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Bogdan Ivan[1], Constantin Dumitrașcu[1], Doru-Costin Darabont[2],
Roland Iosif Moraru3, Constantin Bujor[1]

[1] National University of Science and Technology Politehnica Bucharest,
Faculty of Industrial Engineering and Robotics, Romania
[2] National Institute for Research and Development for
Labor Protection "Alexandru Darabont", Romania,
[3] University of Petroșani, Management and Industrial Engineering,
Department of Industrial Risk Assessment Research Center

Abstract
Urban waste management is a major challenge for contemporary cities, affecting the environment, public health and the economy. This article analyses the impact of new technologies, such as Io T, artificial intelligence, automation and digitalization, on the efficiency of waste collection, sorting and recycling systems. Modern solutions and relevant case studies are presented, highlighting the role of innovation in the transition towards a circular economy and a sustainable urban environment. The paper underlines the need to adopt technology in public policies to transform waste management into a smart, efficient and environmentally friendly process.

Keywords
Urban waste; artificial intelligence; innovation; recycling systems.

I. Introduction

In recent decades, accelerated urbanization, population growth and lifestyle changes have led to a significant increase in the amount of waste generated in the urban environment. Urban waste is not only an environmental challenge, but also an economic and social one, affecting public health, quality of life and the sustainability of cities.

Traditionally, waste management systems have been based on unsorted collection and landfilling, methods that are no longer viable in the current context. They generate high costs, greenhouse gas emissions, soil and groundwater pollution, but also major risks to health and the environment. In addition, many cities face a lack of space for new landfills, outdated infrastructure and insufficient selective collection [1].

Daily waste generation per capita in high-income countries is projected to increase by 19% by 2050, compared to low- and middle-income countries, where it is expected to increase by around 40% or more. The total amount of waste generated by low-income countries is expected to increase more than threefold by 2050 [2]. The East Asia and Pacific region generates most of the world's waste, about 23%, and the Middle East and North Africa region produces the least in absolute terms, about 6%. However, the fastest growing regions are Sub-Saharan Africa, South Asia, the Middle East and North Africa, where, by 2050, total waste generation is expected to double and even triple [3].

In this context, technology becomes an essential ally in the transition to an efficient, sustainable and digitized waste management system. The emergence of innovative solutions such as the Internet of Things (IoT), artificial intelligence (AI), collection automation, smart sorting and digital applications opens up new perspectives in addressing this global problem.

However, while such technologies are widely discussed in policy and academic literature, systematic methodologies for evaluating their real impact remain limited. The aim of this research is to analyse the main emerging technologies that contribute to a more efficient and appropriate waste management in the urban environment by answering the following research question: „How can emerging digital technologies, such as IoT, AI, and blockchain, be systematically evaluated and integrated to improve the efficiency, environmental performance, and sustainability of urban waste management systems?"

The paper aims to highlight both the benefits of these technologies and the current limitations of conventional systems, while providing concrete examples of good practices at the international level.

To answer this question, the study combines statistical and policy data with selected case studies illustrating good practices in technologically advanced waste management. The following section details the methodological framework adopted for data selection, integration, case study analysis, and technology assessment, while also identifying the limitations and future research needs of the study.

II. Methodology

A. Research Design and Data Sources

This study adopted a mixed-method research design, integrating both qualitative and quantitative components to capture the complexity of waste management systems and their technological transformations. The purpose was to link empirical data (such as waste generation rates and recycling performance) with policy frameworks and technological innovations influencing operational practices.

The quantitative aspect of the research was based on secondary data extracted from official and validated sources such as Eurostat, the European Environment Agency (EEA), the World Bank, and the European Parliament's Waste Statistics database. These datasets were chosen for their methodological consistency, cross-national comparability, and coverage of key indicators, including municipal waste per capita, recycling and landfilling rates, and waste treatment distribution. The timeframe for data selection (2006–2024) was designed to capture both long-term trends and the recent acceleration of technological adoption.

The qualitative aspect was grounded in an extensive literature review covering peer-reviewed academic publications, European Union directives, and technical reports from waste management agencies. The purpose was to contextualize the statistical trends within broader policy and innovation dynamics, and to identify emerging technologies relevant to the urban waste sector. The literature review followed a systematic selection protocol: (1) identification of sources using keywords such as "smart waste management," "IoT," "AI sorting," "circular economy," and "urban sustainability"; (2) inclusion of documents published between 2015 and 2024; and (3) exclusion of sources lacking methodological transparency or empirical grounding.

