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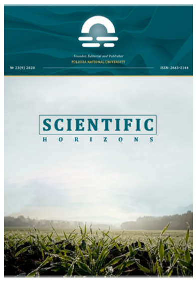

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Economic aspects of implementing environmentally friendly energy sources in the agro-industrial complex (focusing on European countries)

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Abstract. This study examined the impact of environmentally friendly energy sources on the economic sustainability of the agro-industrial complex (AIC). The research identified four primary groups of environmentally friendly energy sources utilised in the AIC: solar energy, wind, biogas, and geothermal energy. Each of these technologies possessed unique characteristics and advantages that are capable of meeting agricultural enterprises' energy needs. Although the AIC significantly contributed to

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carbon dioxide emissions and other pollutants, transitioning to sustainable energy sources can not only reduce the environmental impact but also provide economic benefits, fostering the development of a sustainable and competitive agricultural economy. Examples of the successful adoption of renewable energy sources (RES) in Germany, the Netherlands, and Spain were examined, highlighting their substantial contributions to the economic and environmental sustainability of agribusiness. The study also emphasised economic efficiency, environmental responsibility, and social equity as key principles of sustainable development. The adoption of RES has been shown to reduce energy costs, decrease dependency on conventional resources, and enhance the competitiveness of agricultural enterprises. Simultaneously, the use of environmentally friendly technologies contributed to minimising carbon emissions and improving environmental quality. The discussion addressed the primary challenges and barriers to implementing environmentally friendly energy sources in the AIC, including high initial investment costs, technical limitations, and inadequate infrastructure. To enhance the effectiveness of clean energy adoption, a comprehensive approach was proposed. This approach includes investment in new technologies, government subsidies, educational initiatives, and the establishment of cooperatives

Keywords: sustainable development; biomass; solar panels; wind turbines; environment

INTRODUCTION

In the face of global environmental challenges and climate change, modern industries, including the agro-industrial complex (AIC), are increasingly turning to environmentally friendly energy sources. Currently, a significant portion of the energy required for production processes in the agricultural sector is derived from fossil fuels, resulting in high costs and adverse environmental effects. At the same time, the AIC is a critical sector of the economy, underpinning food security, employment, and the economic sustainability of rural areas. Consequently, identifying solutions to enhance production efficiency and sustainability represents a paramount objective for the agricultural sector. The adoption of environmentally friendly energy sources offers a meaningful step towards achieving this goal.

The utilisation of environmentally friendly, renewable energy sources (RES), such as solar, wind, biogas, and geothermal energy, offers opportunities to reduce the AIC's dependence on volatile supplies of conventional fuels and conserve resources. This is particularly relevant for countries with high RES potential, including many European nations. The abundance of agricultural waste suitable for biogas production, high solar activity, and the availability of land for installing solar panels create favourable conditions for the adoption of green technologies in agriculture. Furthermore, the development of such technologies contributes to job creation, a reduction in the carbon footprint, and improvements in environmental conditions at both local and global levels.

Despite the potential benefits, certain challenges hinder the widespread adoption of environmentally friendly energy sources in the AIC. These challenges include the high initial investment costs, underdeveloped infrastructure, and specific technical limitations that necessitate specialised expertise and equipment. Additionally, organisational and economic barriers, such as limited access to financing and subsidies, pose obstacles, particularly for small and medium-sized agricultural enterprises seeking to implement such technologies. The economic aspects of transitioning to renewable energy in the AIC are studied through the lens of sustainable development, encompassing financial, social, and environmental dimensions. This approach involves analysing costs and benefits, evaluating project payback periods, and assessing the impact of such investments on enhancing the competitiveness and resilience of agriculture. These considerations are critical for formulating strategies aimed at minimising environmental and economic risks.

Several studies conducted by various authors highlight the economic and environmental aspects of using RES in the AIC. Research by S. Gorjian *et al*. (2021) demonstrated that integrating solar panels into farming operations reduced reliance on fossil fuels and lowered operating costs, thereby improving farm profitability. Similarly, A.S. Pascaris *et al*. (2021) corroborated these findings, showing that agricultural enterprises adopting solar energy significantly reduced energy expenses during periods of seasonal electricity price hikes. M.K. Devi *et al*. (2022) focused on the economic benefits of biogas plants, emphasising that agricultural enterprises could efficiently process waste while achieving substantial energy and financial gains. Their data indicated that biogas installations typically recoup investment costs within 5-7 years, making them particularly appealing to large-scale farms with high waste output. O. Myrna *et al*. (2019) underscored the necessity of government support, revealing that subsidies for wind generators and biogas plants increased farmers' willingness to invest in green technologies. These findings were further expanded by S.A. Qadir *et al*. (2021), who demonstrated that fiscal incentives and tax relief measures could accelerate the adoption of environmentally friendly energy sources and amplify their economic impact.

