developed by the authors of this study based on Designing the Bioeconomy for Deep Decarbonisation (2021)*

Studies have shown that the introduction of biotechnology has a considerable impact on reducing greenhouse gases in the agricultural sector. These are biological systems to produce new products from sustainable biomass resources, including aviation fuel, high-performance fuel additives, recyclable bioplastics, enhanced soil microbial cultures to increase crop productivity, new hybrid biotechnologies and chemical synthesis processes, increased aboveground CO_2 capture and underground carbon storage, etc. (Designing the Bioeconomy, 2021). Biotechnological methods and processes in the energy sector can not only replace oil-based products, but also enable the development of new types of products. According to E. Trigo *et al.* (2023), the bioeconomy and the introduction of biotechnological innovations contribute to improved rural development, food production, and increased efficiency in the production of crops, livestock, biofuels, bioplastics, and bioenergy. This allows food systems to transform to become more sustainable and equitable, providing healthy, nutritious food while creating livelihoods and reducing negative impacts. This is the priority for Ukraine's economic recovery. Deep processing of maize allows producing about 18 types of high value-added products.

The potential of using maize as an energy feedstock is one of the most promising areas of bioeconomy and decarbonisation. This is also emphasised by Ukrainian scientists G. Kaletnik *et al.* (2021), who substantiated the technology of growing maize and obtaining alternative fuels, which will have a positive impact on the energy supply of local consumers. Furthermore, C.R. Parra *et al.* (2023) have proved that increasing the share of alternative sustainable energy sources such as biomass is crucial to meet both peak and baseload electricity demand in future scenarios. The dynamics of the key indicators characterising the production and export potential of maize as an energy feedstock and greenhouse gas emissions is presented in Table 1.

Table 1*. Dynamics of production, exports, and greenhouse gas emissions in Ukrainian agriculture in 2013-2023*

Indicator	Years										
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
GDP in factual prices, UAH bn	1,465.20	1,586.92	1,988.54	2,385.37	2,981.23	3,560.30	3,977.20	4,222.03	5,450.85	5,239.11	6,537.83
Volume of agriculture, forestry, and fisheries, UAH bn	128.74	161.15	239.81	279.70	303.42	361.00	356.56	393.08	593.37	449.15	484.15
Share of agriculture, forestry, and fisheries in GDP, %	8.79	10.15	12.06	11.73	10.18	10.14	8.97	9.31	10.89	8.57	7.41
Total exports, USD bn	63.30	53.90	38.10	36.40	43.30	47.30	50.10	49.20	68.10	44.10	36.20
Agroindustrial exports, USD bn	17.04	16.67	14.60	15.30	14.90	18.60	22.10	22.20	27.70	20.90	22.01
Maize exports, bn USD	3.83	3.35	3.00	2.65	2.99	3.51	5.22	4.89	5.85	5.99	5.00
Share of maize in agricultural exports, %	22.49	20.10	20.56	17.34	20.06	18.85	23.61	22.00	21.13	28.67	22.70
Greenhouse gas emissions, total mn t – equivalent (CO_2)	409.00	362.60	319.20	337.60	323.30	339.80	334.10	318.00	330.40	–	–
Greenhouse gas emissions in agriculture, total mn t - equivalent (CO_2)	41.60	41.40	39.40	42.00	41.00	44.40	44.80	41.70	47.00	–	–
Share of greenhouse gas emissions from agriculture in total emissions, %	10.17	11.42	12.34	12.44	12.68	13.07	13.41	13.11	14.23	–	–

Source: *developed by the authors of this study based on research by UN Comtrade Database (2024), State Statistics Service of Ukraine (2024), Annual National Inventory Report, (2023)*

These data suggest that despite the gradual decline in the share of agricultural output from 8.79% of GDP in 2013 to 7.41% in 2023, agri-food exports continue to grow, and their share in total exports will stay significant at 60.8% in 2023. Maize exports account for a significant share of total agri-food exports and grew from 22.49% in 2013 to 22.7% in 2023, amounting to USD 5.0 bn in value in 2023. This indicates an increase in raw material exports instead of highly processed products. At the same time, greenhouse gas emissions in agriculture increased during the study period and reached 14.23% of total emissions in 2021. This confirms the significance and necessity of developing the types of deep processing of agricultural raw materials that reduce the carbon footprint.