Data were processed and visualized using Microsoft Excel to generate comparative charts and trends (Figures 1-3). This allowed for an integrated understanding of both macro-level statistical dynamics and micro-level technological applications.

B. Case Study Selection and Evaluation

In this study, three representative cases were selected: (1) smart containers equipped with IoT sensors, (2) AI-based waste sorting systems, and (3) GPS and IoT-driven route optimization platforms. These examples were chosen through a purposive sampling strategy, guided by inclusion criteria grounded in academic rigor and policy relevance. The selection criteria included:

- Operational relevance: The case had to address one of the main stages in waste management, collection, sorting, or transportation.

- Empirical documentation: The initiative needed to be supported by published data, technical evaluations, or publicly available project results.
- Transferability potential: The model had to demonstrate applicability or scalability in other urban or regional contexts, particularly within the European Union.

Each case study was examined through a multi-criteria evaluation framework, assessing four key dimensions: Efficiency improvement (reduction in operating time, resource use, or costs); Environmental performance (measurable decrease in landfill use, emissions, or contamination); Economic feasibility (analysis of initial investment versus long-term savings); Scalability and technological maturity (readiness level for large-scale implementation).

For example, smart containers were evaluated based on reported improvements in collection frequency and fleet utilization efficiency, while AI-based sorting systems were examined for their increased purity rates in recyclables and operational accuracy. Route optimization cases were analyzed for their ability to lower fuel consumption and CO_2 emissions through predictive algorithms. The synthesis of these cases provided practical validation of the broader theoretical and policy discussions presented in earlier sections, demonstrating the real-world value of emerging waste management technologies.

C. Technological Assessment Framework

To systematically evaluate the technologies identified (IoT, AI, blockchain, robotics, and automation), a multidimensional assessment framework was designed, combining economic, environmental, social, and regional dimensions. This structure was inspired by the European Commission's Digital Europe Programme evaluation criteria and adapted for urban waste management applications.

The economic dimension focused on the cost-benefit relationship and return on investment (ROI). Data on operational savings, reduced downtime, and optimized logistics were used to estimate long-term efficiency gains relative to initial capital investment. In cities where IoT-enabled bins or AI sorting lines have been implemented, studies report cost reductions of 15–30% in logistics operations, validating the importance of this metric.

The environmental dimension evaluated each technology's potential to reduce greenhouse gas emissions, improve recycling rates, and decrease landfill dependency. Life Cycle Assessment (LCA) principles were used qualitatively to assess environmental implications.

The social and institutional dimension captured factors of public acceptability, user engagement, and institutional readiness. Successful technology adoption is strongly correlated with digital literacy, environmental awareness, and the presence of local governance frameworks that support innovation.

Finally, the regional adaptability dimension considered infrastructural capacity and policy alignment across different European regions. For instance, blockchain traceability solutions might be more readily adopted in high-income urban centers with advanced digital infrastructure than in smaller municipalities with limited resources.

This multidimensional evaluation allowed for a holistic comparison of emerging technologies, identifying both synergies (e.g., IoT + AI integration for predictive collection) and barriers (e.g., cost and interoperability issues).

III. State of Art of Urban Waste Management

Urban waste management is one of the most pressing challenges facing modern cities. Against the background of the rapid growth of the urban population and the intensification of economic activities, the volume of waste generated daily has reached alarming levels. According to Eurostat data, in the European Union, each citizen generates an average of between 450 and 600 kg of municipal waste annually, and a large part of it comes from urban areas. Globally (fig.1), the states that produced the largest amount of municipal waste are: the USA with 265.2 million metric tons, followed by China with 215.2 million metric tons and Germany with 53.7 million metric tons (at the level of 2021).