R. Chopra *et al*. (2022) examined the impact of environmentally friendly energy sources on labour productivity, revealing that enterprises utilising RES experienced fewer disruptions caused by power outages, positively influencing productivity and production stability. A. Barbaresi *et al*. (2020) contributed by exploring the long-term prospects of geothermal energy in greenhouse farming, finding that this technology reduces reliance on fossil fuels for cultivating crops in controlled environments. M.M. Rahman *et al*. (2022) investigated the economic effects of combined solar panel and wind turbine systems in agricultural enterprises. Their findings indicated that such hybrid systems enhance energy efficiency while lowering costs and mitigating risks associated with variable weather conditions. Supporting this, L. Melnyk *et al*. (2020) highlighted the successful implementation of similar solutions in European countries, demonstrating their economic feasibility and the potential for enhancing the sustainability of the agricultural sector. K. Senthilkumar *et al*. (2020) concluded that adopting renewable energy in the AIC not only conserves resources but also improves corporate reputation. This enhancement in the image can attract additional investment and create new market opportunities for agricultural enterprises.

These studies collectively confirm that the transition to environmentally friendly energy sources is both environmentally and economically beneficial for the AIC. However, among the topics that are under-researched in the context of using clean energy sources in AIC are: the impact of large-scale renewable energy adoption on the competitiveness of agricultural enterprises and the economic implications of integrating clean technologies under climate and infrastructure constraints. The study aimed to identify the economic advantages of implementing environmentally friendly energy sources in agricultural enterprises. The objectives included analysing the effect of renewable energy on the competitiveness of agricultural enterprises and examining the economic barriers and opportunities for adopting RES in regions facing limitations.

MATERIALS AND METHODS

The study utilised data from open sources, including Eurostat (2024), reports on the development of RES use in European countries, and case studies of its application in agro-companies such as "Schwarz", Royal Pride Holland, and Grupo Jorge (Kornatz *et al.*, 2021; International Energy Agency, 2022; Clark, 2024). The primary focus was on a comparative analysis of the energy efficiency and environmental sustainability of various types of RESs, including solar and wind energy, biogas, and geothermal systems, within the agricultural sector. Key performance indicators were identified during the analysis, such as implementation costs, system lifespan, contributions to reducing carbon dioxide emissions, and economic benefits for agricultural enterprises.

The research methodology was based on a structured analysis of energy intensity, environmental performance, and economic outcomes from the application of RES in the AIC, using examples from countries actively advancing green energy. A comparative assessment was conducted, focusing on key leaders in RES adoption in the agricultural sector: Germany, the Netherlands, and Spain. These countries were selected due to robust government support and successful examples of integrating renewable energy into agricultural processes, allowing consideration of diverse economic, technical, and environmental factors. The study also identified barriers to the implementation of RES in the AIC, including high capital costs, infrastructure-related technical limitations, and the impact of climatic conditions on the efficiency of RES.

Quantitative methods were employed to analyse the energy intensity of different energy sources and their contribution to environmental sustainability. Specifically, data on energy production and consumption volumes, the growth dynamics of RES adoption in agricultural sectors, and financial indicators reflecting the economic efficiency of each technology's implementation were utilised. In addition, the analysis encompassed environmental factors, such as the amount of CO_2 emissions prevented and the reduction in environmental impact achieved through the substitution of fossil fuels with RES. Based on the collected data, a comparative analysis of RES trends in the agricultural sectors of European countries was conducted for the period 2018-2022. This analysis identified the leading countries in the field of green energy. For further examination, a case study method was employed, highlighting successful examples of biogas plant implementation in Germany, solar panels in Spain, and wind turbines in the Netherlands. Each case study included data on technical infrastructure, economic outcomes, and environmental indicators, such as the reduction in carbon footprint and the volumes of methane emissions avoided.

Thus, the research methodology involved gathering and analysing data from multiple sources, conducting a comparative analysis of the energy efficiency and environmental sustainability of RES and examining the factors influencing the economic efficiency and sustainable development of the AIC. The findings provide a foundation for developing recommendations to enhance the effectiveness of RES use in the AIC of European countries.

RESULTS

Environmentally friendly energy sources have become an integral part of the global sustainable development strategy, with their role in the AIC being particularly significant. The AIC is critical for food security, public health, and ecosystem stability. However, it is also a major contributor to carbon dioxide emissions and other pollutants, underscoring the necessity of transitioning to more sustainable and environmentally friendly energy sources (Ingrao *et al.*, 2019). The adoption of renewable energy not only reduces the harmful impact on the environment but also offers economic benefits, fostering the development of a resilient and competitive agricultural economy.

Four primary groups of environmentally friendly energy sources are prominent in the AIC: solar energy, wind energy, biogas, and geothermal energy. Each offers unique characteristics and advantages tailored to meet the energy needs of agricultural enterprises. Solar energy is widely utilised across many countries due to its versatility. Solar panels are installed on the roofs of agricultural buildings, greenhouses, and even in fields, providing farms with electricity for lighting, heating, irrigation, and other essential operations necessary for the uninterrupted functioning of the AIC. Solar energy is particularly advantageous in regions with high solar insolation and in sectors requiring a consistent electricity supply. Wind energy is considered one of the most cost-effective solutions over the long term. Wind turbines generate electricity, particularly in areas with steady wind flows. In the AIC, wind energy can power farm operations, pump water, and support the functioning of storage and production facilities. Wind turbines have a long service life and relatively low operational costs, making them an appealing choice for agricultural enterprises with extensive land resources.

