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Artificial Intelligence in Waste Management in the Context of Implementing Circular Economy

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Abstract

The depth of the ecological crisis raises the issue of implementing innovative solutions and technologies in waste management that align with the principles of the circular economy. This research explores the advantages of using artificial intelligence (AI) in waste management systems in Ukraine. The study employs methods of systems analysis, formalization, abstract and logical analysis, in addition to the linear trend method. A comparative analysis of waste management in Ukraine and EU countries was conducted. It was found that the waste generation level in Ukraine is 11.1 tons per person per year, compared to 4.8 tons in the EU. Only 8.24% of waste in Ukraine is sent for recycling, while this figure reaches 49.6% in the EU. The analysis revealed that insufficient infrastructure, poor-quality legislation, and the destruction caused by the war significantly affect waste management practices in Ukraine. An exhaustive review of current startups and technological solutions in waste management utilizing AI was conducted. The findings show that the implementation of AI in waste management can increase recycling rates by 20-30% and reduce operational costs by 10-15%. It is projected that by 2033, the global AI market for waste management will reach USD 18.2 billion, demonstrating an annual growth rate of 27.5%. The study concludes that applying AI in waste management in Ukraine could significantly reduce waste incineration and increase recycling rates to 70% by 2030, aligning with the goals of the National Waste Management Strategy.

Keywords

Digital technologies; Innovative tools; Sustainable development; Landfills; Startups

Introduction

The primary challenge in rebuilding the agricultural sector in post-war territories will be restoring natural areas affected by ecocide and ensuring their sustainable recovery. This problem also closely affects the issue of waste recycling based on the circular economy model, as the scale, extent, and depth of the environmental disaster require the use of innovative technologies, such as agro drones and robotics to prevent the risks of harm to people, etc. Saving the planet requires new approaches and technologies. One innovative solution is the use of artificial intelligence in waste management.

The artificial intelligence is the ability of computer systems to learn on their own and make decisions based on the data collected. Implementing artificial intelligence enables the development of effective waste management algorithms that reduce the negative impact on the environment (ITU, 2024). AI can be utilized at various stages of waste management, beginning with collection and sorting. By analyzing vast datasets, AI can efficiently classify waste by type and determine the optimal recycling methods. This process helps minimize landfill waste and promotes the reuse of materials (The AI Limited, 2024).

Waste management is an important tool to curb climate change, as it reduces greenhouse gas emissions from landfills. Automation and the circular economy are revolutionizing the future of waste management. Integrating artificial intelligence in waste management is gaining popularity due to its speed and efficiency. Thanks to the development of monitoring systems, an increasing amount of waste data is becoming available for analysis. In addition, businesses are increasingly turning waste into energy and other useful products or raw materials, which promotes circularity and sustainability. Sydney-based Arc Ento Tech is a firm that turns plastic into industrial fuel while using organic waste to make fertilizer and fish feed (The Australian, n.d.). Many authors and researchers have studied the circular economy, especially given its importance in sustainability and environmental initiatives. This field encompasses various aspects including legislative initiatives and regulatory changes that facilitate the shift to a circular economy; business models; new technologies and approaches that help close material use cycles; and practical examples of successful implementation of circular practices across different industries.

The main difficulties faced by companies and government agencies in Ukraine in the transition to circular business models are explored in the works of Derij, Butenko and Zosimenko (2021). The main problems of Ukraine's transition to a circular economy include an insufficient legal framework, a lack of clear policy, low awareness levels, and incomplete infrastructure for waste collection and recycling. Based on this, the authors theoretically substantiate the implementation of Ukraine's environmental policy in the context of sustainable economic development.

For the successful implementation of the circular economy in Ukraine, it is necessary to focus on the development and implementation of an appropriate regulatory framework, raising awareness among entrepreneurs and consumers, as well as creating effective systems for waste management. Savchuk (2023)recommends a more active involvement of businesses in the transition to a circular economy by promoting innovations in

recycling and waste reduction, along with developing state strategies to support sustainable development. The significance of tailoring circular business models to the Ukrainian context is highlighted in the works of Gorbal and Plish (2021). The authors emphasize the need for support from the state and society to achieve sustainable development through regulatory initiatives and financial incentives. Strategies for the reuse of agri-food waste are considered by Facchini *et al.* (2023). The study explored methods to decrease agri-food losses through sustainable practices that not only minimize waste but also generate economic and environmental advantages. They stress the importance of integrating innovative technologies and effective resource management to achieve sustainable development in the agri-food sector. The importance of strategic configuration of digital innovation for the successful renewal of companies' business models is discussed by Cheng *et al.* (2022). The authors explore how companies are using the attributes of digital innovation to transform their business models. They propose a configurational approach that allows firms to adapt digital innovations to the specific requirements of their business models, taking into account various factors such as technological capabilities, market conditions, and organizational resources.

Panetto *et al.* (2020) propose implementing digital technologies in agricultural supply chains to increase their efficiency and sustainability. They emphasize the importance of using AI to streamline processes, reduce waste, and improve resource management. The authors also look at the challenges posed by this transformation and offer practical recommendations to overcome them. Ayed *et al.* (2022) point to the effectiveness of integrated technologies. The integration of different technologies for the transformation of agri-food waste provides higher efficiency compared to the use of separate technologies. Integrating these methods can reduce costs, improve product quality, and reduce negative environmental impacts. The use of artificial intelligence in waste management is gaining increased attention from many researchers due to its potential to solve critical agro-industrial challenges. According to Cheng and Wang (2022), and Ancín, Pindado and Sánchez (2022), these technologies are transforming business practices, impacting workflows, and creating new ways to interact with customers, suppliers, and other stakeholders. Kassim *et al.* (2022) think that artificial intelligence can contribute to the implementation of efficient recycling and disposal systems. By examining data on various material properties, artificial intelligence can devise optimal recycling technologies that lower energy costs and maximize resource recovery. This position is supported by Ayed *et al.* (2022). According to the authors, artificial intelligence contributes to the acquisition of new knowledge and informed decision-making based on the processing of large amounts of data.