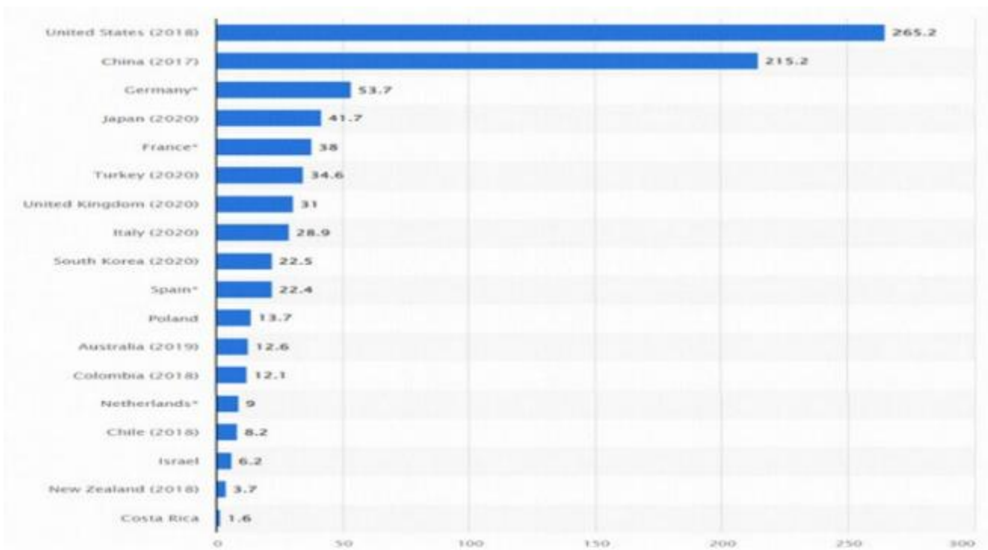

Fig. 1. Situation of municipal waste-generating states in 2021 [2]

At the European Union level, the average amount of municipal waste measured per capita increased in the EU, from 2006 to 2021. Although municipal waste per capita has increased in most EU countries, it has decreased in countries such as

Malta, Cyprus, Spain and Romania (fig. 2). As with the global trend, richer countries tend to produce more waste per capita.

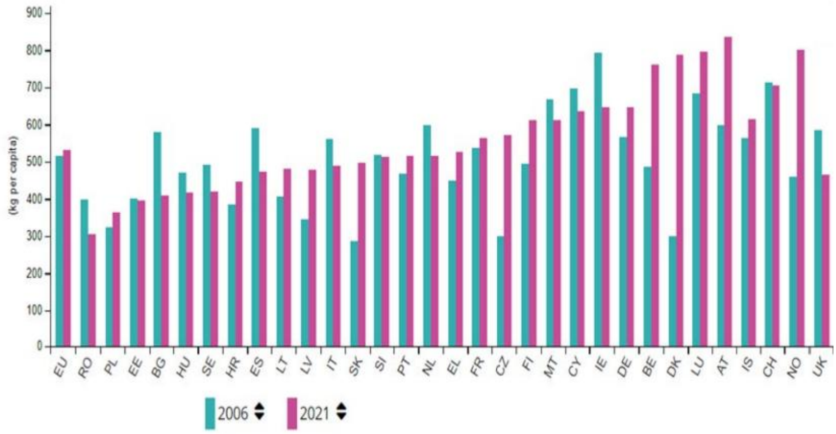

Fig. 2. Municipal waste generated in Europe in 2006 and 2021.[2]

According to data published on the European Parliament's website, 2.2 billion tonnes of waste are generated in the EU every year. About 27% of municipal waste is collected daily and treated by municipalities, mainly generated by households. Around 39.2% of waste was recycled and 32.2% landfilled in the EU in 2020. [3]

In the absence of efficient selective collection, these types of waste often end up mixed in the landfill, considerably reducing the possibility of recycling or energy recovery. In many cities in Romania and other parts of the world, waste management systems are still based on conventional methods:

- *Periodic unsorted collection* – waste is collected in a single container, without sorting at source;
- *Landfill storage* – the most used method, but with a major impact on the environment and public health;
- *Incineration* – used in some European cities, but with risks in terms of pollutant emissions if not properly controlled.

Although some municipalities have introduced containers for separate collection, the recycling rate remains low, mainly due to a lack of environmental education, adequate infrastructure and an effective monitoring system. Among the main problems of current urban waste management systems are:

- *Overcrowding of landfills* – many landfills are close to their maximum capacity;
- *Lack of efficient selective collection* – most recyclable waste is not recovered;
- *High operating costs* – transporting, collecting and storing waste involves considerable financial and logistical resources;

- *Negative impact on the environment* – greenhouse gas emissions, soil and groundwater pollution;
- *Environmental crime* – illegal dumping, uncontrolled burning, and lack of traceability of waste.