Biogas systems play a critical role in processing organic waste on farms. Converting waste into biogas helps minimise methane emissions and other pollutants. Methane derived from biogas can be used for heating and electricity generation. Biogas systems are particularly relevant for livestock farms, where large volumes of organic waste are generated daily and can be converted into energy. This waste management approach reduces environmental pollution and enhances living conditions in rural areas (Igliński *et al.*, 2020). Geothermal energy is utilised for heating agricultural buildings, greenhouses, and production facilities. Its key advantage lies in its stability: geothermal sources are unaffected by seasonal or weather fluctuations, making them particularly valuable in regions with harsh climates. Although the implementation of geothermal systems requires substantial investment, they provide long-term savings, reduce reliance on traditional heat sources, and contribute to lowering carbon emissions (Ramzan *et al.*, 2024).

Sustainable development in the agricultural sector is founded on three key principles: economic efficiency, environmental responsibility, and social equity. Environmentally friendly energy sources are instrumental in achieving these objectives by reducing the sector's environmental impact while enhancing its competitiveness and appeal.

Economic efficiency, within the framework of sustainable development, involves reducing energy costs and improving the profitability of agricultural enterprises. The adoption of RES enables agricultural businesses to manage energy expenses more effectively, reduce dependence on fluctuating prices for conventional resources, and maintain consistently high productivity levels (Qiao *et al.*, 2019). Economically resilient enterprises can utilise energy efficiently without increasing costs, thereby ensuring their survival and growth in competitive markets. Environmental responsibility is a crucial aspect of sustainable development, as the AIC significantly impacts ecosystems. The use of RES contributes to reducing carbon emissions, minimising pollution, and alleviating pressure on natural resources. Implementing green energy solutions allows enterprises to lower their carbon footprint, improve soil and water quality, and create a safer and healthier environment (Aydoğan & Vardar, 2020).

The social dimension of sustainable development is equally significant, as agricultural enterprises play a vital role in rural communities. The creation of new jobs in the renewable energy sector, the improvement of living standards in rural areas, and the provision of access to sustainable and environmentally safe energy sources contribute to social equity and an enhanced quality of life (Janker & Mann, 2020). For instance, new employment opportunities may emerge in the maintenance and operation of green energy systems, attracting young people to rural areas and fostering local economic growth. Such developments not only support the social fabric of rural communities but also align with the broader goals of sustainable development by addressing economic and environmental challenges simultaneously.

The adoption of environmentally friendly energy sources in the AIC offers both economic and environmental benefits. One of the primary economic advantages is the potential for reducing longterm energy costs. Although the installation of solar panels, wind turbines, and biogas systems requires significant initial investments, these technologies enable agricultural enterprises to reduce reliance on external energy suppliers and significantly lower expenses associated with conventional energy resources. In the context of price volatility for oil and gas, this factor becomes particularly important. Additionally, access to government subsidies, grants, and tax incentives for transitioning to green energy further decreases implementation costs, making such investments more appealing and financially viable. From an environmental perspective, renewable energy significantly reduces carbon dioxide emissions and minimises the ecological footprint of agricultural enterprises. For instance, biogas systems that process organic waste help lower methane emissions and reduce reliance on fossil fuels. This approach enhances soil and water quality, which is particularly critical for agricultural enterprises located in regions with sensitive ecosystems. Wind and solar energy also have minimal environmental impact, as their generation does not produce carbon emissions or other pollutants, making them highly suitable for use in the agricultural industry.

In addition to the direct economic and environmental benefits, adopting renewable energy in the AIC enhances corporate image and builds consumer trust. Modern consumers increasingly prioritise the environmental sustainability of the products they purchase. Enterprises utilising renewable energy can market their products as eco-friendly and sustainable, thereby attracting new customers and fostering loyalty among existing ones (Elahi *et al.*, 2022). The energy balance of RES and biofuels in European countries demonstrates a consistent trend towards increased production and consumption of clean energy. In recent years, EU countries and neighbouring states have actively expanded their use of RES, reducing dependence on fossil fuels, lowering carbon emissions, and promoting sustainable development. Table 1 presents data by country, enabling an assessment of progress in individual states and identifying leaders in renewable energy utilisation.