The integration of artificial intelligence into the agro-industrial complex will be a source of hope in the face of growing concerns about global sustainability. Recanati *et al.* (2022) believe that innovative collaboration has the potential to address some of the most pressing challenges of our time, such as sustainable waste management. This collaboration also supports the implementation of circular economy principles, especially in developing countries. Agro-industrial waste is a significant and often underestimated resource for ensuring sustainable food supply chain. Facchini *et al.* (2023) in their research, emphasize that the use of artificial intelligence in the field of waste management in the future will help reduce the negative impact on the environment, which is becoming critical against the backdrop of the global climate crisis.

The study of these aspects enables participation in the ongoing discussion about the need to use artificial intelligence in the waste management system. However, the practical value of using this tool at the level of Ukraine has not yet been sufficiently studied. The primary objective of this review is to substantiate the benefits of integrating AI into Ukraine's waste management system. To achieve this, the study focuses on:

1. Analyzing the current state of waste management in Ukraine and its disparities with EU practices.
2. Conducting a systematic review of startups and technological solutions leveraging AI in waste management.

By addressing these aspects, this review aims to contribute to the ongoing discourse on sustainable waste management and provide actionable insights for policymakers and stakeholders in Ukraine.

Materials and Methods

To achieve the research goal and address the objectives set, a systematic literature review was conducted, focusing on the analysis of modern startups and technological solutions in the field of waste management, including artificial intelligence.

Inclusion & Exclusion Criteria: During the study, inclusion and exclusion criteria for startups and technologies were established. The inclusion criteria comprised technological innovation (integration of artificial intelligence in waste management, such as automated sorting, big data analytics, and IoT platforms), contribution to sustainable development (reducing waste volumes, increasing recycling rates, and minimizing environmental impact), and economic efficiency (reducing costs associated with waste disposal or recycling). The exclusion criteria included solutions that do not adhere to the principles of the circular economy, projects in the early stages of development without tangible results or prototypes, and solutions that fail to address the problem of reducing environmental impact.

Data Sampling: The geographical scope of the study is global and includes an analysis of innovations that demonstrate successful implementation experiences in EU countries and the USA, which can be adapted to the Ukrainian context. The study covers the period from 2017 to 2024, selected based on several significant events. In particular, in 2017, Ukraine adopted the National Waste Management Strategy until 2030, marking the beginning of active modernization in this field. In 2022, due to the consequences of the war, the need for innovative solutions to managing construction waste significantly increased, which led to the active use of artificial intelligence. The data sources include the State Statistics Service of Ukraine[1], Eurostat (2024a, 2024b), scientific publications, and analytical materials. Through systematic analysis, the problem was identified, and the research objective was established. This approach enabled a comprehensive study of waste management in Ukraine, taking into account the interconnections between all relevant factors. Additionally, abstract and logical analysis was applied to substantiate conclusions and develop recommendations. This method focused on exploring how

[1] Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: http://www.ukrstat.gov.ua/ [Accessed on 13 June 2024].

artificial intelligence could improve waste management. A comparison of waste management practices in Ukraine with those in EU countries was conducted to identify differences and potential improvements.

Statistical Analysis: To compare waste management practices in Ukraine with those in EU countries, a statistical analysis of data was conducted using SPSS software, based on data from the State Statistics Service of Ukraine. SPSS was employed to process data on waste volumes, aiming to identify relationships between waste volumes, the number of landfills, and the quantity of recycled waste. A SWOT analysis was conducted to evaluate the strengths, weaknesses, opportunities, and threats associated with the application of artificial intelligence in waste management in Ukraine. Special attention was given to studies related to legislative initiatives and regulatory changes, business models in waste management, new technologies, and approaches to waste recycling. This approach provides a comprehensive examination of the topic, considering both theoretical aspects and practical experience in implementing innovative technologies in the field of waste management.

Results and Discussion

Global Waste Generation Problem

By 2025, global waste production is projected to increase annually, reaching approximately 2.3 billion tons. While developed nations contribute 34% of the world's waste, they represent only about 16% of the global population. Around 15-20% of all waste is recyclable. Inadequate waste management not only poses serious health risks and damages the environment but also exacerbates climate change issues (Verkhovna Rada of Ukraine, 2019). In Ukraine, the level of waste generation was 11.1 tons per person per year, and in the EU countries, this figure averages 4.8 tons (Eurostat, 2024b). Low levels of waste recycling and recovery have led to an annual accumulation of waste volumes in Ukraine. In Ukraine, from 2023, it is impossible to obtain reliable information on the indicators of reuse, recycling and disposal due to the lack of reliable statistical data. As of 2022, the volume of household waste in the country reached 7 million tons. Of this amount of waste, 9.9% was recovered, 1.66% was incinerated, 8.24% was sent for recycling and sorting (49.6% in the EU countries), and the rest of the waste was taken to landfills. The low level of recycling indicates a gap in waste treatment methods between Ukraine and the EU countries (UNEP, 2022).