According to S.R. Padhan *et al.* (2023), maize-based biofuels are promising because they can reduce greenhouse gas emissions, biodegradability, and clean combustion, which increases energy security. However, increasing the production of maize-based biofuels requires breeding strategies such as crossbreeding selected varieties to increase biomass and starch content. Better agronomic practices and extension strategies are also needed to increase yields and promote adaptation among farmers. Using maize as a feedstock for biofuel production can stimulate the agricultural sector, create jobs in agriculture, food processing, and transport, and reduce dependence on foreign oil while preserving foreign exchange reserves.

One of the most promising areas of deep processing is maize starch, which is the basis for the production of packaging materials that are easily destroyed during recycling (Starch modifications, 2023). Starch is widely used in the food industry as a thickener or stabiliser for bread, soups, puddings, cakes, soy, meat products and sauces, vermicelli, ice cream biscuits, instant noodles, sago, chocolates, etc. Furthermore, the functional advantages of starch considerably expand the range of applications in various industries (Fig. 2).

In 2023, the global maize starch market reached 86.4 mn t and, according to IMARC Group, will reach 106.3 mn t by 2032, or an increase of 2.5% (IMARC Group, 2024). In 2032, its size will increase to USD 127.07 bn. (Fig. 3).

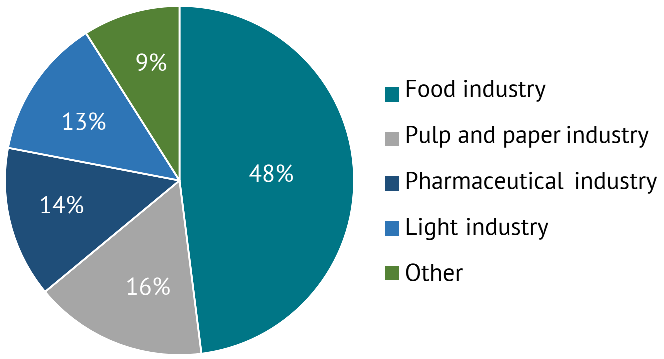

Figure 2*. Areas of application for maize starch, %*
Source: *developed by the authors of this study based on research by Pro-consulting Insights (Starch market in Ukraine, 2021)*

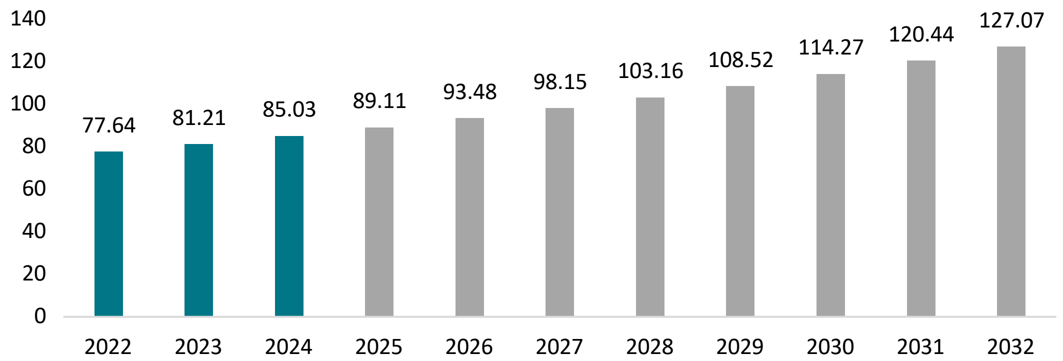

Figure 3*. Global maize starch market development dynamics in 2022-2024 and forecast to 2032, USD bn*
Source: *developed by the authors of this study based on research by Fortune Business Insights (Food Additives & Ingredients, 2024)*

This is also confirmed by the findings of P. Adewale *et al.* (2023), who considered the prospects for the production of starch-based products, namely the growth of non-food production from maize starch, which will provide access to new markets, increase profits, etc., within the framework of the Sustainable Development Goals. The factors contributing to this growth are as follows:

- urbanisation, which leads to busier lifestyles and greater reliance on packaged and processed food;
- demand for culinary semi-finished and processed products, where starch is a key ingredient for texture, stability, and other functional properties;
- development of pharmaceuticals, production of bioethanol and bioplastics;
- emergence of new technological developments, including the use of starch as a potential ingredient in alternative protein products and as a raw material for renewable and biodegradable packaging materials;

■ improvement of the functional properties of starch, including texture, thermal stability, viscosity, and solubility, to improve product quality;

■ population growth and rising incomes, particularly in the Asia-Pacific region (China, India), leading to increased demand for a variety of consumer products, including processed foods, pharmaceuticals, and industrial products based on starch as an ingredient, with a projected average annual growth of more than 5% until 2028.

Ukraine has all the prerequisites for developing maize starch processing and entering the global market: high bioproductive potential of land resources and favourable climatic conditions. The largest producers are Interstarch Ukraine, Vimal Ukraine, the Yuvileinyi modified fats and starches plant, Kremnianskyi Starch Plant, and Dnipro Starch Processing Plant, with over 50 companies across the country. Ukraine has considerable export potential for maize starch, as presented in Table 2.

Table 2*. Exports and imports of maize starch in 2013-2023*

Seq. No.	Year	Export		Import	
		Volume, mn USD	Volume, thsd t	Volume, mn USD	Volume, thsd t
1	2013	10.70	19.44	1.92	3.28
2	2014	8.71	20.81	1.45	3.31
3	2015	9.72	28.11	0.78	1.61
4	2016	9.56	31.44	1.36	1.99
5	2017	18.59	61.16	4.52	10.68
6	2018	20.61	60.63	4.12	9.95
7	2019	28.58	82.70	1.26	1.17
8	2020	28.06	74.43	1.52	1.03
9	2021	38.37	78.74	1.47	0.88
10	2022	52.17	53.44	0.80	0.52
11	2023	30.78	33.94	3.71	5.17

Source: *developed by the authors of this study based on research by UN Comtrade Database (2024) and State Statistics Service of Ukraine (2024)*

These data suggest an almost 3-fold increase in maize starch exports from 2013 to 2023 in value terms. At the same time, imports increased from USD 1.92 mn in 2013 to USD 3.71 mn in 2023. For comparison, total exports of maize, which could become a raw material for starch and other higher value-added products, amounted to USD 4,966.26 mn in value terms in 2023, which is 161.33 times more than exports of maize starch of USD 30.78 mn.

The starch market in Ukraine is characterised by a raw material orientation of agri-food exports, low levels of fixed assets, and insufficient number of employees. During the COVID-19 pandemic, the internal starch market was characterised by a decline in demand for sausage and meat products that use starch, which led to a contraction in the market. This opened opportunities for increased imports of foreign starch. At the same time, the decline in internal demand because of the war has led to the accumulation of starch stocks in producers' warehouses and the need to reorient to foreign markets (starch stocks at the end of 2022 amounted to 50 thsd t, while internal consumption was 12 thsd t). Based on the author's calculations, if Ukraine establishes corn starch production, corn starch exports will have a positive annual growth rate of 7.39% on average by 2030. In 2030, the projected export volumes of the product under study will increase to USD 73.2 mn on average, with a possible deviation ranging from USD 55.0 mn to USD 91.3 mn (Fig. 4).