***Table 1**. Energy balance of RES and biofuels in European countries (2018-2022), TWh*

Country	2018	2019	2020	2021	2022
Belgium	49.41	51.02	57.35	59.58	61.66
Bulgaria	29.56	28.72	29.64	34.01	31.97
Bulgaria	53.12	57.14	59.59	63.93	63.42
Denmark	66.35	69.69	72.11	81.8	80.99
Germany	506.01	527.01	546.91	547.14	572.29
Estonia	13.45	13.72	15.35	15.35	15.36
Ireland	17.23	19.15	20.94	19.1	21.49
Greece	36.53	36.89	38.96	44.64	42.54
Spain	211.24	213.59	222.01	230.57	228.08
France	329.78	336.14	334.97	361.13	349.71
Croatia	25.39	24.85	25.5	29.22	25.89
Italy	340.55	343.23	341.28	351.98	327.48
Cyprus	2.77	2.86	3.23	3.46	3.56
Latvia	21.66	21.17	21.04	22.14	22.19
Lithuania	18.47	18.48	19.26	21.8	20.84
Luxembourg	3.44	3.75	4.65	4.75	4.71
Hungary	32.56	32.92	34.49	37.66	38.69
Malta	0.53	0.57	0.67	0.66	0.73
Netherlands	54.02	63.79	81.52	94.59	103.76
Austria	116.43	121.27	122.09	126.02	119.62
Poland	142.88	147.72	150.62	152.13	158.68
Portugal	71.05	70.48	74.08	77.19	75.81
Romania	70.22	69.93	69.65	74.39	69.88
Slovenia	13.39	13.29	13.88	14.63	12.14
Slovakia	24.07	25.56	24.97	27.04	24.98
Finland	140.23	142.04	139.74	159.45	150.3
Sweden	235.07	249.14	262.78	278.97	276.86
Iceland	63.39	62.18	61.46	60.73	-
Norway	170.54	160.73	181.39	188.22	175.87
Great Britain	235.35	255.64	-	-	-
Bosnia and Herzegovina	20.4	20.89	20.14	21.91	20.96
Montenegro	4.01	3.64	3.49	4.16	3.52
Moldova	9	7.65	7.18	7.62	6.63
Northern Macedonia	4.44	3.93	4.15	4.36	4.21
Georgia	13.43	12.12	11.2	13.23	13.51
Albania	11.86	8.6	8.52	12.14	10.41
Serbia	23.49	23.71	29.08	32.20	29.35
Turkey	222.3	271.43	280.01	280.65	308.66
Ukraine	50.21	50.57	56.73	-	-

***Source:** created by the authors based on Eurostat (2024)*

The data indicate that Germany remains the largest producer of renewable energy in Europe, with an increase in output reflecting its ongoing commitment to adopting green technologies. Similarly, significant growth has been observed in the Netherlands, where production has nearly doubled. Notably, countries such as Norway and Sweden, which already exhibit high levels of RES utilisation, have shown relatively stable growth rates, suggesting that these nations have reached an advanced stage in adopting these technologies.

***Table 2**. Energy balance of RES and biofuels in agriculture and forestry in European countries (2018-2022), TWh*

Country	2018	2019	2020	2021	2022
Belgium	0.493	0.461	0.49	0.407	0.397
Bulgaria	0.057	0.056	0.066	0.119	0.115
Bulgaria	1.561	1.551	1.575	1.783	1.782
Denmark	0.635	0.628	0.611	0.66	0.638
Germany	8.879	8.94	9.51	9.702	9.354
Estonia	0.061	0.044	0.056	0.064	0.059
Ireland	0	0	0	0	0
Greece	0.37	0.379	0.328	0.315	0.348
Spain	0.83	0.831	0.829	0.829	0.856
France	4.168	4.462	4.701	4.996	4.819
Croatia	0.041	0.038	0.04	0.019	0.025
Italy	0.58	0.619	0.612	0.881	0.865
Cyprus	0.028	0.034	0.038	0.037	0.034
Latvia	0.29	0.414	0.379	0.251	0.253
Lithuania	0.176	0.175	0.200	0.208	0.207
Luxembourg	0.051	0.027	0.018	0.004	0.024
Hungary	0.656	0.644	0.586	0.568	0.665
Malta	0.005	0.005	0.006	0.005	0.006
Netherlands	3.242	4.009	4.42	4.719	4.594
Austria	2.023	1.884	1.831	2.164	1.776
Poland	5.859	5.549	5.677	6.733	5.501
Portugal	0.055	0.063	0.065	0.071	0.033
Romania	0.063	0.106	0.116	0.088	0.115
Slovenia	0.031	0.025	0.025	0.033	0.034
Slovakia	0.352	0.26	0.303	0.317	0.256
Finland	1.895	1.868	1.681	1.984	1.893
Sweden	2.394	2.605	2.543	2.319	2.951
Iceland	0.067	0.067	0.048	0.048	-
Norway	0.001	0.003	0.002	0.005	0.001
Great Britain	1.317	1.305	-	-	-
Bosnia and Herzegovina	0	0	0	0	0
Montenegro	0.006	0.007	0.007	0.007	0.006
Moldova	0.013	0.012	0.017	0.015	0.013
Northern Macedonia	0.057	0.056	0.057	0.058	0.053
Georgia	0.011	0.012	0.013	0.012	0.012
Albania	0.154	0.115	0.144	0.144	0.144
Serbia	0.114	0.121	0.168	0.174	0.176
Turkey	7.292	7.292	7.292	7.29	7.29
Ukraine	0.427	0.321	0.322	-	-

***Source:** created by the authors based on Eurostat (2024)*

Germany holds a leading position in the consumption of renewable energy, maintaining consistently high levels. This reflects substantial investments and the active development of the RES sector within the country's agricultural industry. Similarly, high consumption levels are observed in the Netherlands and Poland, although fluctuations are evident, likely due to changes in economic conditions and political factors. Countries such as France and Sweden show steady growth in renewable energy consumption, driven by policies promoting the transition to clean energy in agriculture and the provision of subsidies for this purpose. However, in some countries, RES consumption within the agricultural sector represents only a small proportion of total usage. Despite the significant growth of renewable energy in Europe, its application in the agricultural and forestry sectors lags behind. This suggests that the AIC requires additional investments and incentives to align with the pace of RES integration in other industries.