National Waste Management Strategy

The primary aim of the circular economy is to minimize waste while ensuring economic growth. In 2017, Ukraine adopted the National Waste Management Strategy until 2030, as part of the Association Agreement with the European Union. The implementation of this strategy is planned in three phases: the first phase from 2017 to 2018, the second from 2019 to 2023, and the third from 2024 to 2030. The strategy's objectives align with several EU directives and include specific requirements for product production standards, waste recycling, packaging design, and more. For instance, by 2030, Ukraine aims to recycle 70% of all market-entering packaging, 55% of plastic, and 85% of paper and cardboard. Additionally, by 2030, the plan includes establishing 800 new facilities

for processing secondary raw materials, utilizing and composting biowaste. The disposal volume of household waste should be reduced from 95% to 30%, and the total volume of waste in landfills from 50% to 35%. Moreover, it is intended to create a network of 50 regional landfills that comply with the EU directive.

As of 2022, there were more than 6 thousand landfills and polygons in Ukraine, the area of which was about 9 thousand hectares. Of these, more than a thousand landfills are either overflowing or do not meet safety standards. In addition, more than 300 landfills need to be created in the country. (Zelenkov, 2022).

Current Challenges in the Management of Waste

Ukraine faces a specific problem of waste management, which arises as a result of the predominance of technologies in the national economy that consume significant amounts of resources. At the same time, there has been no adequate response to these challenges for a long time. Large volumes of resource use and specialization in energy-efficient, multi-waste technologies, along with outdated technological infrastructure, lead to significant generation and accumulation of waste. This situation leads to an aggravation of the economic crisis and deepening of socio-economic problems, which requires reforms and development, taking into consideration domestic and world experience in resource and waste management. The issue of waste is emerging as one of the most urgent environmental challenges, particularly from a resource perspective.

The difference between the Ukrainian situation and the situation in other developed countries is that Ukraine has significant volumes of waste generation, insufficient infrastructure and a lack of financial instruments for the implementation of international waste management practices. Meanwhile, the availability of such infrastructure is a prerequisite for all developed economies. The vast accumulation of waste in Ukraine's economy and the insufficient effectiveness of measures for its control, utilization, and disposal deepen the ecological crisis and hinder the country's development. To understand the true scope of the issue, it is crucial to assess the extent of land used for landfills, which remains the primary method of waste storage in the country. Table 1 illustrates the total area occupied by landfills in the region, highlighting key challenges related to territorial load, as well as the environmental, economic, and social consequences of this issue.

As shown in table 1, the areas used for landfills are substantial, creating numerous challenges for long-term territorial planning. This underscores the need to implement recommendations such as separate waste collection and the expansion of recycling initiatives. In Ukraine, there are 5.7 thousand landfills occupying approximately 8 thousand hectares. Among these: 162 landfills are overloaded, 693 fail to meet environmental and safety standards, and 2,197 landfills require reclamation. Additionally, illegal landfills (estimated between 33,000 and 35,000) remain an increasingly serious issue, although their exact size and impact are difficult to assess. This situation significantly complicates land management in Ukraine and necessitates the adoption of effective strategies such as separate waste collection, recycling, and landfill reclamation. A significant portion of Ukraine's land is allocated to landfills, which has several critical consequences.

Table 1: Total area of landfills in Ukraine as of 2022[2]

Administrative-Territorial divisions	*Total area of landfills, ha*		
	Just	*Congested*	*That do not meet safety standards*
Vinnytska	781.6	0	0
Volynska	96.8	77.9	22.7
Dnepropetrovska	875.66	3	172.98
Donetska	85.129	0	3
Zhytomyrska	758.93	91.5	63.38
Zakarpatska	153.32	28.96	38.565
Zaporizhia	5.7	0	0
Ivano-Frankivska	74.9	7.9	8.14
Kyivska	270.377	42.3	204.377
Kirovohradska	518.08	18.69	40.4
Luganska	0	0	0
Lvivska	136,47	11.32	6.5
Mykolaivska	524,4	19.8	225.3
Odeska	1046.32	5.9	39
Poltavska	439.95	21.3	123.96
Rivnenska	429.13	12.2	0
Sumska	146.99	9.76	17.96
Ternopilska	113.5	12.8	3,5
Kharkivska	82.06	37.51	44.55
Khmelnytska	136.13	45.54	0
Cherkasy	202.68	3	32.25
Chernivtsi Oblast	254.2	4.3	0
Chernihivska	797.3	37.2	41.1
C. Kyiv	91.8	0	0
Total in Ukraine:	8021.426	490.88	1087.662

Environmental Impacts

The expansion of landfill areas leads to soil and groundwater contamination, reducing environmental quality. This poses significant health risks, particularly in areas adjacent to landfills. Furthermore, the increasing number of illegal landfills exacerbates the problem of uncontrolled environmental degradation. The lack of proper monitoring and management of these sites results in the release of harmful substances into the soil, water, and air, creating long-term environmental and social risks. The absence of accurate accounting and effective strategies for their elimination also complicates the planning of environmentally safe waste management systems.

[2] Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: http://www.ukrstat.gov.ua/ [Retrieved on 13 June 2024].

Economic Impacts

The use of large land areas for landfills limits opportunities for alternative land use, such as agriculture, construction, or industry. This reduces the economic potential of regions and requires significant financial resources for waste management and land reclamation.

Social Impacts

The proximity of landfills to residential areas negatively affects the quality of life for communities. Concerns about health risks among residents decrease the attractiveness of regions for investment and create discomfort in living conditions. In addition to specific waste stored in landfills, Russia's armed aggression has introduced additional challenges related to the generation of large volumes of construction debris. The destruction of over 100,000 structures has resulted in more than 450,000 tons of construction waste, which is internationally characterized as "ecocide." As of April 2024, the total mass of such waste amounted to 223,237.3 tons, emphasizing the scale of environmental and management challenges. Table 2 illustrates the volume of construction waste generated as a result of the destruction, providing critical context for analyzing the management of these wastes.