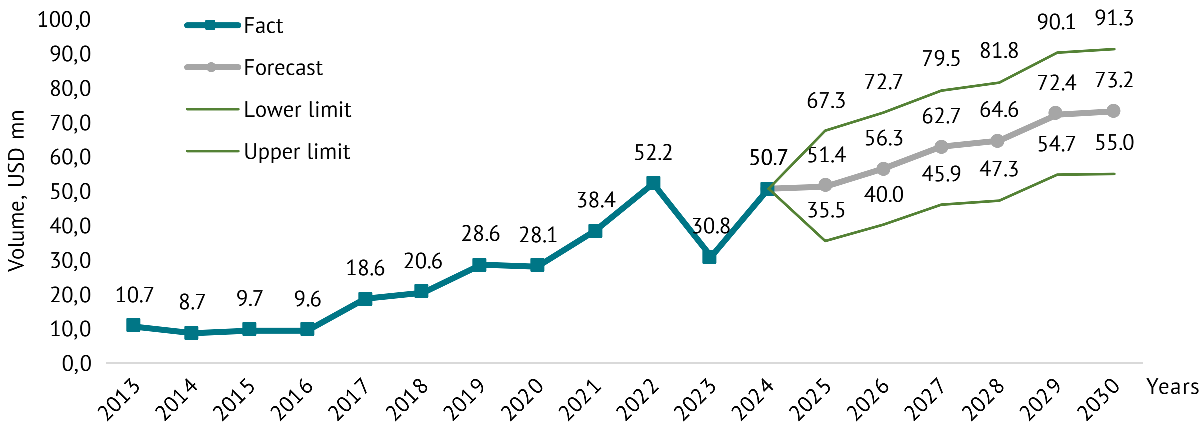

***Figure 4**. Dynamics of maize starch exports in 2022-2024 and forecast for 2025-2030, USD mn*
***Source:** calculated by the authors of this study based on data from the State Statistics Service of Ukraine (2024)*

Another promising area of maize processing, especially relevant in the context of the green transition and achieving sustainable development goals, is the production of bioplastics based on polylactic acid (PLA). According to A.P. Thomas *et al.* (2023), bioplastics play a significant role in the bioeconomy as they are easily recyclable and can mitigate environmental impacts by replacing conventional plastics. This trend is in line with global efforts to reduce plastic waste and promote sustainability. Plastics and industrial chemicals can be created from deconstructed biomass, which contains a series of components not found in fossil resources. G. Fredi and A. Dorigato (2021) point out that biodegradable bioplastics have alternative waste disposal pathways, limiting the amount of plastic waste that enters the environment, while biobased bioplastics can substantially reduce the carbon footprint at the resource extraction stage. Maize-based bioplastics have advantages in terms of performance, recyclability, while reducing energy and resource consumption, namely:

- energy consumption is 65% lower than that of conventional oil-based plastics;
- maize-based biopolymers could reduce greenhouse gas emissions across the industry by 25%, or 16 mn t of CO_2e/year;
- biodegradability – bioplastics decompose quickly and can break down in 45-90 days;
- no toxic fumes during the combustion of bioplastics;
- lower water consumption during bioplastics recycling;
- approaching international environmental standards.

One of the advantages of bioplastics is that they can be composted until they are fully decomposed within three months. The composting equipment ensures that this material decomposes at temperatures ranging from +55°C to +70°C and at a special humidity level. Furthermore, the processing of bioplastics produces considerably less carbon dioxide and other greenhouse gas emissions than the combustion of polymers such as PS (polystyrene), PET (polyethylene terephthalate), PP (polypropylene), and PE (polyethylene), which leaves a smaller carbon footprint (Fig. 5).

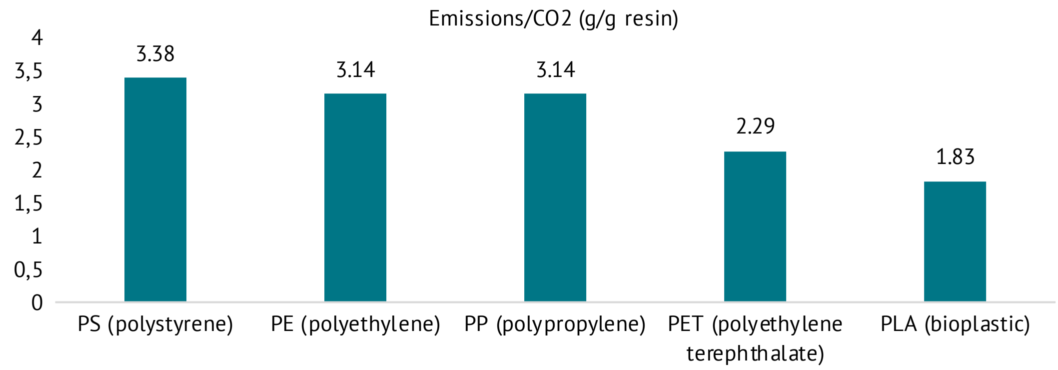

***Figure 5**. Amount of CO_2 emissions into the atmosphere during combustion, g/g of resin*
***Source:** compiled by the authors of this study based on Polyactic Acid studies (2022)*