The adoption of RES in the AIC is actively progressing in European countries, where green energy has become an integral part of national policy and a key focus of agricultural development. Germany, the Netherlands, and Spain showcase successful examples of implementing clean energy technologies, enabling agri-industrial enterprises to reduce energy costs, minimise carbon emissions, and build sustainable economies. The integration of solar, wind, and biogas energy highlights how modern energy solutions can drive growth while supporting the environmental objectives of the agricultural sector.

Germany is considered one of the leading European countries in adopting RES in the AIC. It is at the forefront of biogas utilisation in AIC, with over 9,000 biogas plants operating nationwide. In 2021, Germany produced 28 terawatt-hours of electricity from biogas, accounting for approximately 5% of the country's total electricity production (Kornatz *et al.*, 2021). Biogas plants are used on farms to process organic waste, such as manure and crop residues, into biomethane, which is then utilised for electricity generation, heating, and fuel. The German government's strategy actively supports farmers adopting biogas systems through grants and subsidies. As a result, thousands of German farms use biogas to meet their energy needs, reducing reliance on traditional energy sources and significantly lowering greenhouse gas emissions.

One notable example of biogas utilisation in agriculture is Bioenergie Wollbrandshausen, which successfully employs RES technologies to meet the needs of both agriculture and communal infrastructure. The farm and biogas facility at Bioenergie Wollbrandshausen was established to provide clean and sustainable energy for the local community and surrounding agricultural enterprises. The company processes organic waste, including agricultural residues, manure, and food waste, to produce biogas. This biogas plant converts the materials into methane, which is subsequently used for generating electricity and heat. Such a system not only ensures efficient waste management but also significantly reduces carbon dioxide and other greenhouse gas emissions. The Netherlands is a country with a long-standing tradition of utilising wind energy to meet its needs. Modern Dutch farms are equipped with wind turbines that generate electricity for agricultural operations. In 2022, wind energy accounted for over 18% of the country's total electricity production (International Energy Agency, 2022). In agricultural regions, both standalone wind turbines and entire wind farms have been constructed, capable of supplying energy to multiple farms simultaneously.

A prominent example is Royal Pride, one of Europe's largest tomato producers. The company has outfitted its greenhouses with solar panels and wind turbines, significantly reducing energy costs. Additionally, the greenhouses are equipped with heat recovery systems, enabling further savings on heating. The installations generate sufficient electricity to supply approximately 30,000 households. By reusing heat and CO_2 within their own greenhouses, the company achieves an energy utilisation efficiency of approximately 95%. The Dutch government actively supports such initiatives by offering tax incentives and subsidies, allowing companies to recover the costs of wind energy installations more quickly. The Netherlands is also actively implementing innovations in energy conservation. For example, Dutch greenhouses, which represent a significant portion of the country's agricultural production, are increasingly equipped with advanced solar panels and heat recovery systems. These technologies enable greenhouses to utilise solar energy for heating and lighting, while the heat recovery systems help maintain the required microclimate, reducing reliance on traditional energy sources.

Spain, with one of the highest numbers of sunny days in Europe, is ideally suited for the utilisation of solar energy. In 2024, solar energy accounted for approximately 12% of the country's total electricity production, with a significant share used in agriculture (Clark, 2024). Agricultural enterprises in Spain are increasingly installing solar panels to meet their energy needs. Solar energy is utilised for various purposes, including lighting and operating irrigation systems, particularly in the country's arid regions. Many farmers employ solar-powered pumps to supply water to greenhouses and fields, which not only reduces electricity consumption but also promotes efficient water use. A notable example is Grupo Jorge, one of Spain's leading pork producers. The company has installed solar panels and wind turbines on its farms, generating 98 GWh/year and 489 GWh/year, respectively. This initiative significantly reduces electricity costs. The combination of solar panels and wind turbines allows the company to meet all its energy requirements, supporting the sustainable development of the agricultural sector.

The implementation of RES in Germany, the Netherlands, and Spain has highlighted the economic and environmental advantages available to the AIC. For instance, German farms utilising biogas have saved hundreds of thousands of euros on electricity by generating it from organic waste, which also significantly reduces greenhouse gas emissions. Dutch farmers, relying on wind energy, have decreased their dependency on oil and gas, enhancing their resilience to fluctuations in global market prices. In Spain, solar energy has become a vital resource for farms in arid regions, sustaining irrigation systems while lowering electricity costs. The environmental benefits of adopting renewable energy are equally noteworthy. Biogas installations in Germany and Spain help minimise methane emissions and recycle organic waste, thereby reducing negative environmental impacts. Wind and solar energy in the Netherlands and Spain contribute to lowering the carbon footprint while maintaining the quality of soil, water, and air.