Table 2: Amount of demolition waste in Ukraine as of April 2024[3]

Administrative-Territorial divisions	*Amount of waste from destruction*	
	Tons	*m3*
Vinyasa	-	-
Volynska	-	-
Dnepropetrovska	587.9	16.75
Donetska	4429.7	56456.9
Zhytomyrska	8.0	668.16
Zakarpatska	-	-
Zaporizhia	53.43	19.5
Ivano-Frankivska	1.6	400
Kyivska	189229.4	133487.0
Kirovohradska	14.6	-
Luganska	-	-
Lvivska	2015.8	-
Mykolaivska	6010.3	-
Odeska	1902.2	2.0
Poltavska	-	-
Rivnenska	82.03	-
Sumska	726.0	-
Ternopilska	10.2	445.8
Kharkivska	1123.5	3277.8

[3] Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: http://www.ukrstat.gov.ua/ [Retrieved on 13 June 2024].

Administrative-Territorial divisions	*Amount of waste from destruction*	
	Tons	*m3*
Khmelnytska	1362.1	541.5
Cherkasy	2612.9	117.6
Chernihivska	6700.0	2600.0
Kherson	-	-
C. Kyiv	1078.1	-
Total in Ukraine:	223237.3	235780.9

The volume of demolition waste as of April 2024 highlights the extensive challenges associated with managing construction debris caused by armed aggression. The significant volume of this waste emphasizes the critical need for effective recycling and disposal strategies. The total amount of waste (223,237.3 tons) underscores the enormous quantity of materials requiring proper management. This creates both technical and administrative challenges. Without appropriate disposal measures, this waste can cause significant contamination of soil, water resources, and air. Considering the international classification of such large-scale waste generation as "ecocide," its management is critically important for Ukraine's environmental safety. The large volume of waste in affected regions complicates infrastructure recovery, deteriorates living conditions, and poses health risks due to exposure to toxic materials. Managing construction waste demands substantial financial resources, including costs for transportation, sorting, recycling, and disposal, placing a significant burden on local budgets. These challenges highlight the importance of implementing a systematic approach to waste management. Waste generation occurs across various sectors of the national economy, requiring the adoption of a unified strategy. In EU countries, following European standards, five key principles of an effective waste management system have been implemented: collection, sorting, recycling, incineration, and disposal (Figure 1). Studying this experience could provide a foundation for developing a similar model in Ukraine, addressing its current challenges.

In 2022, according to the State Statistics Service of Ukraine, the lack of effective waste management tools, particularly in sorting and separate storage, led to the accumulation of 7 million tons of household waste. The mixing of food waste with packaging and other household materials complicates sorting and processing, significantly hindering recycling efficiency. While the agricultural, forestry, and fisheries sectors demonstrated relatively high waste utilization rates of 76%, other industries, such as the processing sector, contributed substantially to the country's waste problem, producing 23.3 million tons. Furthermore, with 2.8% of landfills over capacity and 12% failing to meet environmental standards, Ukraine faces critical challenges in managing its waste sustainably.[4]

Environmental and Legal Impact

These challenges are compounded by broader systemic issues that threaten environmental security on a global scale. It is important to recognize that environmental

[4] Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: http://www.ukrstat.gov.ua/ [Retrieved on 13 June 2024].

crimes, crimes against humanity, and war crimes disrupt global environmental security, and endanger the right of future generations to a safe environment. The ongoing Russian invasion impacts not only Ukraine but the global community as well, disregarding established legal standards for environmental protection. International cooperation in the field of combating offences that harm the environment provides for various forms of interaction between states and international organizations to prevent irreparable damage to the environment and humanity as a whole. The handling of such large volumes requires significant financial, human and technological resources.