The global bioplastics and biopolymers market is expected to reach USD 93.1 bn by 2032, at an annual average growth rate of 11.3% during the forecast period from 2025 to 2033. At the same time, the growth of maize-to-bioplastics production capacity also has potential risks. Specifically, G. Atiwesh *et al.* (2023) found that the production of bioplastics from plants such as maize requires the conversion of land for plastic production instead of meeting food needs, as almost 25% of agricultural land used for grain production is used for biofuels and bioplastics. This could lead to a considerable increase in food prices, which would have negatively affected the economically disadvantaged groups.

The bioplastics market in Ukraine is growing and new players are entering the market. This is primarily due to the regulatory framework in the context of compliance with the requirements of the European Green Deal. On 1 June 2021, the Verkhovna Rada of Ukraine adopted Law of Ukraine No. 1489-IX (2021). It is aimed at reducing the consumption of plastic bags in Ukraine. It also makes provision for restrictions on the distribution of plastic bags to improve the environment and reduce the anthropogenic impact on the environment. The Law does not apply to biodegradable plastic bags, but prohibits the distribution of ultra-thin, thin oxo-degradable plastic bags. Thanks to the Law, demand for biodegradable bags almost doubled in 2022, and consumption of plastic bags decreased by 40-90% depending on their type.

An innovative technology to produce bioplastics from maize has been developed in Ukraine by BIOC, a start-up that meets international standards for product quality and safety. BIOC bioplastics are triple copolymerised and are fully biodegradable. In its structure, modified maize starch makes up 50 to 75% (Innovative technology, 2024). Ukraine, which has a considerable potential for bioplastics production, continues to import it, as presented in Table 3.

Table 3. *Exports and imports of bioplastics in 2013-2023*

Seq. No.	Year	Export		Import	
		Volume, mn USD	Volume, thsd t	Volume, mn USD	Volume, thsd t
1	2013	0.097	0.016	27.0	6.6
2	2014	0.183	0.033	24.6	6.4
3	2015	0.171	0.050	19.9	6.1
4	2016	0.143	0.020	21.5	–
5	2017	0.087	0.030	26.2	7.5
6	2018	0.130	0.028	28.5	7.8
7	2019	0.138	0.021	27.5	–
8	2020	0.154	0.023	25.9	–
9	2021	0.149	0.028	29.6	–
10	2022	0.391	0.067	19.5	4.4
11	2023	0.043	0.012	29.1	7.3

Source: *developed by the authors of this study based on research by UN Comtrade Database (2024) and State Statistics Service of Ukraine (2024)*

These data show that during 2013-2023, the volume of bioplastics imports, except for 2014, 2015, 2020, and 2022, tended to grow. Export volumes are insignificant and fluctuated during the study period from USD 0.097 mn in 2013 to USD 0.043 mn in 2023. Based on forecasts, it was determined that bioplastics exports will grow until 2030 but will not reach the level of 2022. At the same time, considering the increase in the production of bioplastics from maize in Ukraine, the projected exports of the product under study in 2030 could reach a maximum level of USD 0.47 mn, but will average USD 0.29 mn in 2030 (Fig. 6).