The adoption of RES in the AIC of European countries faces several significant challenges and barriers that hinder the transition to a more environmentally friendly and sustainable model of farming. Despite substantial efforts and policy support, the shift to RES is often complicated by economic, technical, environmental, and social factors. Foremost among these challenges is the high cost of implementing RES. The installation of solar panels, wind turbines, or biogas plants requires substantial investment, making the transition to RES economically burdensome for small and medium-sized agricultural enterprises. Access to financing remains another hurdle; while some countries offer subsidies and grants to support RES development, these are often insufficient to cover initial costs, and the process of securing funding is frequently mired in complex bureaucratic procedures (Ainou *et al.*, 2023). Small-scale farmers, in particular, face difficulties accessing these programmes due to a lack of information and the resources needed to complete application processes.

Technical limitations also play a significant role in the transition to RES in AIC. For instance, not all RES can be seamlessly integrated into agricultural operations due to geographical constraints. Wind energy requires consistent airflow, which may not be feasible in all regions, while solar energy depends on the availability of sunny days, posing challenges, particularly in northern European countries. Effective integration of RES into agricultural systems necessitates advanced infrastructure, which, for many farms, entails upgrading power grids and establishing energy storage systems to regulate supply (Cantarero, 2020). Although RES are generally regarded as environmentally friendly, their implementation in AIC can lead to specific environmental challenges. For example, the installation of large solar panels or wind turbines demands considerable land area, which could pose a problem for agricultural land use, especially in regions with limited land availability. Similarly, the use of biomass as an energy source carries risks, as it requires substantial quantities of organic material. This reliance can place additional pressure on forest and agricultural resources, potentially impacting biodiversity.

A significant barrier is the social perception and resistance to changes from traditional farming methods. Agricultural regions with a long history of relying on conventional energy sources may exhibit scepticism towards innovations, particularly if local farmers are unaware of the benefits of RES and their environmental implications. The lack of information regarding the longterm economic and environmental advantages of adopting RES also hinders their acceptance among farmers and agricultural communities (Lennon *et al.*, 2019). Enhancing the effectiveness of renewable energy adoption requires an integrated approach that combines economic, technical, and social strategies. This is particularly crucial in the AIC, which demands sustainable solutions to reduce energy costs, protect the environment, and ensure food security. One key strategy for improving the efficiency of RES in agriculture involves investing in advanced technologies such as high-efficiency solar panels, biogas plants, and wind turbines tailored specifically for rural settings. For instance, innovations in solar panels capable of functioning effectively under low light conditions could enable wider adoption in European countries with temperate climates. Implementing such advancements necessitates support from both the government and the private sector, alongside accessible subsidies and grants for farmers.

The effective implementation of RES is unattainable without government involvement. While European countries already operate successful support mechanisms, these could be further strengthened. For example, subsidies for RES installations, tax incentives, and preferential loans for farmers investing in RES significantly reduce financial barriers. Such programmes might also include reimbursements for part of the equipment costs or concessional financing. Germany provides a successful example where government programmes facilitate widespread adoption of RES in AIC, ensuring long-term support and stability for farmers transitioning to green energy.

A lack of awareness regarding available RES technologies and their benefits for AIC remains a barrier for many farmers. Consequently, educational initiatives and information campaigns are essential to disseminate knowledge about RES. These programmes could be tailored for all levels of stakeholders in the agricultural sector, from smallholder farmers to managers of large agricultural enterprises. In Sweden, for instance, training programmes and workshops equip farmers with practical knowledge on implementing RES.

For many rural regions, the primary challenge remains the lack of infrastructure to connect to RES. The installation of wind turbines, solar panels, or biogas plants requires a certain level of accessibility and support from energy networks. In regions where such infrastructure is already in place, such as the Netherlands, farmers actively utilise RES. Developing this infrastructure demands additional investment but promises significant long-term reductions in energy costs. Collaboration among agricultural enterprises in adopting RES can result in substantial cost reductions and increased efficiency. Cooperatives, where multiple farms share biogas facilities or collectively invest in wind turbines, exemplify this strategy. In France, this model has gained traction and proven effective, particularly for smaller farms that cannot independently afford the investment in RES.

To actively promote RES, quotas and mandatory standards could be introduced to increase the share of clean energy in the agricultural sector's overall consumption. For instance, the United Kingdom has implemented mandatory standards for agricultural producers, requiring a certain level of RES usage. While such measures require time for adaptation, they foster sustainable practices and provide economic incentives for farmers to transition to green energy. Modern digital technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), can significantly enhance the efficiency of RES. IoT sensors enable real-time monitoring of solar panels and wind turbines, ensuring optimal energy utilisation and minimising losses. In Spain, energy management systems based on data analytics have been developed, allowing agricultural enterprises to flexibly allocate energy according to operational conditions and specific needs.

The integration of environmentally friendly energy sources into the AIC requires coordinated efforts at governmental, private, and community levels. Strategies focused on funding, education, infrastructure development, and collaboration can help overcome barriers and optimise the use of RES in agriculture. These approaches not only enhance efficiency but also improve the sustainability of the agricultural sector, offering a cleaner and more cost-effective alternative to traditional energy sources.

