

UDC 658.56:628.4:330.341.1

JEL Classification: Q56, Q53, O32

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DEVELOPING A WASTE MANAGEMENT MECHANISM FOR AGRO-INDUSTRIAL ENTERPRISES BASED ON THE IMPLEMENTATION OF INNOVATIONS

Effective waste management in agro-industrial enterprises is a crucial factor for the sustainable development of the sector and the preservation of environmental safety. The implementation of innovative technologies, such as anaerobic digestion, bioenergy plants, automated agricultural waste sorting, chemical recycling, and plasma gasification, not only minimizes the negative environmental impact but also optimizes resource use, generates energy, and produces secondary materials. A comprehensive waste management mechanism that integrates digital monitoring technologies, internal eco-policies of enterprises, and state support ensures economic efficiency, competitiveness, and social responsibility of the agro-industrial complex. Moreover, the adoption of modern managerial and technological solutions contributes to more rational resource utilization, increased productivity, and the development of sustainable production practices in the agro-industrial sector.

Keywords: management mechanism, waste, innovation, agro-industrial complex, circular economy, environmental technologies.

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ФОРМУВАННЯ МЕХАНІЗМУ УПРАВЛІННЯ ВІДХОДАМИ ПІДПРИЄМСТВ АПК НА ОСНОВІ ВПРОВАДЖЕННЯ ІННОВАЦІЙ

Стаття присвячена дослідженню управління відходами підприємств агропромислового комплексу України на засадах впровадження інновацій. Аналіз статистичних даних засвідчив, що хоча частка відходів АПК в загальній структурі є невеликою, ці відходи можуть становити підвищену екологічну загрозу через токсичність або біологічну активність. Дослідження висвітлює основні виклики, серед яких відсутність системної нормативно-правової бази, застарілі практики утилізації, нерозвинена інфраструктура, низький рівень цифровізації та обмежена інвестиційна привабливість. Обґрунтовано необхідність формування механізму управління відходами, що інтегрує технологічну модернізацію, цифрові рішення, економічні стимули, освітні програми та інституційну підтримку. Особлива увага приділяється сучасним підходам, таким як анаеробне зброджування для виробництва біогазу, плазмова газифікація, автоматизовані системи сортування на основі штучного інтелекту, хімічна переробка та технології дистанційного моніторингу. Такі інноваційні рішення розглядаються як ключові для забезпечення ресурсоефективності, зниження екологічних ризиків та створення нових можливостей для виробництва енергії й вторинної сировини. Чітке розуміння етапів процесу управління відходами підприємств АПК з урахуванням впровадження інновацій надало можливість сформувати відповідний механізм. Запропонований механізм управління підкреслює важливість ранньої ідентифікації джерел відходів, розвитку регіональних переробних хабів та впровадження систем екологічного менеджменту на основі ISO 14001 та показників ESG. Інституційна співпраця з місцевими органами влади, галузевими асоціаціями та міжнародними програмами визначена як ключовий рушій впровадження. Таким чином визначено, що інтеграція інноваційних технологій, фінансової підтримки та цифрових інструментів моніторингу забезпечить перехід агропромислового сектора до сталого, циркулярного та інноваційно-орієнтованого розвитку, підвищивши його конкурентоспроможність як на внутрішньому, так і на глобальному рівні.

Ключові слова: механізм управління, відходи, інновації, АПК, циркулярна економіка, екологічні технології.

Problem statement. The issue of rational waste management is particularly important in the context of sustainable development of Ukraine's agro-industrial complex. Given the strategic importance of the agricultural sector for the national economy, minimizing the negative impact on the environment requires the search for new technological and managerial solutions. Outdated waste

disposal practices, limited infrastructure, and fragmented implementation of innovations significantly hinder the potential for transition to an environmentally responsible production model.

In today's world, leading countries are increasingly integrating the principles of the circular economy through the use of the latest waste treatment technologies, the develop-

ment of digital monitoring systems, and the introduction of renewable energy sources. The domestic agricultural sector, which is in the process of adapting to European environmental standards, faces a number of challenges: the lack of clear mechanisms for handling agricultural waste, insufficient funding for modernizing facilities, weak information support, and a low level of integration of digital solutions.

