Received: 28.05.2024. Revised: 08.08.2024. Accepted: 05.09.2024.

EKONOMIKA APK

https://doi.org/10.32317/ekon.apk/4.2024.10

Ekonomika APK, 31(4), 10-22

UDC 338.43:631.95

Agricultural sector circular economy development: Agroecological approach

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▸ **Abstract.** This study aimed to investigate the feasibility of using agroecological concepts to establish a circular economy in the agricultural industry. The paper examined circular economy as a novel economic development paradigm that seeks to optimise resource utilisation and reduce waste, particularly in the agriculture industry. The main principle of the circular economy is resource conservation, which includes the rational use of land, water and energy, as well as the preservation of biodiversity and the improvement of soil fertility. An analysis was conducted on the economic advantages of adopting a circular economy in the agriculture industry, which include the reduction of production costs, enhancement of productivity, and generation of new employment opportunities. The study also addressed the importance of digitalisation, which can significantly increase the efficiency of agricultural production using modern digital technologies for monitoring soil conditions, managing water resources and optimising processes. This paper examined the effects of the war in Ukraine on the agricultural industry, specifically highlighting a substantial decrease in the output of key crops and livestock products. A comprehensive examination of the destruction of infrastructure, soil, and water contamination exposed severe environmental issues resulting from the attacks. The successful circular concepts implemented by European countries such as the Netherlands, Sweden, Denmark, and France can be applied

▸ **Suggested Citation**: Dovgal, O., Potryvaieva, N., Bilichenko, O., Kuzoma, V., & Borko, T. (2024). Agricultural sector circular economy development: Agroecological approach. *Ekonomika APK*, 31(4), 10-22. doi: 10.32317/ekon.apk/4.2024.10.

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to the post-war revival of the Ukrainian agriculture industry. The study also addressed the experience of the Ukrainian company Kernel, which successfully implements circular practices such as recycling of production waste, use of biomass and introduction of precision farming, which reduces environmental impact and increases production efficiency. Based on the analysis, recommendations for the post-war reconstruction of Ukraine's agricultural sector were proposed, including the identification of priority regions for recovery, stimulation of innovation and modern technologies, support for small and medium-sized farms, development of irrigation systems, environmental restoration and protection, international cooperation and support, and education and training

▸ **Keywords:** environmental pollution; resource conservation; post-war reconstruction; war waste; sustainable development; climate change; greenhouse gas emissions

▸ Introduction

The circular economy is a novel economic development paradigm that seeks to reduce waste and optimise resource utilisation. The fundamental concepts of this approach involve the recovery, recycling, and reutilization of resources in manufacturing operations. Within the agricultural sector, the circular economy presents novel prospects to enhance the sustainability of agricultural industry and mitigate the adverse environmental effects. The significance of establishing a circular economy in the agricultural industry is motivated by multiple causes. The agricultural sector is a significant consumer of natural resources, including water, land, and energy. Traditional approaches to agriculture often lead to soil depletion, water pollution and ecosystem degradation. The increasing global population and the phenomenon of climate change necessitate the development of novel strategies to guarantee food security and adjust to emerging environmental contexts. Within this particular framework, the circular economy has the potential to effectively mitigate the environmental impact and enhance the productivity of the agricultural industry.

The challenge of implementing a circular economy in the agricultural sector is the need to change traditional production practices and introduce new technologies and methods of resource management (Gavkalova *et al.*, 2024). The main challenges include the need for financial investment, changing the mindset and behaviour of farmers, and the need to develop an effective regulatory framework. In addition, there is a need to develop infrastructure for the processing and reuse of agricultural waste, as well as to create markets for circular economy products. Addressing these challenges requires cooperation between government agencies, the private sector and academia to ensure a comprehensive approach to transforming the agricultural sector.

The agroecological approach encompasses the incorporation of biological processes into agricultural production, the application of organic fertilisers, crop rotation, intercropping, and other techniques that promote the sustainable management of agricultural systems (Shahini *et al.*, 2022). Implementing this strategy decreases reliance on finite resources and decreases the release of greenhouse gases, which is crucial in the context of addressing climate change. Apart from the environmental advantages, the implementation of the circular economy in the agricultural industry can yield substantial economic benefits. The introduction of resource-efficient technologies and processes can reduce production costs, increase competitiveness and create new jobs in the waste processing and management sector (Dykha *et al.*, 2024).

Upon analysing the current research, it is feasible to pinpoint some notable studies that have made a substantial impact on the advancement of the circular economy in the agricultural industry and the agroecological approach. S. Kara *et al.* (2022) emphasised the importance of introducing closed production cycles in agriculture. The authors emphasised that such cycles can significantly reduce waste and increase resource efficiency. D. Breus & O. Yevtushenko (2023) assessed the impact of agroecological methods on soil fertility and biodiversity. They contended that the application of organic fertilisers and intercropping resulted in a decrease in soil erosion and an enhancement of soil structure. O. Shubravska *et al.* (2019) investigated the environmental benefits of the agroecological approach. The researchers concluded that including biological processes in production helps to decrease greenhouse gas emissions and preserve water resources. J.A. Aznar-Sánchez *et al.* (2019) investigated methods of increasing resource efficiency in agriculture. They highlighted the importance of organic waste processing for biogas and compost production. M. Duque-Acevedo *et al.* (2020) analysed the legal and regulatory frameworks needed to support the circular economy in the agricultural sector. They underscored the significance of public policy in fostering innovation and investment in this field. A.M. Dumont *et al.* (2021) studied the social aspects of implementing agroecological practices. They noted that such practices can contribute to the development of local communities and increase the social responsibility of farmers. S. Sehnem *et al.* (2019) explored the possibilities of creating new markets for circular economy products. The authors concluded that consumers increasingly prefer environmentally friendly products, which opens new prospects for farmers. An analysis of the role of technology in the implementation of the circular economy was conducted by A. Berxolli *et al.* (2023). They underscored the need to advance novel techniques for garbage recycling and the utilisation of sustainable energy sources. Furthermore, the influence of agroecological techniques on the sustainability of food systems was also examined by A. Wezel *et al.* (2020). The authors emphasised that the incorporation of these methods can greatly mitigate the adverse effects of agricultural output on the environment.