DISCUSSION

The findings of the study highlight the significant role of RES in achieving sustainable development within the AIC. As a critical component of the economy, agriculture influences food security, ecosystems, and public health. However, given the high levels of carbon emissions and other pollutants, the adoption of RES is essential for establishing a more environmentally responsible and economically sustainable agricultural system. The primary types of renewable energy, including solar, wind, biogas, and geothermal energy, have demonstrated their effectiveness in the agricultural sector. Each type offers unique characteristics and benefits that cater to the specific needs of agricultural enterprises. For instance, solar energy is ideal for regions with high levels of sunlight, providing farms with electricity for lighting, heating, and irrigation. Wind energy is particularly relevant in areas with consistent airflows, where it can power equipment and water pumps. Biogas systems enable farms to process organic waste, converting it into a source of energy while reducing environmental pollution. Finally, geothermal energy provides consistent heating, which is especially valuable in regions with harsh climatic conditions. P.A. Østergaard *et al.* (2020) conducted a comparative analysis of different types of renewable energy, highlighting that geothermal energy is the most stable but also the most expensive and challenging to implement in agricultural enterprises. Contrary to more recent findings, which consider geothermal energy a promising avenue for sustainable development, the study emphasised that it remains less accessible for small and medium-sized enterprises.

C.M. Kumar *et al.* (2023) focused on the integration of solar energy into farms. Their research highlighted that in certain climatic regions, solar panels are underutilised due to insufficient solar radiation, and the costs associated with their installation and maintenance may exceed the anticipated benefits. This finding contrasts with current results emphasising the versatility of solar panels. However, the author's conclusions are significant in recognising regional disparities and the need to develop technologies capable of performing efficiently across various climatic conditions.

H.M. Usman *et al.* (2024) examined the adoption of wind turbines on farms, noting that their use is often associated with challenges such as the requirement for large land areas and high noise levels. In contrast to current conclusions regarding the long-term economic efficiency of wind energy, the author argued that only a limited number of farms can provide the suitable conditions needed for turbine installation. This perspective underscores the importance of selecting appropriate locations and highlights the necessity of addressing infrastructural constraints and potential conflicts with rural communities.

Economic efficiency is a key advantage of using RES in the AIC. While the installation of solar panels, wind turbines, and biogas plants requires substantial initial investment, these expenditures enable agricultural enterprises to significantly reduce reliance on conventional energy sources in the long term. Additionally, access to government subsidies, grants, and tax incentives enhances the appeal of such investments, allowing farmers to recover costs more quickly. M.R. Elkadeem *et al.* (2019) investigated the economic feasibility of RES adoption on farms and highlighted economic barriers that hinder the transition to green energy, particularly for small and medium-sized enterprises. In contrast to current findings, which confirm the economic viability of RES, the author argued that the installation costs for smaller farms remain prohibitively high, serving as a deterrent. M. Saleem (2022) similarly emphasised the necessity of governmental financial support to overcome these barriers. This support could include subsidies for equipment installation, tax incentives, and accessible loans, aligning with the current conclusions regarding the critical role of state assistance.

L.T. Clausen and D. Rudolph (2020) examined the role of financial mechanisms in supporting farmers transitioning to RES. Their research revealed that in countries with highly developed credit systems and preferential programmes for adopting green energy, such farms exhibit the greatest economic resilience. In contrast to current findings, which emphasised the long-term economic benefits of renewable energy utilisation, the authors argued that without accessible financial tools for farmers, the transition process could be significantly delayed.

From an ecological perspective, renewable energy significantly reduces the carbon footprint and minimises the environmental damage associated with AIC. For instance, biogas plants on farms facilitate the utilisation of organic waste, decreasing methane emissions and reducing reliance on fossil fuels. Wind and solar energy also exert minimal environmental impact, as their generation does not involve carbon dioxide or other pollutant emissions. U.K. Pata (2021) similarly focused on the environmental benefits of renewable energy but highlighted concerns related to biodiversity. The author identified that large-scale biogas installations could increase the demand for biomass, placing pressure on natural resources and potentially threatening biodiversity if resource harvesting is conducted without adequate oversight. This perspective contrasts with current findings, which present biogas systems as a sustainable solution for the AIC. However, the author's observation regarding the need for environmental regulations is valid; implementing additional controls could ensure more rational biomass use and mitigate potential adverse effects.

At the same time, despite positive outcomes, the adoption of renewable energy in AIC faces several challenges. The high cost of implementing RES remains a significant barrier, particularly for small and medium-sized farms. Technical constraints, such as the need for consistent wind for wind energy or sufficient sunlight for solar panels, complicate integration in certain regions. Additionally, advanced infrastructure is required to connect RES to the grid and ensure efficient energy storage and distribution. A.G. Olabi and M.A. Abdelkareem (2022) examined the impact of renewable energy on climate resilience, concluding that transitioning to green energy mitigates the effects of climate change but necessitates substantial infrastructure upgrades for effective energy utilisation. Similarly, D.E. Gernaat *et al.* (2021) argued that the successful implementation of renewable energy also depends on the development of energy grids and distribution systems. This partially contrasts with the current claim that renewable energy can be integrated into nearly any agricultural enterprise. The authors emphasised that infrastructural limitations must be addressed when scaling up renewable energy, reinforcing the argument for modernising rural energy infrastructure.