Against this background, there is a growing need to develop effective, adaptive, and economically sound waste management mechanisms for agro-industrial enterprises based on modern innovations. The implementation of such mechanisms will not only contribute to the ecological modernization of production but also ensure the long-term competitiveness of the sector both in the domestic market and at the international level.

Analysis of recent research and publications. In today's world, the issue of effective waste management is becoming particularly relevant due to the constant growth in production and consumption. Accordingly, the generation of industrial, household, and agricultural waste is also growing, which puts serious pressure on ecosystems and necessitates the modernization of approaches to resource management. According to the Ministry of Environmental Protection and Natural Resources of Ukraine, more than 60% of solid household waste is recycled worldwide, while in Ukraine only 5.6% is recycled, another 1.4% is incinerated, and the rest of the waste accumulates in landfills and dumps, which cover an area of more than 9,000 hectares [1].

In a global context, there is active implementation of the concept of resource reuse, which is both environmentally sound and economically beneficial, as it reduces business costs, creates jobs, and reduces dependence on imported raw materials. For example, aluminum recycling can cut production costs by almost half compared to primary extraction [2].

According to estimates by the European Bank for Reconstruction and Development, the development of the processing sector in Ukraine could generate an additional UAH 4–5 billion in GDP each year and create up to 400,000 new jobs. The use of industrial waste as secondary raw materials reduces the environmental impact and cuts production costs [3].

Particular attention is paid to agricultural waste management, which is experiencing dynamic growth due to the demand for organic fertilizers, the development of bio-energy, and investments in new technologies. Cooperation between agricultural enterprises and companies specializing in waste disposal increases processing efficiency, reduces costs, and promotes environmental safety [4].

Thus, analysis of recent studies shows that waste minimization and the implementation of innovative waste management technologies are key to building a sustainable economy. Today's challenges require a comprehensive approach that combines technical modernization, the development of inter-sectoral cooperation, and effective government policies to support sustainable practices.

Formulating the purposes of the article. The purpose of the article is to develop scientific and practical recommendations for the formation of a waste management mechanism for agricultural enterprises through the introduction of innovations.

Methodology. The following general and specific scientific methods were used during the study: monographic

method – for a detailed study of existing theoretical and practical aspects of waste management in the agro-industrial complex; methods of analysis and synthesis – for studying the current state of waste management in the agro-industrial complex and summarizing approaches to its management; graphical method – for constructing a diagram of the waste management mechanism, taking into account the introduction of innovations; a systematic approach to presenting the management mechanism as a set of interrelated elements.

Presentation of the main research material. The waste management system in Ukraine's agro-industrial complex is still in its infancy, due to both a historical lack of strategic planning in the field of environmental safety and underdeveloped infrastructure. All types of agricultural entities, from farms to cooperatives, generate agricultural waste, but a significant portion of this waste remains outside effective management control [5].

The dominant source in the structure of waste generation by type of economic activity in Ukraine in the period from 2010 to 2020 (Fig. 1) is the extractive industry and quarrying, whose share has consistently exceeded 80% throughout the period. This highlights the structural features of the Ukrainian economy, which is focused on raw materials, while the agricultural sector, despite its strategic importance for GDP and exports, has a relatively low level of waste generation.

In the structure of waste generation by type of economic activity, agriculture, forestry, and fisheries account for a negligible share. Between 2010 and 2020, the share of the agricultural sector ranged from a maximum of 2.95% in 2016 to a minimum of 1.15% in 2020.

Agricultural waste is classified by origin into plant, animal, and agrochemical (residues of fertilizers, pesticides, veterinary drugs). Although their share in the total volume of waste is relatively small, it is this waste that can pose an increased environmental threat due to its toxicity or biological activity. The problem remains the improper storage of more than 8,500 tons of unusable chemical plant protection products – without licensed processing facilities, these substances accumulate in unsuitable places, posing a threat to the environment [5].

The insufficient level of regulatory control over the management of agricultural waste, in particular the lack of a unified accounting system, approved standards, and technical instructions for the collection and processing of such waste, greatly complicates its centralized management. Systemic problems include poor awareness among farmers of alternative processing methods, low investment attractiveness of the sector, and the virtual absence of local capacity for the disposal of animal by-products [7].