O. Dovgal & N. Potryvaieva (2024) discuss the pressing issue of increasing the efficiency of the agricultural sector of Ukraine through the introduction of circular economy principles. The study addressed the case of Myronivsky Hliboproduct, which demonstrates the benefits and challenges of this approach. Considerable focus was given to the examination of waste in biogas operations, which not only mitigates CO2 emissions but also enhances the efficiency of resource utilisation within the organisation. Furthermore, the report detailed the challenges encountered by the company following the comprehensive Russian incursion in 2022 and the actions implemented to ensure long-term growth. V. Shebanin *et al.* (2023) studied the implementation of sustainable development at the regional level, which is critical in modern conditions. The authors emphasised the need to coordinate natural resources, investments, and scientific and technological orientation to meet the future needs of humanity. The study explored the notion of circular economy as a crucial factor for the sustainable growth of businesses and regions since it guarantees the more effective utilisation of resources and enhances environmental safety.

Despite significant progress in the study of circular economy and agroecological practices, several topics require further research. The issue of integrating new technologies into circular processes in the agricultural sector in the context of their economic feasibility and practical implementation, has not been sufficiently considered. Many studies focus on theoretical aspects and general principles, while specific examples of technology implementation and their effectiveness remain insufficiently covered.

The objective of the study was to evaluate the feasibility of adopting a circular economy in the agricultural industry using an agroecological methodology. The study aimed to examine contemporary technologies that enable the adoption of the circular economy in the agricultural industry and their influence on economic productivity. Also, to evaluate the social challenges of farmers' adjustment to agroecological practices and their consequences on local communities. In addition, to evaluate the efficacy of current government policies and programs in promoting the circular economy, and to provide suggestions for enhancing their effectiveness.

▸Materials and methods

Data from the Area, gross harvest and crop yields (n.d.), Livestock production, number of livestock and feed supply (n.d.) were used to analyse the current state of the Ukrainian agricultural sector and assess the impact of the war on crop and livestock production. The data covers the period from 2014 to 2023, which was used for regression and trend analysis to identify long-term trends and changes in production. A regression analysis was conducted to evaluate the correlation between hostilities and the yield of key crops such as wheat, corn, barley, sunflower, and soybeans, as well as livestock products including meat, milk, eggs, and wool. The study employed a comparative analysis to evaluate the structural changes in the agricultural sector. This research revealed alterations in the composition of the harvest and their consequences on several categories of agricultural goods.

The assessment of the environmental and economic consequences of the war in Ukraine was based on reports by international organisations, including the World Bank, which analysed damage and direct losses in the agricultural sector (Neyter *et al.*, 2024). To assess the environmental impacts, a trend analysis of data from the State Ecological Inspectorate of Ukraine on the level of soil and water pollution because of military operations, including pollution with heavy metals, pesticide residues and other pollutants, was conducted in the study (The weekly infographic..., 2023). The effectiveness of circular practices was assessed based on the criteria of economic profitability, including reduced costs and increased revenues, and environmental impact, including reduced CO_2, CH_4 and N_2O emissions.

Specific technologies that were already successfully applied in different European countries were analysed in detail. Closed water systems in the Netherlands, precision agriculture in Sweden, waste-to-energy in Denmark and France, and reforestation projects in Germany and Switzerland were studied. A comparative analysis was employed to tailor these techniques to the specific circumstances of the Ukrainian agricultural industry, enhancing the environmental condition, boosting production, and promoting sustainable growth. Specifically, the implementation of closed water systems, precision agriculture, cutting-edge waste management technology, and reforestation initiatives can greatly enhance the environmental conditions in Ukraine.

This study examined the adoption of circular practices in the Ukrainian agricultural firm Kernel using data obtained from the company's corporate filings. A comparative analysis was conducted of the methods of recycling production waste, using biomass for energy production and precision agriculture. The effectiveness of these methods was assessed based on economic feasibility, including an analysis of the company's profitability and competitiveness, as well as environmental criteria, such as reducing the company's environmental footprint by reducing CO_2, CH_4 and N_2O emissions (Kernel annual report, 2023). Therefore, the study integrated regression, trend, and comparative analysis to evaluate the influence of the war on the agricultural industry. It also included an examination of the economic and environmental viability of adopting circular practices derived from both international and national experiences.

▸ Results

The circular economy is a novel economic development paradigm that prioritises the optimisation of resource utilisation and reduced waste generation. This notion holds considerable significance in the agricultural sector, given that agriculture is among the most resource-intensive businesses and has a substantial environmental footprint. The fundamental concept of the circular economy is to establish self-contained cycles in which trash generated by one operation is transformed into a valuable resource for another. This reduces the consumption of primary resources and reduces pollution. In the agricultural sector, circular processes can include recycling organic waste into compost or biogas, using perennial crops, integrating intercropping, and applying biological plant protection methods (Haque *et al.*, 2023). Resource conservation is a fundamental concept at the core of the circular economy in the agricultural industry. This entails not only the equitable utilisation of land, water, and energy but also the preservation of biodiversity and the enhancement of soil fertility. The substitution of chemical fertilisers with organic fertilisers, together with the implementation of crop rotation and intercropping, can enhance soil structure and mitigate erosion.

The agroecological approach, which is an integral part of the circular economy, involves the integration of biological processes into agricultural production. This includes the use of natural mechanisms to control pests, and the use of cover crops to preserve soil moisture and improve soil fertility. Agroecological methods reduce the use of synthetic chemicals and pesticides, which in turn helps to reduce environmental pollution and improve product quality. The economic benefits of implementing a circular economy in the agricultural sector are also significant (Reynaud *et al.*, 2019). The use of resource-efficient technologies can reduce production costs, increase productivity, and create new jobs in waste processing and management. For instance, the production of biogas from organic waste can be an additional source of income for farmers, as well as reduce dependence on fossil fuels.