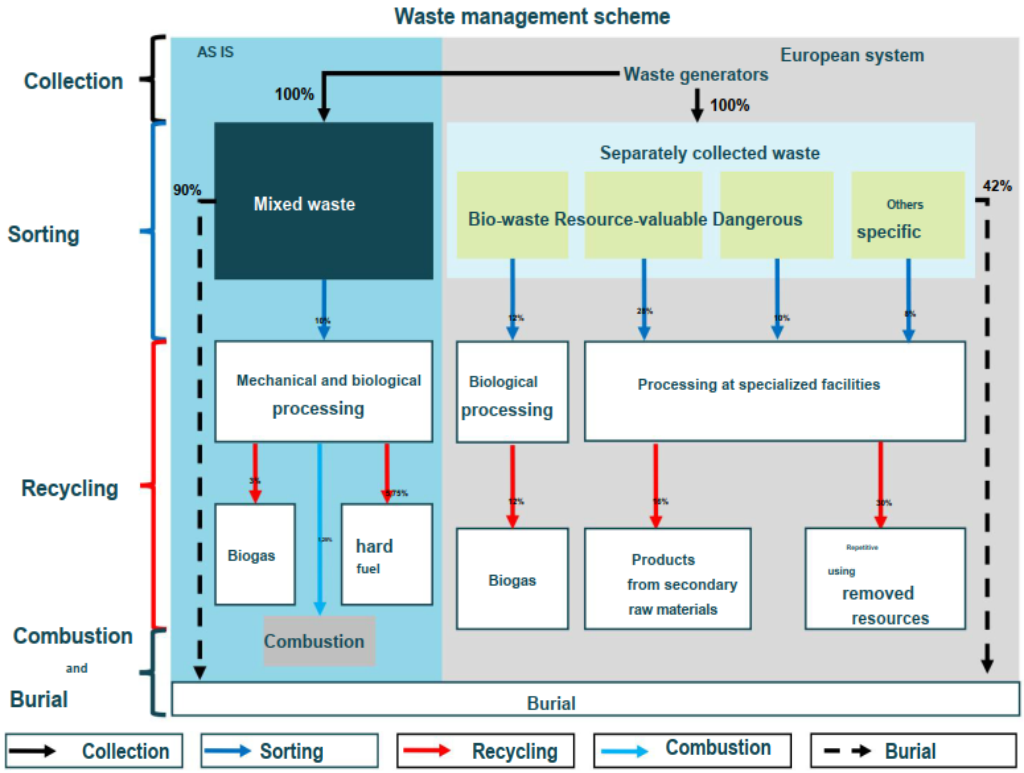


Figure 1: European Waste Management Model (Eurostat. (2024a)

Legal Framework and International Standards

One of the main obstacles to waste management is the absence of a comprehensive legislative framework, including specific recycling standards. As Ukraine advances in its European integration efforts, examining the legal basis for ecocide accountability within EU countries is essential, reinforcing the global movement to criminalize ecocide. Currently, international law provides limited environmental protection, directly and indirectly, during times of armed conflict. Such protection is found in significant humanitarian agreements, like the UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD Convention) and the Additional Protocol to the Geneva Conventions of August 12, 1949, for protecting war victims (Ministry of Infrastructure of Ukraine, 2023).

National and EU Regulatory Integration. Ukraine is committed to harmonizing its national laws with EU environmental principles under the Association Agreement with the EU (Table 3).

Table 3: The current state of Ukraine's regulatory framework compared to the EU and other international obligations (EU4Environment, 2023)

National Regulatory and Legal Acts	*EU Directives*	*National Strategies*
Law on Waste Management (from 2023) Law of Ukraine on Public Procurement Draft Law of Ukraine on Packaging and packaging waste Draft Law of Ukraine on Waste Mining Activity	Directive 2008/98/EC on waste and repealing certain Directives Directive 94/62/EC on packaging and packaging waste Directive 1999/31/EC on the landfill of waste Directive 2006/21/EC on the management of waste from extractive industries and amending Directive 2004/35/EC Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) Regulation EU 2023/1542 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC	National economic strategy for the period until 2030 State strategy of regional development for 2021-2027 (updated) Strategy for the development of industrial parks for 2023-2030 (2023). Strategy for the economic security of Ukraine for the period until 2025 The main principles (strategy) of the state environmental policy of Ukraine for the period until 2030 and the National Action Plan until 2025 National waste management strategy in Ukraine until 2030 National waste management plan until 2030 Strategy for environmental security and adaptation to climate change for the period up to 2030

Lack of coordination between authorities in the field of circular economy and inconsistency of terminology in regulations may lead to the introduction of ineffective measures. The vast majority of EU directives, which were noted in the National Waste Management Strategy of Ukraine until 2030, have not yet been integrated into national legislation. Draft legislative acts envisaged by the National Waste Management Plan of Ukraine until 2030 have not yet been adopted and have not entered into force effect. The uncertainty of the deadlines complicates the monitoring and implementation of commitments, which undermines the trust of partners and can lead to the loss of opportunities for Ukraine and slow down its integration into the European space. The necessary tools are currently being developed to support the transformation of the recycling market, but cross-sectoral coordination between authorities and the definition of the range of issues for recovery, that meet the purpose of the circular economy remains an important issue (Figure 2).

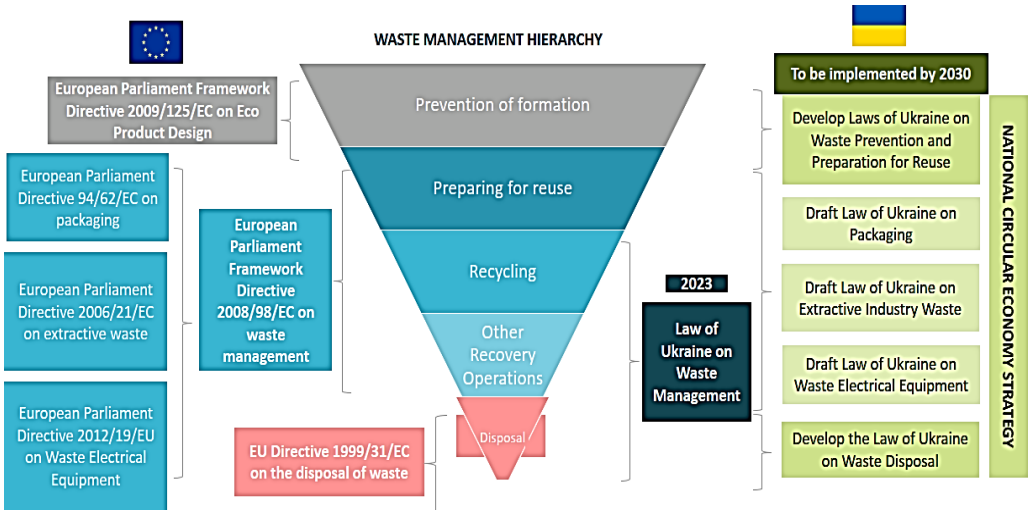


Figure 2: Waste Management Hierarchy: Comparing the EU and Ukraine in Perspective of a Circular Economy Strategy (EU4Environment, 2024)

Figure 2 compares the waste management hierarchy between the EU and Ukraine, highlighting gaps and opportunities within the circular economy framework. Ukraine's progress in adopting EU-aligned strategies remains inconsistent, with significant room for improvement in meeting environmental sustainability goals.