Existing minimization methods include burning plant residues, burying animal carcasses in livestock burial grounds, using biothermal pits, and the fragmented introduction of biogas plants. At the same time, the effectiveness of these approaches is low: according to UABIO, the potential for using biomass for biogas production is only 1–6% realized, depending on the type of raw material [5].

National legislation declares a hierarchical approach to waste management: from prevention to recovery and, only as a last resort, disposal. However, in practice, these principles are often ignored due to the lack of control and support mechanisms. In particular, recovery in the form of energy use (incineration or anaerobic decomposition)

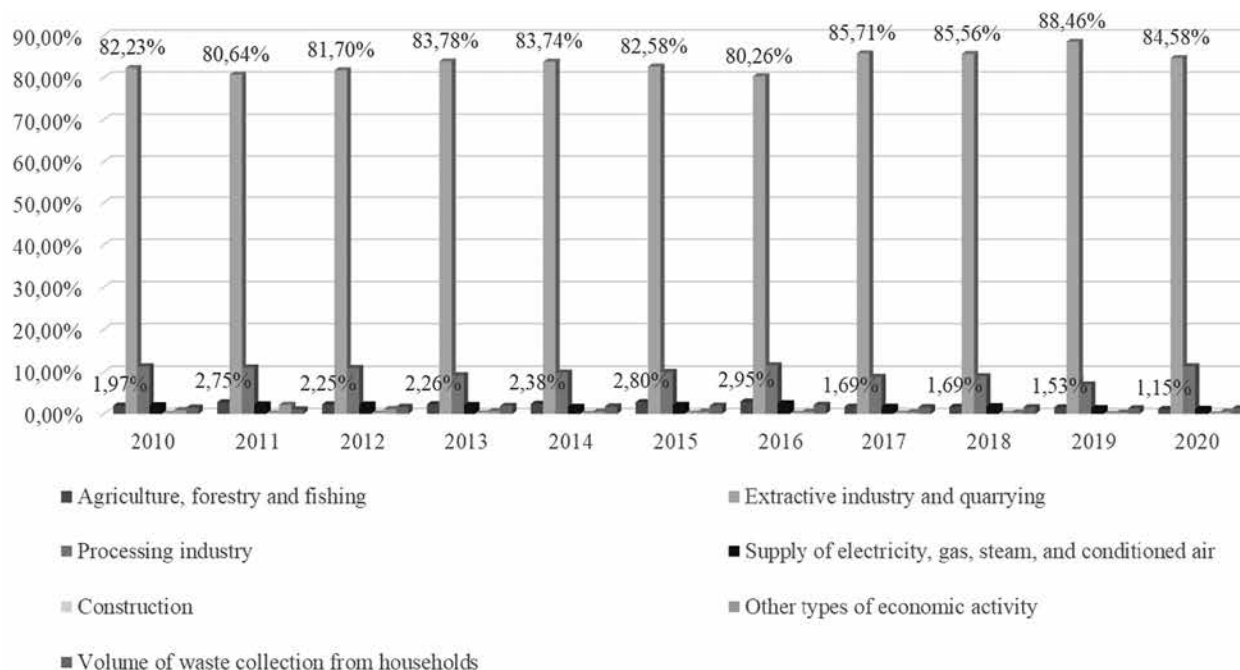


Figure 1. Structure of waste generation by type of economic activity in Ukraine in the period from 2010 to 2020, %

Compiled by the authors based on [6]

remains almost inaccessible to most small and medium-sized farms [8].

The European waste management model is based on five key principles: prevention, reuse, recycling, energy recovery, and final disposal. In Ukraine, however, the conditions for the full implementation of even the most basic of these principles are lacking. The most promising areas remain the development of bioenergy and the utilization of waste in the form of animal feed and composting, but these solutions require a regulatory, financial, and educational foundation [9].

Thus, current waste management methods used by agribusinesses remain limited in scope, technologically outdated, and fragmented. Areas for improvement include:

- developing standard technical instructions for different types of agricultural waste;
- creating a network of regional centers for processing by-products;
- introduction of economic incentives (green tariffs, subsidies);
- mandatory training of farmers in modern waste management methods;
- harmonization of the Ukrainian waste classification with European standards.