The adoption of digitalisation plays a significant role in the execution of the circular economy within the agricultural industry. Modern digital technologies can be employed to monitor soil conditions, manage water resources and optimise processes that can significantly increase the efficiency of agricultural production. Innovations such as sensors, drones, and precision farming systems help to reduce resource waste and increase productivity (Boz & Martin-Ryals, 2023).

The agricultural sector in Ukraine accounts for roughly 10% of the country's gross domestic product and employs a significant portion of the population, particularly in rural regions. Characterised by highly fertile soils, especially black soil which accounts for 30% of the global supply, Ukraine possesses significant potential for cultivating key commodities such as wheat, sunflower, maize, barley and soybeans. Another important aspect is the export of grains and oilseeds, which significantly contributes to the country's trade balance. This phenomenon gives rise to the substantial productivity of prominent agricultural commodities including wheat, corn, barley, sunflower, and soybeans. Furthermore, Ukraine holds a prominent position as a global exporter of grains and oilseeds, exerting a substantial influence on its trade balance. Production growth in the agricultural industry from 2012 to 2020 was driven by the implementation of advanced technologies and innovations, which enhanced production efficiency and the competitiveness of products in global markets. However, the war negatively impacted the sector, through the destruction of infrastructure, landmines and environmental pollution, which reduced yields and export potential (Fig. 1).

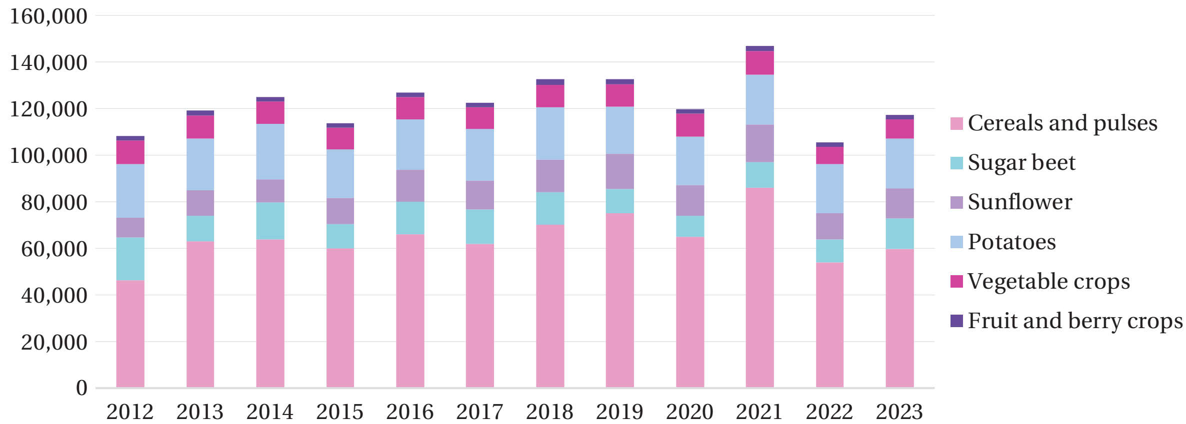

Figure 1. Gross agricultural production in Ukraine from 2012 to 2023, measured in thousand tonnes
Source: compiled by the authors based on the data from Area, gross harvest and crop yields (n.d.)

The war in Ukraine has inflicted extensive harm on the agricultural industry, resulting in a substantial decrease in the yield of key commodity crops. Despite a partial rebound in 2023, the production quantities still fall short of the levels seen before the war. This highlights the necessity for sustained assistance and reconstruction of agriculture in response to persistent difficulties. Presented in Table 1 are the production volumes of livestock products.

Table 1. Estimated output of primary livestock products in Ukraine from 2012 to 2023

Year	Meat (in slaughter weight), thousand tonnes	Milk, thousand tonnes	Eggs, million	Wool, t
2012	2,209.6	11,377.6	19,110.5	3,724
2013	2,389.4	11,488.2	19,614.8	3,520
2014	2,359.6	11,132.8	19,587.3	2,602
2015	2,322.6	10,615.4	16,782.9	2,270
2016	2,323.6	10,381.5	15,100.4	2,072
2017	2,318.2	10,280.5	15,505.8	1,967
2018	2,354.9	10,064	16,132	1,908
2019	2,492.4	9,663.2	16,677.5	1,734
2020	2,477.5	9,263.6	16,167.2	1,573

Table 1, Continued

Year	Meat (in slaughter weight), thousand tonnes	Milk, thousand tonnes	Eggs, million	Wool, t
2021	2,438.3	8,713.9	14,071.3	1,497
2022	2,206.7	7,767.7	11,921.8	1,237
2023	2,239.5	7,430.4	11,379.4	1,187

Source: compiled by the authors based on the data from Livestock production, number of livestock and feed supply (n.d.)

Table 1 presents the production metrics of the primary animal products in Ukraine, illustrating notable fluctuations in output levels between 2012 and 2023. There has been a downward trend in milk, eggs and wool production, especially since 2015. Meat production remains more stable, although it has also experienced some fluctuations. The significant decline in production in 2022 and 2023 is due to the negative impact of the war, which highlights the need to take measures to support and restore livestock production in the country.

The war in Ukraine has caused severe damage to infrastructure, and soil and water pollution, which has had a significant negative impact on the agricultural sector. An analysis of damage and direct losses conducted by the World Bank and its partners shows that different sectors of the economy suffered the greatest losses: housing (17% of total damage), transport (15%), energy (10%), industry and trade (14%), and agriculture (12%) (Neyter *et al.*, 2024). However, losses in agriculture are underestimated and hidden.