Technological advances have also significantly improved the efficiency of waste collection. Many waste management companies are currently using GPS tracking systems on their collection vehicles to optimize routes and schedules, reducing fuel consumption and emissions [4]. In addition, sensor-equipped smart bins alert collection teams when they are full, preventing overfilling and ensuring timely waste removal. These innovative technologies streamline waste collection processes and help to monitor and manage waste levels more effectively, leading to a cleaner, greener environment.

New initiatives, such as community composting systems and reusable waste collection bags, further reduce the environmental impact of waste disposal. These improvements not only benefit the environment, but also contribute to the creation of more sustainable and livable communities for future generations [5].

Optimising waste collection routes and programmes is essential for modern waste management in urban areas. By effectively using advanced technologies such as GPS tracking and route-planning software, local authorities can increase operational efficiency, reduce costs, and lessen the environmental impact of waste transport [6].

Implementing smart waste collection solutions, such as sensors that monitor bin fill levels and notify collection teams when bins need to be emptied, further improves waste management practices.

Smart waste collection systems are transforming waste management in urban areas. These innovative systems use technologies such as sensors and data analytics to optimize the collection process, reducing costs and improving efficiency. By monitoring waste levels in bins in real-time, these systems can only schedule collection when bins are full, minimizing unnecessary lifts and reducing carbon emissions from collection vehicles.

IV. Emerging Technologies in Waste Management

Technology is playing an increasingly important role in the transition to a more efficient, sustainable and intelligent waste management system. In recent decades, digitalization, automation and artificial intelligence have opened new directions for optimizing waste collection, sorting and recovery. This chapter presents the most relevant emerging technologies applied in the municipal waste sector.

Modern technology is becoming an essential component in addressing the growing challenges of waste management in smart cities. This is also influenced by the growing demand for efficient, environmentally friendly and sustainable waste management solutions.

The main way in which IoT makes its presence felt is by incorporating smart devices and sensors into the urban landscape, tasked with monitoring and collecting waste data [4]. With a data-centric approach, this system allows for more efficient management of waste collection and disposal, transport logistics and recycling efforts. The waste management system can use integrated tracking and data sharing technologies, thus optimizing processes specific to the waste life cycle, such as collection, recovery and prevention of waste generation.

An IoT-based waste management system (fig. 3) comprises smart garbage containers equipped with sensors that monitor their fill level, allowing waste management and analysis in real time [6]. Data from these bins can then be transmitted wirelessly to a central hub, facilitating prompt waste collection and preventing overflow. The sensors installed in these systems also measure the weight and level of waste inside the trash can, communicating this information to waste management systems. This technological amalgam, with blockchain that provides traceability, transparency and audit features in a decentralized and secure manner, is proving essential in improving waste management.

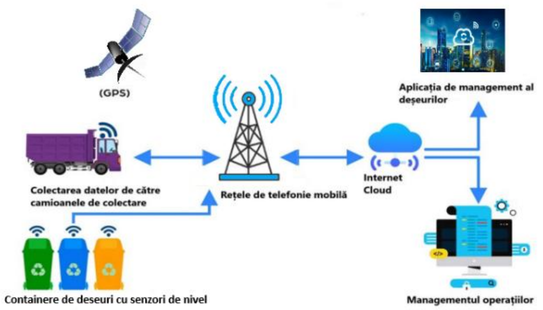

Fig. 3. General architecture of an intelligent waste management system

Long-range network (LoRaWAN) technology is a key technology for IoT architectures. This technology can support various services within the smart waste management system, including smart bins and storage containers that interact with users, as well as video surveillance units equipped with machine learning capabilities that can, for example, detect a potential fire.

Smart bin technology uses artificial intelligence to redirect waste efficiently, with minimal labor consumption and the lowest degree of traffic congestion. A smart basket can be made by combining several technologies, such as Artificial Intelligence of Things (AIoT), computer vision, robotics, RFID tags, near field communication (NFC), sensors, wireless sensor networks, compactors, actuators, smart monitoring systems, and dashboards. Thus, information about recyclable materials can be received directly by integrating the smart bin with a dashboard for real-time monitoring. Landfill companies can thus streamline their workflows and reduce the time it takes to check trash cans by using monitoring indications [7].