It should be emphasized that most problems in the agricultural waste management system are systemic in nature and cannot be solved solely by technological means. That is why it is important to ensure a multi-level approach – a combination of technical, organizational, informational, and educational measures. Otherwise, the implementation of innovations will remain fragmented and will not deliver the expected results.

In the current context of transformation of the agricultural sector, the introduction of innovations in waste management is becoming an important condition for the formation of sustainable production processes. The diversity of

waste from the agro-industrial complex (organic residues, manure, biomass, agrochemicals, etc.) requires specialized, effective, and technologically flexible solutions.

One of the most promising areas is anaerobic fermentation, which allows animal waste to be converted into biogas. This technology solves two problems at once: waste disposal and energy production. In agricultural production, the fermentation of manure, corn silage, or beet pulp allows for the production of electricity and organic fertilizer as a by-product. Bioenergy plants have already proven their effectiveness in a number of EU countries, and their gradual introduction in Ukraine creates conditions for reducing farmers' dependence on fossil fuels [10].

Another innovative approach is the use of artificial intelligence (AI) in waste sorting processes. Machines that work with machine learning algorithms can automatically identify fractions of agricultural waste for further processing. In the agro-industrial complex, this is particularly relevant when sorting packaging materials, films, containers from agrochemicals, and other by-products of production. Automating such processes increases accuracy, speeds up processing, and reduces labor costs [10].

In addition to automated sorting systems, remote monitoring technologies play an important role, in particular satellite analytics and sensors built into containers or production facilities. These solutions enable real-time tracking of waste generation, rapid response to critical situations, and logistics planning based on actual data. Modern management models in the agricultural sector should include digital tools for monitoring, forecasting waste volumes, and calculating optimal logistics routes for their processing or disposal. Such systems minimize losses and enable informed management decisions [11].

Chemical processing is another innovative approach that is gaining momentum. It involves breaking down complex compounds, such as plastics or agrochemical residues, into

their primary chemical components. This approach allows even materials that were previously considered unsuitable for recycling to be processed. This can be particularly useful in agricultural production, where significant volumes of fertilizer and plant protection product containers accumulate [10].

Plasma gasification technology is also noteworthy. Although it requires significant initial investment, it allows organic and complex waste to be converted into hydrogen and a glass-like mass. The installation of such complexes costs between \$5 million and \$10 million, but with high utilization rates, they can pay for themselves in 10–15 years. For the agro-industrial complex, this could be a profitable solution in regions with high concentrations of waste, such as near large livestock clusters or grain elevators [12].

At the same time, barriers to the implementation of innovation in agribusiness enterprises should be taken into account. These include high capital intensity, the need for staff training, limited awareness of available technologies, and a lack of government incentives. To overcome these barriers, it is necessary to have a clear understanding of the waste management process at agribusiness enterprises (Fig. 2) and to develop a mechanism (Fig. 3) that includes financial support from the state (subsidies, incentives), educational programs for producers, and the adaptation of legislation to European standards for agricultural waste management.

An important component of an effective mechanism is the early identification of potential sources of waste in the production cycles of an enterprise. Thanks to the introduction of preliminary resource efficiency assessments, it is possible not only to reduce the amount of waste generated, but also to optimize the consumption of materials, energy, and water.

To this end, it is advisable to use environmental auditing tools, in particular Life Cycle Assessment, which allows the most rational solutions to be predicted at the stage of designing production processes.

A special role in ensuring the adaptability of the mechanism is played by scaling innovations according to the type of enterprise. For large agricultural companies, it is advisable to implement capital-intensive technologies such as anaero-

bic digestion and plasma gasification, which make it possible to process large volumes of organic and mixed waste while generating energy and secondary materials. In the case of small and medium-sized producers, effective solutions include mobile composting systems, shared collection points, or the creation of regional hubs for the utilization of agricultural residues.

An essential element of the mechanism is the creation of an internal environmental policy for the enterprise. Individual environmental standards, sorting and logistics procedures, and reporting systems should not be declarative, but integrated into all production and management processes. The implementation of a policy with elements of ISO 14001, an environmental management system (EMS), ensures compliance with national and European requirements. At the same time, the use of the PDCA (Plan Do Check Act) principle allows for a response to changes in the market, technological, and regulatory environment.