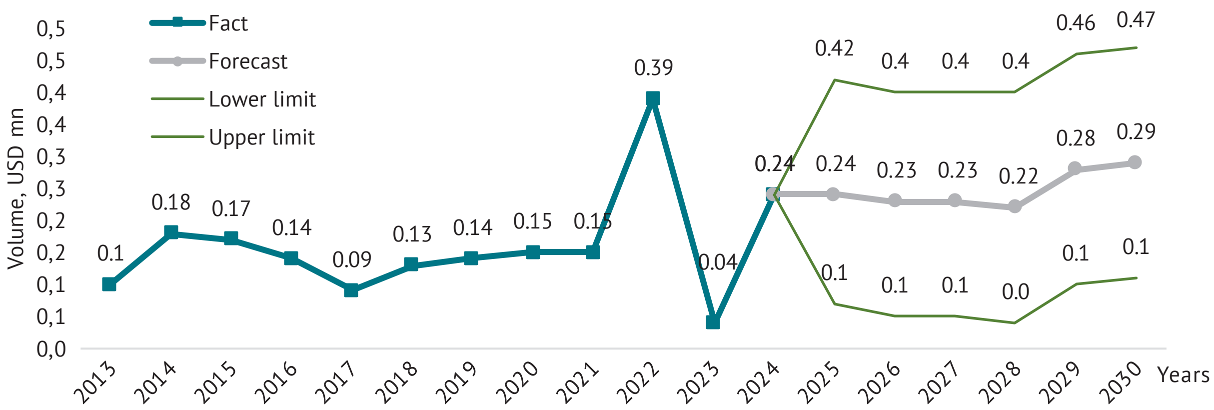

***Figure 6**. Forecast of bioplastics exports by 2030, USD mn*
***Source:** calculated by the authors of this study based on data from the State Statistics Service of Ukraine (2024)*

Among its many uses, maize can be used as a feedstock for alternative energy sources, including bioethanol. C. Bataille *et al.* (2018) concluded that the reduction of energy-intensive industrial greenhouse gas emissions in line with the commitments of the Paris Agreement (United Nations Framework Convention on Climate Change, 2015) can be achieved through energy efficiency measures using renewable energy sources, which will be cost-effective.

Demand for bioethanol is growing globally from various feedstocks, including barley, rye, wheat, and maize. To meet this demand, it is necessary to increase grain production by 10-15 mn t annually. In 2022, Ukraine's bioethanol production capacity was estimated at around 381 thsd t per year. Therewith, almost three quarters of them (282,000 t) are located over 200 km away from the combat zone, which makes it possible to continue its production. According to a survey conducted by the Ukrainian Association of Bioethanol Producers, production volumes in 2019 were 80 thsd t, in 2020 – 73 thsd t, and in 2021 – 77 thsd t (Bioethanol, 2023). In 2023, the volume of bioethanol exports amounted to USD 3.56 mn (Table 4).

***Table 4**. Exports and imports of bioethanol in 2013-2023*

Seq. No.	Year	Export		Import	
		Volume, mn USD	Volume, thsd t	Volume, mn USD	Volume, thsd t
1	2013	0	–	0.006425	0.000295
2	2014	4.96	5.62	4.573133	5.616666
3	2015	0.0007	0.0013	0.001171	0.000842
4	2016	0	–	0.003727	0.000511
5	2017	0.02	0.02	0.000145	0.000010
6	2018	0.00	–	0.003728	0.001734
7	2019	0.05	0.06	0.006478	0.001584
8	2020	5.44	8.11	0.000854	–
9	2021	0.32	0.40	0.100431	0.081683
10	2022	4.70	5.41	0.001448	0.000158
11	2023	3.56	5.10	0.002482	0.000125

***Source:** developed by the authors of this study based on research by the UN Comtrade Database (2024) and the State Statistics Service of Ukraine (2024)*

The bioethanol produced in Ukraine is mainly used for domestic consumption, which indicates the need to increase the volume of maize processing in the internal market. Maize has the highest product yields, for instance, 100 t of maize produces 46.7 m^3 of bioethanol, 36.5 t of CO_2 and 90 t of DDGS. In 2022, Ukraine harvested 27 mln t of maize, and in 2023 – approximately 30.1 mln t. At the same time, the share of processed maize for bioethanol did not exceed 2.5%. There are many companies operating in the Ukrainian bioethanol market, including the largest ones such as Naftogaz Bioenergy, the Renewable Energy Agency, Biomass Science and Technology Centre, MHP Eco Energy, GTS Operator of Ukraine LLC, GALS AGRO LLC, Kernel, Vitangro Group, and many others.