Circular Economy and AI integration

The implementation of waste directives in Ukraine could lead to an annual GDP increase of 3%. By 2035, introducing a closed-loop processing cycle is projected to contribute approximately 3% of Ukraine's annual GDP growth, or $8.8 billion. In Ukraine, the implementation of the Circular Economy Strategy opens up new markets, which has a direct and indirect impact on macroeconomic indicators.

Phase 1 (2023-2025): Adoption of laws to regulate market interactions.
Phase 2 (2026–2030): Partial implementation in residential and agro-industrial sectors.

Phase 3 (2031 and beyond): Transition to a circular economy, with gradual waste reduction aligned with European standards.

The multiplier effect in related industries is significant due to resource optimization, waste reduction and innovation.[22] To achieve these goals, Ukraine should adopt the experience of the best international practices for circular production. UNIDO's (2024) Report Circular Economy for Industrial Development in Ukraine: Status Study selected four best practices for each of the priority manufacturing sectors (Table 4).

Ukraine faces several challenges in implementing its circular economy strategy, particularly in waste management: flaws in legal regulations, manufacturers' lack of commitment to environmental principles, and inadequate recycling infrastructure e.g., insufficient sorting stations, recycling facilities, and collection systems complicate waste handling. Additionally, public awareness of the circular economy's benefits remains low.

Artificial intelligence is a powerful tool for advancing circular economy strategies, increasingly serving as an innovative asset in waste management. Leveraging its ability to analyze and process extensive datasets, AI is revolutionizing waste management strategies, promoting more efficient and sustainable practices. In their research, Ayed and Hanana underscore the efficacy of AI in waste management, illustrating how data processing empowers machines to make well-informed decisions(Ayed *et al.*, 2022). By applying advanced algorithms and machine learning, waste management companies can gain insights into waste characteristics and composition, aiding informed decisions in recycling and waste reduction. AI can support various waste management stages, from collection to sorting. By analyzing large datasets, it classifies waste by type, identifies optimal recycling methods, and reduces landfill volume.

Table 4: List of best practices and their alignment with the circular strategies of the CE Framework

Best Practices	*Connection with the strategic Circular Group Economy*	*Linking to the Circular Strategy*
EDP Company, from exhaust gases Steel Brewery production up to Electricity (Spain)	Turning waste into fuel Waste-to-energy production Interaction with industry companies to create Shared Value and Synergy Definition	Obtaining energy from waste or producing fuel and energy resources from waste. Collaborating with companies in the industry to participate in business projects or scientific research that support the development of a circular economy, such as industrial symbiosis.
SIGUREC, Initiative "Smart machines for Waste Recycling" (Romania)	Reuse, repurpose and recycle waste within the same industry	Repurposing waste products and materials for reuse within the same industry sector. Processing waste into materials and products of lesser value is still utilized within the same industry. Establishing collection

Best Practices	*Connection with the strategic Circular Group Economy*	*Linking to the Circular Strategy*
		programs to prepare products and components for reuse or recycling specifically within the same sector.
ZIKOM Company, IT Recovery-equipment (Poland)	Delivery of goods to customers with the help of business models, that provide maximum Value	Sale of reusable spare parts. Sale of replacement parts. Reuse, repurpose, and recycle the waste within the same industry.
The initiative "Vive Textile Recycling» (VTR) (Польща)	Reuse, repurpose, and recycle the waste within the same industry.	Repurposing waste products and materials for reuse within the same industry sector. Reprocessing waste into lower-cost materials and products that can be utilized in the same industry. Implementing collection programs to ensure that products and components are adequately prepared for reuse or recycling within the same sector.

AI also contributes to efficient recycling systems by analyzing material characteristics, developing energy-saving recycling methods, and maximizing resources' renewable potential. Artificial intelligence enables waste management organizations to significantly enhance recycling rates. Algorithms can swiftly identify reusable materials. This not only reduces the volume of waste directed to landfills but also aids in the conservation of valuable resources. Artificial intelligence can also optimize recycling processes. By analyzing data on the types and volumes of waste, algorithms can recommend the most effective treatment methods. For example, they can apply whether incineration, anaerobic digestion, or composting are the best options for a particular type of waste, which reduces negative environmental impacts and improves resource recovery. Joshi (2022) observes that numerous waste collection systems are antiquated, with inefficient route planning leading to congestion and increased fuel consumption. AI enables the development of optimized routes for garbage trucks and helps identify when bins need emptying. This dynamic, adaptable waste management system benefits businesses, organizations, and the public. Israeli startup Algoretail (2024) machine learning to streamline procurement in retail, covering the entire journey from supplier to warehouse and store shelves. Their Algoretail IO tool forecasts sales based on data, helping to prevent losses from perishable goods, such as bread, milk, and butter, nearing expiration. The Algoretail IO tool has been widely used in fruit and vegetable distribution. Fruits and vegetables have a limited shelf life due to their rapid spoilage, and therefore delays in delivery, manual ordering and the lack of accurate data on the stocks of these products in each retail outlet only added to the problems and errors. Specific parameters of fruits and vegetables are taken into account in the automated order module, which was implemented by Algoretail (2024). This allows you to automatically create orders based on projected sales volumes. Due to this, the level