Social aspects also play a crucial role, as the transition to RES requires a shift from traditional agricultural practices. A lack of information about the benefits and long-term profitability of RES hinders the popularisation of green technologies among farmers. M. Kumar (2020) examined the social dimensions of RES adoption in rural regions, finding that the shift to green energy enhances living standards and attracts younger generations to rural areas by creating new employment opportunities. These findings align closely with current results, which also highlight that job creation in the renewable energy sector strengthens rural economies and fosters social development. This perspective underscores that social benefits are equally significant in promoting the sustainable development of the agricultural sector. The research findings emphasise the importance of a comprehensive approach, involving government support, investment in innovation, infrastructure development, and information and educational campaigns, to successfully integrate RES into the AIC.

CONCLUSIONS

This study conducted a comprehensive assessment of the utilisation of RES in the AIC as an integral part of sustainable development strategies. RESs have become increasingly important for ensuring food security, protecting human health, and safeguarding ecosystems. While AIC remains a significant source of carbon dioxide and other pollutants, transitioning to more sustainable and cleaner energy sources is a necessary step. The research identified four key groups of environmentally friendly energy sources utilised in AIC: solar, wind, biogas, and geothermal energy. Each of these technologies offers distinct characteristics and advantages. For instance, solar panels are gaining popularity due to their versatility, as they can be installed on rooftops or fields, providing farmers with electricity for lighting and irrigation. Wind energy, recognised as the most economically efficient option in the long term, is suitable for regions with consistent wind flows, supplying energy to farms and agricultural facilities.

One of the critical aspects of sustainable development is economic efficiency, which involves reducing energy costs and enhancing the profitability of agricultural enterprises. The adoption of RES enables farms to manage their energy expenses effectively, reducing dependency on fluctuations in the prices of conventional resources. Environmental responsibility, in turn, lies in reducing carbon emissions and minimising pollution, making agribusinesses more sustainable and competitive. Examples from Germany, the Netherlands, and Spain illustrate how the use of biogas, wind, and solar energy allows farmers to lower energy expenses and reduce their environmental footprint while simultaneously increasing profitability. In Germany, for instance, over 9,000 biogas plants convert agricultural organic waste into biomethane, which is utilised to generate electricity and heat. In the Netherlands, wind energy plays a significant role in the energy mix of the agricultural sector. Modern farms install wind turbines, which provide electricity and help reduce energy costs by up to 30%. Similarly, Spain, benefiting from high levels of solar irradiation, actively develops solar energy in agriculture. Many farmers install solar panels to power their operations, cutting electricity expenses by up to 25%.

Overall, the transition to RES in AIC offers significant economic and environmental benefits. Despite existing barriers, such as high initial costs and insufficient infrastructure, targeted governmental support, farmer education, and the establishment of cooperatives can greatly facilitate this process. The study highlights the need to integrate modern technologies and promote sustainable practices within the agricultural sector, ultimately contributing to sustainable development in farming. A limitation of this study is its focus on selected European examples, which may not fully capture the situation in other regions with differing economic and climatic conditions. Future research could explore the impact of local policies and economic factors on the adoption of RES in AIC in other countries, particularly in developing regions.

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CONFLICT OF INTEREST

None.

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Економічні аспекти впровадження екологічних чистих джерел енергії в агропромисловому комплексі (на прикладі країн Європи)

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Анотація. Дане дослідження спрямоване на аналіз впливу екологічно чистих джерел енергії на економічну підтримку агропромислового комплексу. У рамках дослідження виокремлено чотири основні групи екологічно чистих джерел енергії, що використовуються в агропромисловому комплексі: сонячна енергія, вітер, біогаз і геотермальна енергія. Кожна з цих технологій має унікальні характеристики та переваги, здатні задовольнити енергетичні потреби сільськогосподарських підприємств. Незважаючи на значний внесок агропромислового комплексу у викиди вуглекислого газу та інших забруднюючих речовин, перехід на стійкі джерела енергії може не тільки скоротити негативний вплив на навколишнє середовище, а й забезпечити економічні переваги, сприяючи створенню стійкої та конкурентоспроможної сільськогосподарської економіки. Розглянуто приклади успішного впровадження цих джерел у Німеччині, Нідерландах та Іспанії, де відзначено значний внесок поновлюваних джерел в економіку та екологічну стійкість агробізнесу. Робота також акцентувала увагу на економічній ефективності, екологічній відповідальності та соціальній справедливості як ключових принципах сталого розвитку. Впровадження відновлюваних джерел енергії сприяє зниженню витрат на енергію, зменшенню залежності від традиційних ресурсів та покращенню конкурентоспроможності сільськогосподарських підприємств. Водночас, використання екологічно чистих технологій допомагає мінімізувати вуглецеві викиди та покращити якість довкілля. Обговорювалися основні проблеми та бар'єри, що заважають впровадженню екологічно чистих джерел енергії в агропромисловому комплексі, такі як високі початкові інвестиції, технічні обмеження та брак інфраструктури. Для підвищення ефективності впровадження чистих джерел енергії пропонувався комплексний підхід, що включає інвестиції в нові технології, державні субсидії, освітні ініціативи та створення кооперативів

Ключові слова: сталий розвиток; біомаса; сонячні панелі; вітрові установки; навколишнє середовище