The factors that determine the prospects for using maize as a feedstock for future biofuels in Ukraine are as follows:

- both maize kernels and maize stalks are used for bioethanol production;
- due to its long shelf life and the ability to be processed throughout the year, maize is an alternative source of energy for industrial production;
- considerably higher than in other crops (soybean and sunflower yields of 3 t/ha, maize yields of 10 t/ha of grain and 10 t/ha of stalks) allows for the production of 3.1 t/ha of protein feed and enables the production of bioethanol (3.5 t/ha) (Ukrainian technology company, 2024);
- Ukraine's compliance with the requirements of the European Green Deal. Back in 2021, the Verkhovna Rada of Ukraine adopted in the first reading the Law of Ukraine No. 3356-d (2021) on the mandatory use of liquid biofuels (biocomponents) in the transport sector. Fuel producers in the EU specify a 5% or 10% bioethanol content in fuel, which affects pricing, and this stimulates internal production of bioethanol in the European Union. In Ukraine, it is planned to increase the share of bioethanol to 5% in transport fuel. This will bring the quality of Ukrainian fuel closer to European standards and will have a positive environmental effect and contribute to the sustainable development of the national agricultural sector (Draft Law of Ukraine, 2024).

Under martial law, the role of alternative energy sources, specifically bioethanol, in the context of ensuring national energy security has significantly increased. Apart from the transport sector, companies in related industries, such as chemicals and mining, have begun to consume bioethanol more actively. Based on forecasts, it was determined that bioethanol exports will grow slowly until 2030, and will not only reach the level of 2020 exports but also exceed it. Considering the growth of maize-based bioethanol production in Ukraine, the projected export volumes of the product under study in 2030 may reach a maximum level of USD 13.69 mn, and on average will amount to USD 9.3 mn (Fig. 7).

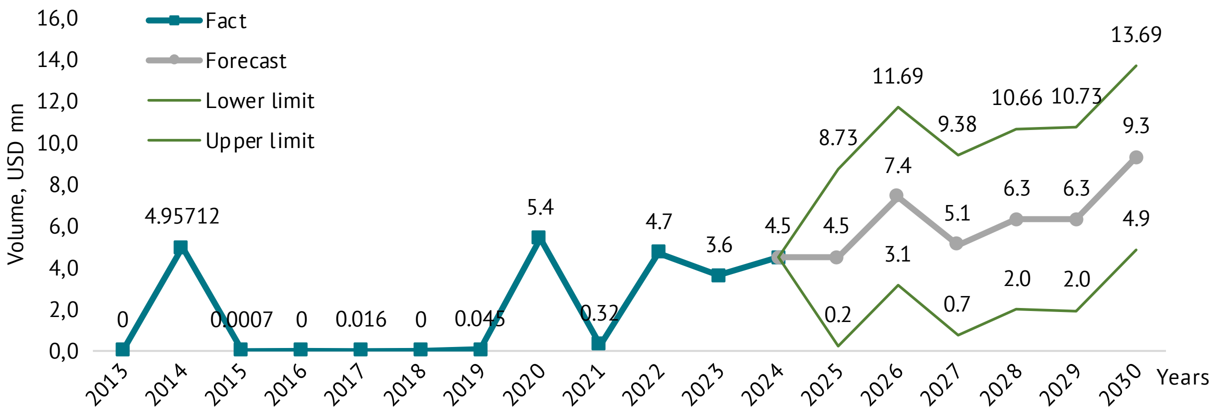

***Figure 7**. Forecast of bioethanol exports by 2030, USD mln*
***Source:** calculated by the authors of this study based on data from the State Statistics Service of Ukraine (2024)*

In 2024, Ukraine will gradually introduce the practice of adding bioethanol to fuel, but the vast majority of it is exported to the EU. G. Seber *et al*. (2022) substantiated the benefits of using sustainable aviation fuels from vegetable oils as one of the most promising short- and medium-term options for mitigating greenhouse gas emissions from aviation. A. Arias *et al*. (2024) focused on current trends in the production of biofuels for the marine and aviation sectors, considering the principal goals set, existing rules and directives in regulating these activities, analysing the type of biofuels and technologies used for their production. This once again confirms the importance of developing national bioethanol production. The inclusion of this area in the strategic directions of Ukraine's industrial recovery will help to increase national bioethanol production.