Institutional support involves cooperation with industry associations, research institutions, and local authorities. It is important to establish public-private partnership mechanisms that will promote the development of local processing capacities, the sharing of technologies, and the attraction of investment. International support programs such as Horizon Europe, LIFE, and Green Deal, which offer grant funding for innovation in the bioeconomy, waste management, and digital transformation of the agricultural sector, have particular potential [13–15].

A key factor in effectiveness is a monitoring and control system based on quantitative indicators. These indicators include: the proportion of waste that has been reused; the proportion of biomass converted into energy; the reduction in specific waste management costs; and the frequency of environmental emergencies. These KPIs not only allow progress to be tracked, but also ensure transparency in reporting to partners, the public, and regulators.

One of the pressing issues that the mechanism must address is the gap between existing technological solutions and the readiness of enterprises to integrate them. This requires the creation of scientific and advisory centers that will provide

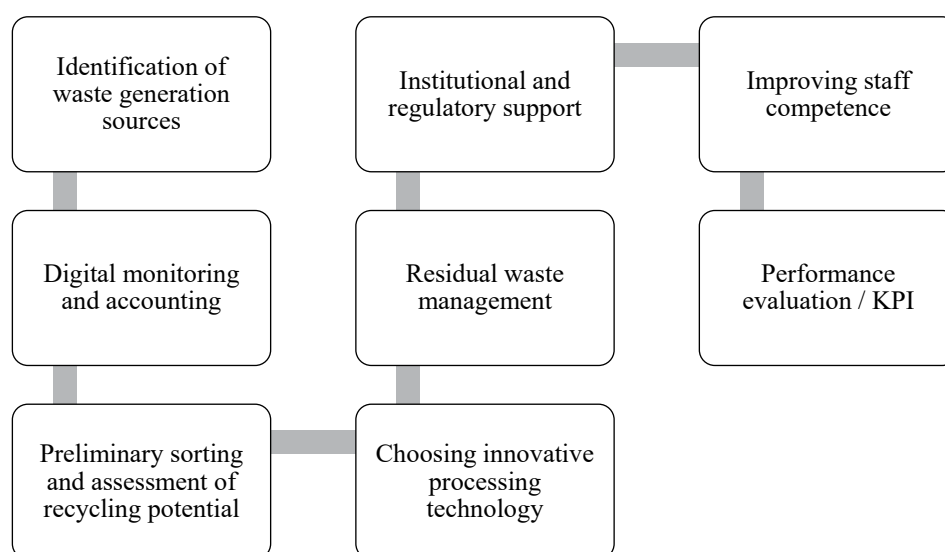


Figure 2. Stages of the waste management process at agribusiness enterprises, taking into account the introduction of innovations