Data from the State Ecological Inspectorate of Ukraine indicate that aggressive Russian actions caused significant environmental and agronomic problems (The weekly infographic..., 2023). 594.5 thousand m^2 of soil were contaminated with harmful substances, which impairs their fertility and makes them unsuitable for agricultural use. A large part of the land (17.8 million m^2) was covered with the remains of destroyed objects and ammunition, making it difficult to cultivate and use these areas for agricultural purposes (Neyter *et al.*, 2024). The shelling resulted in the burning of 721.8 thousand tonnes of oil products, which significantly polluted the air and soil. This pollution affects water and soil quality, making it difficult to grow crops. In addition, more than 38 thousand tonnes of emissions from the combustion of Russian equipment were released into the atmosphere, which also harms the environmental situation. More than 352 thousand tonnes of waste were generated, polluting both air and land. Fires caused by missiles and shells destroyed 66.8 thousand hectares of forests, which not only worsened the environmental situation but also contributed to soil erosion and loss of natural resources. At the same time, the mining of territories has become another serious problem. The clearance of these territories, which cover an area of approximately 200 thousand km^2, requires significant resources and time, which delays the restoration of agricultural land.

In summary, the war in Ukraine has severely damaged the agricultural sector through direct destruction of infrastructure, soil and water contamination, as well as long-term problems related to landmines and environmental pollution. Urgent measures are needed to restore the agricultural sector, including the clean-up of contaminated areas, restoration of infrastructure and maintenance of environmental safety. The post-war reconstruction of the Ukrainian agricultural sector requires the integration of innovative practices that will effectively restore agriculture, reduce the negative impact of the war, and ensure sustainable development. The implementation of a circular economy by European countries might be a significant benchmark and a valuable source of practice for Ukraine.

European countries such as the Netherlands and Sweden demonstrate efficient ways of using resources in the agricultural sector. The Netherlands is a global leader in the implementation of closed-water cycles in agriculture. Water recycling systems are used in greenhouses where different crops are grown. These systems collect, purify and reuse water, which significantly reduces its consumption and costs. For example, in Dutch greenhouses, up to 90% of water can be reused, reducing water consumption by 50-70% compared to traditional methods (Gonzalez-Martinez *et al.*, 2021). For Ukraine, where the war has severely damaged infrastructure and resources, the introduction of such technologies can significantly reduce water consumption and improve water quality. In reconstructed areas where irrigation systems have been destroyed, the use of closed water cycles will allow for efficient use of available resources, reduce water pollution, and increase crop productivity.

Swedish agriculture actively employs precision farming technologies to maximise the utilisation of fertilisers and herbicides. Precision agriculture includes the utilisation of sensors, satellite imaging, and drones to closely observe and assess the state of soil and plants. This allows farmers to accurately determine the fertiliser and pesticide requirements of each area of the field, which reduces their consumption and improves soil fertility. For instance, in Sweden, precision farming has reduced fertiliser costs by 20-30% and increased yields by 10-15% (Dietmann & Stålhammar, 2020). For Ukraine, where the use of chemical fertilisers and pesticides may be limited due to infrastructure damage and pollution, these technologies could be a solution to improve soil fertility and increase yields. Precision farming will additionally mitigate the adverse effects on the environment and afford a more sustainable methodology for agricultural output.

The recycling and waste management practices used in Denmark and France can be adapted to restore areas affected by war. Denmark is a leader in the use of organic waste for biogas production. Cooperative biogas plants have been set up in many rural areas to process organic waste from farms, the food industry and households. France is actively implementing urban biogas plants that process organic waste from large cities such as Paris. These plants produce biogas that is used to power public transport or heat homes. In Ukraine, where agricultural waste disposal and soil contamination are serious problems, using waste to produce biogas or compost can help improve soil fertility and reduce dependence on external resources. Organic waste processing technologies can create valuable fertilisers and reduce the negative impact of waste accumulation. European countries are actively implementing agroecology practices to improve the ecological balance. Agroforestry is a method of integrating woody plants into agricultural systems. In France, this approach is widely used to combat soil erosion and improve soil structure. In agroforestry systems, trees are planted along fields to help stabilise soils, reduce erosion and increase fertility. Woody plants also provide a natural defence against wind erosion and help retain soil moisture (Hotelier-Rous *et al.*, 2020). For Ukraine, where large areas have been affected by the war and where soil erosion is a pressing issue, the introduction of agroforestry could be an important step in recovery. Planting trees and shrubs at field boundaries and in the aisles will reduce erosion, improve soil structure and increase soil fertility. It will contribute to the restoration of biodiversity and the creation of new ecological niches for local flora and fauna.

In Germany and Switzerland, projects are being implemented to restore forests that have been destroyed or degraded. These projects include re-planting trees, restoring natural forest ecosystems and maintaining vegetation diversity. One of the key projects in Germany is the Waldklimafonds (Forest Climate Fund), which was established by the government to restore and adapt forests to climate change. As part of this initiative, extensive replanting of trees, specifically chosen native species that are more well-suited to the new climatic circumstances, has been conducted. The reforestation of thousands of hectares of forest nationwide has effectively mitigated CO_2 emissions and generated employment opportunities within the forestry industry. In Switzerland, one of the most significant projects was the Lothar Project, launched after the 1999 Lothar storm, which destroyed large areas of forest. The project restored more than 25 thousand hectares of forest, making them more resilient to future storms and extreme weather conditions. The economic benefits of this project have been significant: the conservation and restoration of forest resources have become an important factor for the Swiss woodworking industry and support for local tourism. Furthermore, green infrastructure, including green corridors and ecological networks, significantly contributes to the enhancement of air quality and the mitigation of pollution. For Ukraine, where the war has caused significant damage to natural ecosystems, restoring forests and green infrastructure will be critical to improving the environmental situation. In the UK and the Netherlands, green surfaces are being created to absorb pollutants and provide natural air purification. Green infrastructure, such as urban parks, green roofs and walls, helps to reduce the concentration of pollutants in the air and improve the overall environmental situation. For Ukraine, the implementation of such initiatives can help restore damaged areas and improve air quality.