of stocks in each object of the retail chain corresponds to daily consumption. These technologies offer a range of benefits, including increased efficiency, improved product quality and safety, reduced waste, and environmental sustainability. French startup Trizzy (2024). Has launched an AI-powered assistant for waste management, designed to assist businesses and community groups. Accessible via websites, social media, and mobile apps, this assistant can identify various waste types, answer users' questions on disposal methods, and provide details on waste collection times, composting schedules, and nearby recycling centres. Additionally, Trizzy's platform features a marketplace for reusable goods, fostering a circular economy approach. With the help of the Trizzy virtual assistant, Tetra Pak, an international company specializing in food processing and packaging, together with Orlait, which sells the dairy brand J'aime le Lait d'Ici, equipped milk bottles with QR codes. Consumers can use QR code scanning to get any information about the composition, processing, and certification of packaging. This initiative is part of the transparency process and is in line with the environmental commitments of international companies (Maddyness, 2022). The American startup has introduced Zabble Zero, a cloud-based enterprise mobile platform designed to achieve zero waste. This innovative solution automates the collection and analysis of waste data for waste management professionals and integrates seamlessly with back-office systems. By leveraging machine learning algorithms, the platform offers real-time insights and recommendations, expediting decision-making processes for managers. Named after the Zabbalins, Egypt's "garbage people," Zabble's software is already being utilized in several municipalities across California. Utilizing this platform allows companies to markedly decrease the amount of waste directed to landfills and reduce their carbon footprint.

The effectiveness of the use of artificial intelligence in the processing of agricultural products has been repeatedly pointed out in the works of. Lezoche *et al.* (2020). This automates the processes of sorting, classifying, and packaging agricultural products. It can be used to predict yields and identify food safety risks. By leveraging the latest AI-based technologies, it enhances productivity and efficiency in the food supply chain, while simultaneously advancing agriculture and preserving biodiversity. In Ukraine, artificial intelligence is being utilized in waste management at the foundational level, including the use of intelligent containers and automated sorting systems (current implementation stage). In EU countries, these technologies are already integrated and used at a more advanced level, with a high level of automation and precision. In EU countries, AI systems for waste management are part of broader urban ecosystems, where all elements interact with each other. In Ukraine, such integrated solutions are not yet widely available Common. In EU countries, new innovative solutions are constantly being developed and implemented, such as robotic sorting systems and AI-based forecasting. In Ukraine, such technologies are just beginning to appear, which creates the potential for rapid development in this area table 5.

The application of artificial intelligence (AI) in waste management has demonstrated notable success in various cities globally. In Singapore, an AI-powered waste sorting system utilizing advanced sensors and machine learning algorithms has reduced landfill usage by 30% and increased recycling rates by 20% (V8 Environmental, n.d.). In Barcelona, 'smart bins' equipped with AI technology have optimized waste collection routes, cutting emissions from garbage trucks by 40% (Blue Sky Creations, n.d.). In San Francisco, an AI system employing image recognition technology for sorting recyclables has lowered landfill waste by 35% and boosted revenue from recyclables by 20% (CBS

News, n.d.). Overall, the integration of AI in waste management facilitates a reduction in operational costs by 10-15%, an increase in revenue from recyclables by 20-30%, and a decrease in waste disposal expenses by 30-40% (Fast Company, 2023). Environmentally, this results in a reduction of greenhouse gas emissions from garbage trucks by 30-50%, an increase in recycling rates by 20-40%, and a reduction in soil and water pollution by 15-25% (Fast Company, 2023). Although Ukraine currently lacks specific examples of AI implementation in waste management, the country is moving towards modernizing its systems, as demonstrated by the adoption of the National Waste Management Strategy for 2030. The introduction of AI technology could significantly accelerate waste processing in Ukraine, where only 8.24% of waste is currently recycled, compared to 49.6% in the EU. This will help achieve strategic goals, including increasing recycling to 70% by 2030 (DLF Attorneys-at-law, n.d.).

Table 5: Application of Artificial Intelligence in Waste Management in Ukraine and Developed Countries (Bigbelly Worldwide, 2024; Dnepr Express, 2019)

In Ukraine	*In the EU and the USA*
Smart Waste Containers: Projects with smart containers are already being implemented in Ukraine, which use sensors to monitor the occupancy of containers. For example, startups such as Ecois. It is developing systems that notify when waste needs to be removed, optimizing garbage truck routes.	*Advanced Smart Containers:* Many cities in the U.S. and Europe use smart bins with more advanced features, such as recognizing waste types and automatically sorting them. Companies like Bigbelly integrate such containers with real-time monitoring systems.
Machine learning-based sorting systems: Some sorting stations in Ukraine use artificial intelligence for automated recognition and sorting of waste. This allows you to improve recycling efficiency and reduce human error.	*Robotic sorting systems:* In Sweden and the Netherlands, robots based on artificial intelligence are actively used to sort waste in factories. Such systems can recognize and sort materials з great accuracy and speed.
Data Analysis Platforms: Use of platforms to process a large array of information by an order of magnitude to optimize recycling and recycling processes. Such platforms help to predict waste volumes and develop strategies to reduce it.	*Analytical and predictive models:* Japan and Germany have adopted AI-driven forecasting models to enhance urban waste management. These systems allow for accurate predictions of future waste volumes, efficient resource allocation, and a reduction in environmental impact.
IoT-based waste management platform Under the "Smart City" initiative in Dnipro, the city is exploring the implementation of a unified IoT-enabled platform for managing urban waste. This platform would integrate data from multiple sources — such as smart bins, waste collection trucks, and sorting facilities — to develop an optimized waste management ecosystem.	*Internet of Things (IoT) and Integration with Urban Systems:* In Singapore, the integration of IoT and artificial intelligence makes it possible to organize systematic waste management systems, where smart containers, garbage trucks, and sorting stations operate in a single ecosystem, streamlining the entire process.