AI-based waste sorting technologies use equipment and software that use image analysis to sort recyclables with a much higher accuracy and recovery rate than conventional systems.

New technologies offer significant potential for the modernization of urban waste management systems. From automated collection and sorting to the integration of artificial intelligence and mobile apps, cities can become cleaner, more efficient, and more sustainable. However, implementing these solutions requires investment, collaboration between the public and private sectors, and the active involvement of citizens.

V. Limitations and future research

Despite its structured approach, this study acknowledges several limitations. The most significant constraint lies in its dependence on secondary data, which, although reliable, may not capture the full variability of local contexts or recent pilot projects. Differences in national reporting standards and temporal inconsistencies among datasets can also affect cross-comparability.

The case study component, while illustrative of best practices, does not constitute a statistically representative sample of all technological innovations in waste management. Each example reflects a specific local context and may not be generalizable to regions with different socio-economic or infrastructural conditions. Moreover, the absence of fieldwork or direct stakeholder interviews limits the empirical depth of the analysis, particularly concerning user behavior and organizational change.

Future research should therefore pursue empirical validation of the proposed evaluation framework through pilot testing, participatory observation, and cost–environmental modeling. Combining technical analysis with social research methods would offer a more comprehensive understanding of how technology can transform urban waste management toward sustainability.

VI. Conclusions

Urban waste management is one of the major challenges of modern society, especially in the context of accelerated urbanization and increased consumption. From the analysis carried out in this article, it is clear that traditional collection and storage methods are no longer enough, and the transition to a smart and sustainable model is not only necessary, but urgent.

New technologies, such as IoT sensors, artificial intelligence, collection automation, mobile apps and digital platforms, contribute significantly to optimising the entire waste management chain. These solutions not only streamline operational processes and reduce costs, but also bring important environmental benefits, by increasing the recycling rate, reducing pollution and actively involving citizens in waste sorting.

The transition to a modern system is possible and often brings tangible results in the short term. However, the success of these technologies depends on key factors such as political will, strategic investments, infrastructure development, and public environmental education.

In conclusion, the cities of the future will be those that adopt these innovative technologies early, transforming waste management from a chronic problem into an opportunity for sustainable, efficient and intelligent development.

Bibliography

[1] G. Voicu, Engineering of Ecological Landfilling of Solid Waste, Politehnica Press Publishing House, Bucharest, 2016.

[2] Eurostat (2023a). Municipal waste generated 2006 and 2021. Available online at: https://ec.europa.eu/ eurostat/statistics- principal_waste_statistics, 2023.

[3] European Parliament, Waste management in the EU in facts and figures (infographic), https://www.europarl.europa.eu/pdfs/news/expert/2020/11/story/20180328STO00751, 2023

[4] P. Nowakowski, K. Szwarc, U. Boryczka, Combining an artificial intelligence algorithm and a novel vehicle for sustainable e-waste collection, Science of The Total Environment, Volume 730, 2020.

[5] A.H. Farrokhi, A. Makui, R. Ghousi, M. Rabbani, Developing a hazardous waste management system with consideration of health, safety, and environment, *Computers & Electrical Engineering*, Volume 82, 2020.

[6] J. Lella, V. R. Mandla, X. Zhu, Solid waste collection/transport optimization and vegetation land cover estimation using Geographic Information System (GIS): A case study of a proposed smart-city, *Sustainable Cities and Society*, Volume 35, p. 336-349, 2017.

[7] O. V. Bold, G. A. Mărăcineanu, Storage, Treatment and Recycling of Waste and Materials, Matrixrom Publishing House, Bucharest, 2004.

[8] D. Căilean (Gavrilescu), C. Teodosiu, An assessment of the Romanian solid waste management system based on sustainable development indicators, *Sustainable Production and Consumption*, Volume 8, 2016

[9] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste
[10] Ministry of Environment and Climate Change, available at http://www.mmediu.ro/gestionarea-deseurilor/transport-depozitare-incinerare, Accessed: May 22, 2025
[11] Gestionarea deseurilor, available at http://www.mmediu.ro/beta/domenii/gestionarea-deseurilor/, Accessed: May 20, 2025
[12] Principiile gestionarii deseurilor, available at https://www.green-environment.ro/, Accessed: May 22, 2025