Local initiatives in Italy and other European countries demonstrate the importance of developing local economies through the implementation of circular practices. In Italy in the Tuscany region, agricultural waste recycling projects are being implemented that provide numerous economic benefits. One of these projects is the establishment of composting stations where organic waste is converted into high-quality compost for soil fertilisation. This not only reduces the amount of waste that needs to be disposed of but also reduces the need for chemical fertilisers. As a result, fertiliser costs are reduced, soil fertility is improved, and the risk of environmental pollution is reduced. The cost of agricultural production is also reduced due to greater efficiency in the use of natural resources. Another example of a successful initiative in Italy involves the use of olive oil residues. These residues are processed into biomass, which serves as an alternative fuel for heating greenhouses. This reduces the consumption of traditional energy resources such as gas or electricity, which in turn reduces energy costs. In addition to decreasing greenhouse gas emissions, the use of biomass also enhances the resilience of greenhouses to climate change (Cristiano, 2021). Such practices have also been noted in Germany, where agricultural cooperatives share machinery and waste management, reducing costs and environmental impact. In Ukraine, where the war has severely damaged infrastructure and the economy, these innovative approaches could be an important factor in the recovery of the agricultural sector. Supporting local producers and agribusinesses that use the latest tillage and waste management techniques can help reduce costs and increase efficiency. For example, the creation of local clusters and cooperatives will help farmers pool resources to share machinery and equipment, which will reduce costs and provide access to new technologies. The experience of European countries in rehabilitating infrastructure can serve as a useful guide for Ukraine. Therefore, it is crucial to allocate resources towards the restoration of agricultural infrastructure, encompassing trash collection and recycling systems, irrigation systems, and energy solutions that adhere to the concepts of a circular economy. This will not only help restore production capacity but also ensure its sustainability and efficiency in the long term.

Kernel is a prominent agricultural enterprise in Ukraine that aggressively adopts circular economy principles to enhance production efficiency and minimise environmental footprint. The company uses an integrated approach to resource management, focusing on waste recycling, biomass utilisation and precision farming. A fundamental activity of the organisation is the recycling of production waste. Kernel transforms waste from sunflower processing, such as husks and oilcakes, into useful products for livestock. Instead of disposing of this waste as garbage, the company collects it, processes it and turns it into high-quality animal feed. This process involves drying, grinding and mixing the waste with other ingredients to achieve optimum feed quality. Through this practice, Kernel reduces the amount of waste going to landfills and reduces the cost of purchasing feed. The company also actively uses biomass as a renewable energy source. Production waste, such as sunflower husks, is processed into biomass, which is used to produce biofuels and heat. This process involves pelletising and burning biomass in specialised boilers, which generates energy for the company's production needs. The utilisation of biomass diminishes reliance on fossil fuels and contributes to the mitigation of greenhouse gas emissions, therefore yielding a favourable environmental outcome. In addition, it allows the company to reduce energy costs, as part of its energy needs are covered by internal resources. Kernel is also implementing precision farming technologies to improve resource efficiency and reduce its environmental impact. The use of Global Positioning System technologies, drones and specialised software tools can be used to accurately determine the needs of crops for fertilisers, water and other resources. Data monitoring and analysis systems help farmers make informed decisions about tillage and fertilisation. This includes the use of sensors, satellite imagery and soil analysis. Thanks to precision agriculture, the company reduces the cost of fertilisers and chemicals while increasing yields and product quality. It also helps to preserve soil and reduce the negative impact on the environment. Table 2 shows the main indicators of the company's gas emissions.

Table 2. Kernel's key emissions indicators from 2021 to 2023, thousand tonnes of CO_2

Emission	2021	2022	2023
By type			
CO_2	291.7	521.5	416.9
CH_4	22	22.8	23.4
N_2O	712.2	719.9	615.2
By business segment			
Oilseeds processing	19	9.1	6.6
Infrastructure and trade	58.4	81.3	62.2
Agriculture	941.1	1,172.7	986.2
Fuel consumption	135.5	103.2	124.8
Fertiliser application	697.3	708.6	602.4
Changes in soil carbon reserves	83.9	335.4	232.8
Bovine methane from enteric fermentation	24.4	25.5	26.2
Other	7.4	1.2	0.7
Biogenic (burning sunflower husks)	349.5	348.9	509.8
Total	1,025.9	1,264.2	1,055.6

Source: compiled by the authors based on Kernel Annual Report (2023)

CO_2 emissions increased significantly from 291.7 thousand tonnes in 2021 to 521.5 thousand tonnes in 2022 but decreased to 416.9 thousand tonnes in 2023. CH_4 and N_2O emissions also increased in 2022 but then decreased in 2023. By business segment, oilseeds processing and agriculture showed a decrease in emissions, while infrastructure and trade fluctuated. Total emissions increased from 1,025.9 thousand tonnes in 2021 to 1,264.2 thousand tonnes in 2022 but decreased to 1,055.6 thousand tonnes in 2023. These data show that Kernel is working to reduce its environmental impact by implementing efficient technologies and practices, although some aspects require further optimisation, including an increase in biogenic emissions in 2023.

Kernel's circular economy practices significantly reduced the amount of waste and the cost of its disposal. Recycling waste into feed and biomass improves the use of available resources, reducing energy and raw material costs. The use of precision farming increases productivity and reduces the need for chemicals. Minimising the volume of waste deposited in landfills and decreasing the reliance on fossil fuels has a beneficial effect on the environmental conditions in the surrounding area. Utilising biomass as an energy source and implementing precision agriculture techniques contribute to the mitigation of greenhouse gas emissions and the enhancement of soil health. Kernel's experience in implementing circular practices shows that agricultural companies can significantly increase their efficiency and sustainability by applying innovative approaches to resource management. The use of waste, biomass and precision farming can reduce costs, conserve natural resources and improve the environment. Such techniques can be used as a blueprint for other agricultural businesses aiming to attain sustainable development and protect the environment.