R. Hechelmann *et al*. (2023) covered the prospects of using biomethane to reduce greenhouse gas emissions for eight German manufacturing companies in various industries by conducting a greenhouse gas emissions inventory and identifying operational measures to reduce emissions, considering GAP and cost-effectiveness, which became the basis for developing a decarbonisation roadmap. The present study does not present all the possibilities of in-depth processing of maize as a promising energy agricultural raw material. Further research could be aimed at substantiating new maize processing technologies and bringing them into line with European technical regulations, which would help reduce greenhouse gas emissions in the context of decarbonisation.

CONCLUSIONS

Ukraine has not yet fully exploited its bioeconomic potential in maize processing, focusing mainly on commodity exports and fossil fuels. A considerable portion of value added, profits, foreign exchange earnings, and job opportunities stay abroad. One of the most promising areas of deep processing is the production of maize starch. Based on the author's calculations, if Ukraine establishes corn starch production, corn starch exports will have a positive annual growth rate of 7.39% on average by 2030. In 2030, the projected export volumes of the product under study will increase to USD 73.2 mn on average, with a possible deviation ranging from USD 55.0 mn to USD 91.3 mn.

Maize-based biopolymers can reduce greenhouse gas emissions by 25%, or 16 mn t of CO_2e/year. Based on forecasts, it was determined that bioplastics exports will grow until 2030 but will not reach the level of 2022. At the same time, considering the increase in the production of bioplastics from maize in Ukraine, the projected exports of the product under study in 2030 may reach a maximum level of USD 0.47 mn, but will average USD 0.29 mn in 2030. Based on forecasts, it was determined that bioethanol exports will grow slowly until 2030 and will not only reach the level of 2020 exports but also exceed it. Considering the growth of maize-based bioethanol production in Ukraine, the projected export volumes of the product under study in 2030 may reach a maximum level of USD 13.69 mn and will average USD 9.3 mn.

Prospects for further research on this topic include scientific support for the development of other areas of deep processing of maize as a biological and energy crop, including the production of gluten, amino acids, paints, varnishes, biogas, biodiesel, etc., the development of which is important for achieving the Sustainable Development Goals, namely combating climate change, environmental pollution, depletion of fossil mineral resources, and the spread of renewable energy sources, transition to rational production models, and ensuring food security.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Перспективи переробки кукурудзи для розвитку біоекономіки та декарбонізації в Україні

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Анотація. Відповідно до умов Європейського зеленого курсу, зокрема щодо переходу до зеленої економіки, декарбонізації та сталої моделі інклюзивного зростання, Україна взяла на себе зобов'язання досягнути кліматичного нейтралітету до 2060 року. Воєнні виклики, зумовлені повномасштабним вторгненням рф в Україну, вимагають поглибленого вивчення та обґрунтування механізмів розвитку перспективних напрямів глибокої переробки власної сільськогосподарської сировини для забезпечення продовольчої безпеки, розвитку внутрішнього ринку та повоєнного відновлення економіки країни. Метою дослідження був аналіз та оцінка можливостей переробки української кукурудзи в контексті розвитку біоекономіки, зокрема для виробництва таких продуктів як крохмалю, біопластику та біоетанолу. Дослідження здійснювалися за системним підходом із використанням методів екстраполяції та використання експоненціального згладжування і побудови довірчого інтервалу для оцінки прогнозу. Доведено, що в Україні є всі можливості для зростання обсягів виробництва більшої продуктової лінійки продуктів глибокої переробки кукурудзи. Реалізація потенціалу переробки кукурудзи як біологічної та енергетичної сировини в українській економіці для повоєнного відновлення залежить від створення інноваційної інфраструктури в частині біоекономіки, за рахунок зміцнення стратегічного партнерства між сільськогосподарськими виробниками, науковими установами та органами державної влади, кластерного розвитку та стимулювання експортної діяльності. Практичною цінністю роботи є розроблені рекомендації щодо реалізації можливостей переробки кукурудзи для розвитку біоекономіки та прискорення декарбонізації в Україні

Ключові слова: сталий розвиток; Зелена угода; вуглецевий слід; глибока переробка сільськогосподарської сировини; додана вартість; зелена енергетика