Developed by the authors

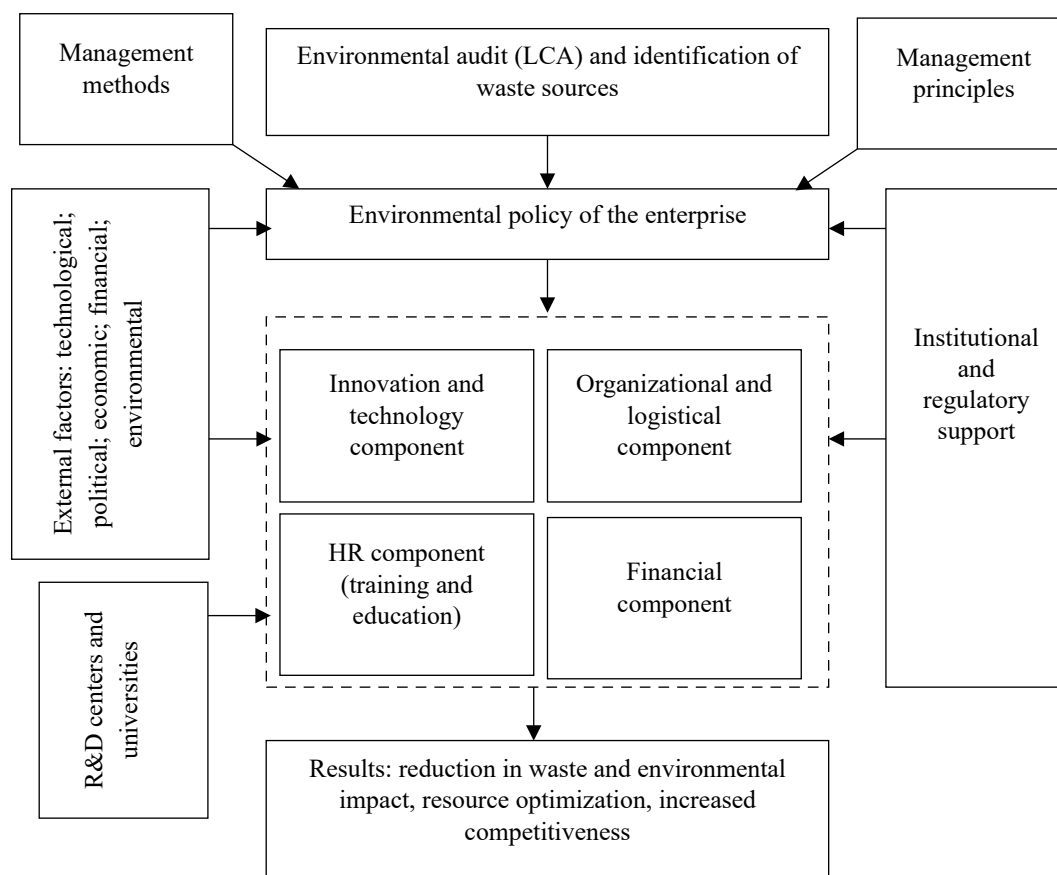


Figure 3. Waste Management Mechanism of Agro-Industrial Enterprises Based on Innovation Implementation

Source: developed by the authors

methodological support to agricultural producers in implementing innovations and adapting solutions to local conditions and technological specifics. Such centers can operate in cooperation with agricultural universities, technology parks, or regional environmental agencies. Their task should be not only to educate, but also to evaluate technologies according to criteria of environmental friendliness, energy efficiency, and economic feasibility.

In addition, it is important to include an environmental motivation component in the mechanism's structure, which will shape a new culture of management decisions. This may include not only financial incentives, but also non-financial mechanisms: rating companies according to the degree of implementation of sustainable solutions, highlighting best practices in government and industry reports, and giving priority in competitions for government support. Creating a positive image of environmentally responsible business provides additional motivation for change and strengthens the social legitimacy of enterprises in the eyes of consumers and communities.

In the long term perspective, the waste management mechanism should become not only a functional tool but also an integral part of a company's environmental strategy. In particular, the integration of ecological practices into overall corporate responsibility policies, the application of ESG indicators, enhanced reporting, and transparent disclosure of "green" investments open up new opportunities for positioning in both domestic and international markets.

Thus, the modern waste management mechanism of agro-industrial enterprises should be based on the prin-

ciples of systematicity, adaptability, digitalization, technological modernization, personnel training, and institutional interaction. Only the integration of these components will ensure not only the minimization of negative environmental impact, but also the creation of an economically efficient, competitive, and socially responsible model of agricultural production.

Conclusions. The study found that waste management in Ukraine's agro-industrial complex is in its infancy and is characterized by a number of systemic problems: lack of an adequate regulatory framework, insufficient infrastructure for disposal and recycling, limited awareness among farmers, and poor integration of digital solutions. The proposed mechanism for waste management in agribusiness enterprises based on the introduction of innovations includes: the formation of a comprehensive approach that includes technical, organizational, informational, and educational components; active use of modern technologies (anaerobic digestion, plasma gasification, automated sorting systems, remote monitoring, chemical processing); the development of institutional support and public-private partnerships. An important factor in effectiveness is the formation of an enterprise's environmental policy and environmental strategy, the implementation of an environmental management system, and the implementation of monitoring and evaluation systems based on the use of ESG indicators.

The proposed recommendations are of practical importance for agribusiness enterprises, as their implementation will optimize waste processing, reduce costs, and increase the efficiency of secondary resource use.

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Стаття надійшла: 29.08.2025

Стаття прийнята: 16.09.2025

Стаття опублікована: 09.10.2025