Developing a circular economy in the agriculture sector is becoming a crucial undertaking in Ukraine, considering the context of sustainable development and postwar rebound. With this objective in mind, the government is enacting several laws and programs designed to bolster environmental efforts and promote the effective utilisation of resources in agriculture. One crucial endeavour is the National Trash Management Strategy, which seeks to minimise trash and enhance recycling. The objective of the policy is to establish infrastructure for the gathering and treatment of agricultural waste while encouraging the use of organic fertilisers and composting.

Another important role is played by the State Programme for Support of Organic Production, which is aimed at developing organic farming. The programme provides financial support to farmers who adopt organic production methods, including the use of natural fertilisers and biological pest control methods. This reduces the use of chemicals and improves soil quality. The state bioenergy development programme advocates for the utilisation of biomass in energy generation. This includes the promotion of biogas generation from agricultural waste and the optimisation of biomass utilisation for heat generation. The implementation of such measures serves to diminish reliance on fossil fuels and mitigate the release of greenhouse gas emissions. An important component of the circular economy support is the Small and Medium-Sized Farmer Support Programme, which aims to stimulate cooperation between farmers and develop local markets. The initiative offers financial assistance for the implementation of ecologically sustainable technologies and methods in agriculture, including precision farming, agroforestry, and water resources management. Also worth mentioning is the National Climate Change Action Plan, which includes measures to adapt agriculture to climate change. This involves the development of sustainable agricultural systems, including the use of resistant plant varieties, optimisation of water use and the introduction of agroforestry.

In general, Ukrainian government policies and programmes aim to create conditions for sustainable development of the agricultural sector by implementing circular practices, reducing environmental impact and increasing resource efficiency. These measures are important steps towards restoring ecosystems and improving the economic situation of the agricultural sector in the post-war recovery. For the post-war reconstruction and recovery of the Ukrainian agricultural sector, a comprehensive strategy that addresses environmental, economic and social aspects needs to be developed. First, priority regions and sectors should be identified for recovery based on the degree of damage and potential for development. For example, the recovery of key agricultural regions such as Kherson, Zaporizhzhia and Kharkiv, which have suffered significant damage, will be a priority for recovery. The introduction of circular practices, such as the use of agricultural waste for biofuel and biogas production, will contribute to energy independence and reduce greenhouse gas emissions (Kapoor *et al.*, 2020). For instance, as the experience of different countries shows, processing sunflower residues into biofuels can significantly reduce the need for traditional fuels.

Composting organic waste and using it as fertiliser will improve soil fertility, which is particularly important for restoring degraded land. For instance, farmers can use crop residues to create compost, which will improve soil structure and increase yields. Encouraging innovation and modern technologies, including precision farming to optimise the use of fertiliser and water, will reduce costs and increase yields. Deploying drones for field monitoring and precise application of fertilisers would mitigate the excessive use of pesticides and minimise the adverse environmental effects. The implementation of irrigation infrastructure and efficient water management practices will alleviate water scarcity in dry regions. For instance, the introduction of drip irrigation in the southern regions of Ukraine will significantly reduce water consumption and increase the efficiency of its use, as is the case in the Netherlands. Supporting small and medium-sized farms through financial incentives such as subsidies, soft loans and grants will help restore production. The development of cooperatives and local markets will provide access to inputs and sales. For example, the creation of cooperatives for the joint purchase of equipment and inputs will help reduce costs for individual farmers.

Support for the transition to organic production methods, including training and advisership to farmers, will facilitate the certification of organic products and their subsequent export to international markets. For example, organising trainings for farmers on organic farming will increase their knowledge and adoption of environmentally friendly practices. Reconstruction of transport and logistics infrastructure will ensure efficient transportation of agricultural products. Restoration and modernisation of agricultural enterprises and production facilities will ensure production restoration. For instance, repairing and upgrading railway lines will provide faster delivery of products to various markets. Ecological restoration and protection, including measures to restore degraded land, reforestation and planting, and cleaning up contaminated soil and water resources, will improve the environment. Like restoration in Germany and Switzerland, planting forest strips around fields will help reduce soil erosion and improve the local climate. International cooperation and support, including financial assistance, technical support and exchange of experience, will facilitate the implementation of best practices and technologies. For instance, cooperation with European partners to exchange knowledge and experience in the field of agroecology will help to implement best practices in Ukraine. Environmental insurance is a critical element in the implementation of a circular economy in the agricultural sector, as it provides financial protection against risks associated with environmental damage and pollution (Shebanina *et al.*, 2023). In the context of recovery from war or natural disasters, environmental insurance helps to reduce financial risks for farmers and agribusinesses, which helps to stimulate investment in sustainable development and new environmental practices. This allows agricultural enterprises to implement innovative circular solutions with the confidence that in the event of environmental problems, they will receive the necessary support to quickly recover and continue their operations.

Training and education through the organisation of training programmes and the establishment of further education centres will ensure a skilled workforce. For instance, the creation of training centres for agronomists and technicians will improve the knowledge and skills of local workers. The development of medical, educational and social infrastructure in rural areas will ensure decent living and working conditions. The implementation of these suggestions will bolster the revival and advancement of the Ukrainian agricultural industry, guaranteeing its long-term viability, effectiveness, and ecological integrity during the post-war period of recovery.