Ukraine still has to go through the implementation and adaptation of these technologies, but there are already positive examples and significant potential for further development, which requires large investments. In the EU and the US, the circular economy and artificial intelligence technologies are being actively integrated into national and regional policies. For example, the EU is implementing the Circular Economy Action Plan (Environment, 2023), which includes stringent requirements for waste recycling and incentives for innovative technologies such as artificial intelligence in this area. Ukraine is just taking the first steps towards integrating the principles of the circular economy and artificial intelligence technologies into waste management. Implementation of the National Waste Management Plan until 2030 is an important step, but this document is still in the process of adaptation. The legal framework is evolving but often does not comply with international best practices. Legislative initiatives are aimed at the integration of European standards, but their effectiveness is reduced due to insufficient implementation and the lack of clear control mechanisms. In the U.S. and EU countries, there is substantial support from both the public and private sectors. Investments in technologies that promote the circular economy and the use of artificial intelligence are considered strategic and are significantly larger in scale compared to Ukraine. For instance, the EU Green Deal allocates substantial resources for the development of these technologies. In contrast, public investment in the circular economy and the adoption of artificial intelligence in Ukraine is limited, with much of the funding derived from international grants and aid programs. This constraint hampers the speed and scale of implementing innovative solutions.

As waste management processes become more efficient and precise, investments in AI-powered solutions are increasing. Projections indicate substantial growth potential for this sector by 2030. By 2033, the global AI market in waste management is expected to reach approximately $18.2 billion, up from $1.6 billion in 2023, reflecting a compound annual growth rate (CAGR) of 27.5% between 2024 and 2033 (Market.us, 2024). Ukraine is actively participating in this trend. The Ministry is collaborating with international entities, particularly the European Union's LIFE program, which allocates funds for innovative projects, including those focused on waste management and AI integration/ Investment strategies will predominantly target enhancing funding for automated waste sorting systems that employ machine learning and computer vision technologies to improve accuracy and decrease recycling costs; implementing intelligent route optimization systems for waste collection vehicles to reduce fuel consumption and CO_2 emissions; investing in analytical platforms for predicting waste generation and planning infrastructure based on big data analytics (Big Data); and engaging the private sector in the development and deployment of innovative AI-driven waste management solutions.

Innovations in Waste Management Technologies and Prospects

Investing in AI-driven waste management systems is expected to decrease waste incineration and boost recycling, reuse, and recovery due to several factors. According to Market.us (2024), AI enables enhanced waste efficiency by streamlining waste collection, sorting, and recycling processes. This is achieved through accurate waste volume forecasts, identifying efficient disposal methods, and uncovering new recycling opportunities. Moreover, AI technology automates waste sorting, as noted by Blue Sky Creations (n.d.), allowing for a higher recovery rate of reusable materials. This

innovation aligns with the findings by ALGORETAIL (2024), which emphasizes AI's role in optimizing recycling techniques and increasing revenue from recycled materials.

AI contributes significantly to environmental protection. For instance, Blue Sky Creations (n.d.) reports a 40% reduction in emissions from garbage trucks due to AI-optimized waste collection routes in Barcelona. Additionally, the integration of AI in waste management improves sustainability by decreasing soil and water pollution (Market.us, 2024). While Ukraine faces challenges in adopting AI in waste management, the adoption of the National Waste Management Strategy for 2030 demonstrates the country's commitment to modernizing its waste management systems. Currently, only 8.24% of waste is recycled in Ukraine compared to 49.6% in the EU (DLF Attorneys-at-law, n.d.) AI-driven technologies could significantly increase recycling rates, as similar technologies in other countries have shown (CBS News, n.d.). Despite these opportunities, Ukraine must overcome several barriers, including insufficient legislation, limited infrastructure, and financial constraints (Market.us, 2024). Moreover, public awareness and skilled labour shortages are critical issues. Addressing these challenges through investments in education, infrastructure, and international cooperation can help Ukraine achieve its strategic goals of sustainable waste management and environmental security.

Conclusions

The research suggests that Ukraine is in the initial stages of adopting circular economy principles and integrating artificial intelligence (AI) in waste management. There is a significant disparity between EU countries in terms of waste recycling and utilization: only 8.24% of waste is recycled in Ukraine, versus 49.6% in the EU. Underdeveloped infrastructure, overcrowded landfills, and non-compliance with environmental standards necessitate immediate attention. Systemic issues in policies and regulations have been identified: there is a lack of coordination between state bodies, inconsistency in terminology, and a low level of integration with European directives. Four leading international practices in circular manufacturing have been examined, the implementation of which would improve Ukraine's economic and environmental situation.

Regarding the use of AI, Ukraine is still in its early stages, whereas EU countries have made considerable advancements in this field. The adoption of AI could potentially increase waste recycling rates by 20-30% and reduce operational costs by 10-15%. To fully realize the potential of AI and circular economy principles, it is crucial to develop a legislative framework to support innovative technologies, invest in the modernization of waste collection and recycling infrastructure, raise public awareness, and involve the private sector in adopting circular economy practices. AI pilot projects should be initiated in various regions of Ukraine, and opportunities for integrating AI with other digital technologies should be explored. The implementation of these measures will not only enhance environmental sustainability but also foster economic development by creating new markets and jobs in the green economy sector. The adoption of circular economy principles and the application of AI in waste management are crucial for Ukraine's sustainable development and its integration into the European framework.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5	Author 6
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes	Yes
Collected the data	No	No	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	No	Yes	Yes	Yes	Yes
Wrote the article/paper	No	No	Yes	Yes	No	No
Critical revision of the article/paper	Yes	Yes	No	No	Yes	Yes
Editing of the article/paper	No	Yes	Yes	No	No	No
Supervision	No	Yes	No	Yes	No	No
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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