▸ Discussion

In the context of post-war recovery, the study's findings validate the considerable potential for establishing a circular economy in Ukraine's agriculture sector. The concept of economic development, characterised by the optimisation of resource utilisation and reduction of waste, holds significant relevance for the agricultural industry, which is highly resource-intensive and environmentally detrimental. Implementing closed cycles, in which waste generated by one operation is repurposed as a resource for another, effectively decreases the use of primary resources and mitigation of pollution. M.R. Mosquera-Losada *et al.* (2019) examined the influence of perennial crops on soil fertility within the context of a circular economy. The investigation was carried out on controlled trial fields utilising perennial crops like lucerne, clover and perennial grasses. The study conducted by J.F. Velasco-Muñoz *et al.* (2022) demonstrated that the implementation of these crops had a substantial impact on the mitigation of soil erosion and the enhancement of its organic composition. Following three years of utilising perennial crops, it was seen that the soil's organic matter content had a 15% rise, while erosion exhibited a 25% reduction. The findings of the research indicate the potential of crop rotation and an agroecological approach to improve soil fertility in Ukraine, which is important for the restoration of affected land.

O. Dovgal & N. Potryvaieva (2024) discuss the pressing issue of increasing the efficiency of the agricultural sector of Ukraine through the introduction of circular economy principles. The study addressed the case of Myronivsky Hliboproduct, which demonstrates the benefits and challenges of this approach. Considerable focus was given to the examination of waste in biogas operations, which not only mitigates CO_2 emissions but also enhances the efficiency of resource utilisation within the organisation. Furthermore, the report detailed the challenges encountered by the company following the comprehensive Russian incursion in 2022 and the actions implemented to ensure long-term growth. V. Shebanin *et al.* (2023) studied the implementation of sustainable development at the regional level, which is critical in modern conditions. The authors emphasised the need to coordinate natural resources, investments, and scientific and technological orientation to meet the future needs of humanity. The study explored the notion of circular economy as a crucial factor for the sustainable growth of businesses and regions since it guarantees the more effective utilisation of resources and enhances environmental safety.

F.C. Silva *et al.* (2019) focused on the impact of circular practices on the economic efficiency of farms. They conducted a detailed comparison of the costs and revenues of farmers who implement circular practices with those who follow traditional methods. Their study used data from different regions where farmers were implementing practices such as organic waste reuse, biomass processing and energy-efficient technologies. For Ukraine, these results demonstrate the potential for significant cost savings and increased income for farmers through the implementation of circular practices. This may be particularly relevant in the context of post-war recovery, where cost-effectiveness is critical to stabilising the agricultural sector.

The findings underscore the significance of resource conservation as a fundamental tenet of the circular economy. Substituting chemical fertilisers with organic fertilisers, implementing crop rotation, and incorporating perennial crops can enhance soil structure and mitigate erosion. These approaches have the potential to greatly enhance soil fertility and make a substantial contribution to the sustainable development of the agricultural industry (Biyashev *et al.*, 2024). I.P. Sharma *et al.* (2020) analysed the impact of intercropping on biodiversity conservation. They used a mixture of different crops in fields to increase the resilience of agroecosystems. Their results showed that the use of intercropping increases biodiversity and improves the resilience of agroecosystems to climate change. Intercropping contributes to the creation of more resilient agroecosystems. The results show that intercropping improves biodiversity and resilience to climate change. For Ukraine, the integration of intercropping can contribute to the creation of more resilient agroecosystems, which will help in climate change adaptation and biodiversity conservation in the affected regions.

The agroecological approach, which is an integral part of the circular economy, involves the integration of biological processes into agricultural production (Nunes & Sytnychenko, 2024). Harnessing natural mechanisms for pest control and implementing cover crops to retain moisture and enhance soil fertility can minimise reliance on synthetic chemicals and pesticides. Consequently, this contributes to the mitigation of environmental degradation and the enhancement of product quality. M. Tariq *et al.* (2020) studied the impact of biological plant protection methods on crop yields. To manage pests and diseases, they employed biological products derived from microbes and beneficial insects. The research conducted has demonstrated that the implementation of biological techniques can effectively decrease the reliance on pesticides without substantially diminishing crop production. Biological methods can be an effective alternative to chemicals. The study also shows the effectiveness of biological methods of plant protection, providing concrete data on the preservation of yields. Ukrainian adoption of biological approaches can mitigate the adverse effects of chemical pesticides on the environment and human health, playing a crucial role in the restoration of ecosystems and enhancement of agricultural product quality.

The results also show that the economic benefits of implementing a circular economy in the agricultural sector are significant. The use of resource-efficient technologies can reduce production costs, increase productivity and create new jobs in waste processing and management. For example, the production of biogas from organic waste can be an additional source of income for farmers and reduce dependence on fossil fuels. M. Ellacuriaga *et al.* (2021) focused on the cost-effectiveness of organic waste conversion to biogas. They investigated the profitability of biogas plants on medium and large farms. M.R. Atelge *et al.* (2020) showed in their results that investments in biogas plants can pay off within 5-7 years and provide additional income to farmers through the sale of electricity and heat. The authors also noted that the use of biogas reduces greenhouse gas emissions by 40%. The authors' findings confirm that biogas plants can be a profitable investment solution for agricultural enterprises in Ukraine. It not only reduces energy costs but also reduces greenhouse gas emissions. Biogas plants can be an effective tool for the economic recovery of the agricultural sector and reduce the ecological footprint.

Digitisation is a crucial component of the circular economy within the agricultural industry. The use of modern digital technologies to monitor soil conditions, manage water resources and optimise processes can significantly increase the efficiency of agricultural production

(Skarbøvik *et al.*, 2014). Sensors, drones, and precision farming systems reduce resource losses and increase productivity. E. Bwambale *et al.* (2022) investigated the impact of digital technologies on water use efficiency in agriculture. They conducted experiments with precision irrigation systems on different types of soils and crops. The results showed that the introduction of such systems can reduce water use and increase yields by optimising water regimes and reducing water losses. The authors' study found that the use of digital technologies, such as precision irrigation, increases resource efficiency and yields. For Ukraine, the introduction of modern digital technologies in water management can significantly improve the efficiency of agricultural production and ensure optimal water use in the face of climate change.

Data analysis shows that the Ukrainian agricultural sector has suffered significant losses due to the war. This emphasises the need to introduce circular practices to restore and support local economies. The results of the study show that the introduction of practices such as recycling organic waste into compost or biogas, using perennial crops, integrating intercrops and applying biological plant protection methods can help restore productivity and improve the environmental status of agricultural areas. Y. Fan & C. Fang (2020) focused on the role of government programmes in supporting the circular economy in the agricultural sector. They analysed the effectiveness of various government initiatives and subsidies that promote the implementation of circular practices on farms. A. Muscio & R. Sisto (2020), in turn, found that effective government programmes significantly accelerate the adoption of circular practices in agriculture. They emphasised that government subsidies and grants not only provide financial support for farms but also stimulate innovation and new technologies in the agricultural sector. The authors' findings highlight the importance of state support for the implementation of circular practices. For Ukraine, subsidies and programmes can provide the necessary financial support for farmers and stimulate innovation in the agricultural sector.

The research findings validate that implementing a circular economy in the agricultural industry can greatly enhance the recovery and sustainable development of regions. This necessitates proactive backing from the government, including the formulation and execution of laws and programs targeted at bolstering environmental schemes and optimising resource utilisation in agriculture. Such measures are important steps towards restoring ecosystems and improving the economic situation of the agricultural sector in the post-war recovery.

Conclusions

The results obtained in this study confirm that the implementation of circular practices can contribute to both environmental restoration and economic growth of the agricultural sector. The circular economy has been proven to be an innovative model that allows for the creation of closed production cycles and efficient waste management. The use of resource-efficient technologies, such as closed water cycles, precision agriculture and waste recycling, helps to reduce production costs, increase productivity and create new jobs.

An agroecological strategy, which incorporates biological processes into agricultural production, minimises the use of synthetic chemicals and pesticides, therefore mitigating environmental damage and enhancing product quality. The practical importance of this strategy lies in its contribution to the sustainable growth of the agricultural industry, which serves to decrease reliance on external resources and enhance long-term economic efficiency.

The war in Ukraine has severely damaged the agricultural sector, leading to a significant decline in the production of major crops. The experience of European countries, such as the Netherlands, Sweden, Denmark and France, highlights the importance of implementing circular practices in the Ukrainian agricultural sector. An important example is the experience of Kernel, which is actively implementing circular practices. The introduction of waste recycling technologies, the use of biomass as an energy source, and the application of precision agriculture allowed the company to significantly reduce its total emissions from 1,264 thousand tonnes in 2022 to 1,056 thousand tonnes in 2023.

The study's practical utility lies in its ability to pinpoint particular circular technologies and approaches that might be implemented in Ukraine to rejuvenate the agriculture sector. This encompasses the implementation of closed production cycles, enhanced waste recycling, the utilisation of biomass as an energy source, and the optimisation of agricultural operations through the application of contemporary technologies. The adoption of these methods will not only aid in the rehabilitation of the environment but also yield the economic advantages essential for the continued growth of Ukraine's agricultural industry.

An inherent constraint of the study is the absence of data regarding the influence of particular circular practices on the revival of the agricultural industry in Ukraine. This gap arises from the scarcity of long-term observations and the occurrence of infrastructure damage. Further investigation should concentrate on a comprehensive examination of the efficacy of various circular technologies in particular recovery scenarios and their influence on economic and environmental outcomes.

Acknowledgements

None.

Conflict of interest

The authors of this study declare no conflict of interest.

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Розвиток циркулярної економіки в аграрному секторі: агроекологічний підхід

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▶ **Анотація.** Це дослідження мало на меті дослідити доцільність використання агроекологічних концепцій для створення циркулярної економіки в сільськогосподарській галузі. У документі розглядається циркулярна економіка як нова парадигма економічного розвитку, спрямована на оптимізацію використання ресурсів і зменшення відходів, особливо в сільськогосподарській галузі. Основним принципом циркулярної економіки є збереження ресурсів, що включає раціональне використання землі, води та енергії, а також збереження біорізноманіття та підвищення родючості ґрунтів. Було проведено аналіз економічних переваг впровадження циркулярної економіки в сільському господарстві, які включають зниження витрат виробництва, підвищення продуктивності та створення нових робочих місць. Також розглянуто значення цифровізації, яка дозволяє значно підвищити ефективність сільськогосподарського виробництва через використання сучасних цифрових технологій для моніторингу стану ґрунтів, управління водними ресурсами та оптимізації процесів. У цій статті досліджено вплив війни в Україні на сільськогосподарську галузь, особливо підкресливши значне зниження виробництва основних сільськогосподарських культур і продуктів тваринництва. Комплексне дослідження руйнування інфраструктури, ґрунту та забруднення води виявило серйозні екологічні проблеми, спричинені атаками. Успішні циклічні концепції, реалізовані такими європейськими країнами, як Нідерланди, Швеція, Данія та Франція, можуть бути застосовані до післявоєнного відродження українського сільського господарства. У досліджені також розглянуто досвід української компанії “Кернел”, яка успішно впроваджує циркулярні практики, такі як переробка відходів виробництва, використання біомаси та впровадження точного землеробства, що дозволяє знизити екологічний вплив та підвищити ефективність виробництва. На основі аналізу запропоновано рекомендації для післявоєнної відбудови аграрного сектору України, які включають ідентифікацію пріоритетних регіонів для відновлення, стимулювання інновацій та сучасних технологій, підтримку малих і середніх фермерських господарств, розвиток іригаційних систем, екологічне відновлення та захист, міжнародну співпрацю та підтримку, а також навчання і підготовку кадрів

▶ **Ключові слова:** забруднення навколишнього середовища; збереження ресурсів; післявоєнна відбудова; відходи війни; сталий розвиток; зміна клімату; викиди парникових газів