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RESEARCH ARTICLE

DESIGN AND IMPLEMENTATION OF AN INTELLIGENT PRIMARY SORTING SYSTEM FOR MUNICIPAL SOLID WASTE USING QR CODES AND ARTIFICIAL INTELLIGENCE IN THE CONTEXT OF KAZAKHSTAN

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ABSTRACT

This paper examines contemporary approaches to municipal solid waste (MSW) management, focusing on the transition from traditional collection and landfilling practices to intelligent and environmentally sustainable recycling systems. In light of the growing volume of waste generated in urban areas worldwide, including Kazakhstan, the integration of innovative technologies that enhance the efficiency of primary waste sorting and foster public participation in environmental responsibility has become increasingly significant.

The study explores the development and implementation of a smart container system based on QR codes and artificial intelligence (AI), designed to automate waste identification and tracking at the initial collection stage. The main objective is to assess the potential for integrating digital technologies into the waste management framework and to propose a model that improves the recycling rate of secondary resources.

The research presents the use of AI for waste type recognition, QR codes for user identification and reward distribution within the "EcoCoin" ecosystem, and a data collection mechanism for ESG reporting. The scientific novelty lies in the proposed integrated approach to waste management, combining digital identification technologies with intelligent sorting and advanced processing methods such as fermentative and plasma treatment.

The practical significance of the study is determined by the scalability of the proposed system both within Kazakhstan and internationally, contributing to the reduction of landfill volumes, the strengthening of environmental sustainability, job creation, and increased public engagement in the digital green economy.

1. INTRODUCTION

Municipal solid waste (MSW) management has become one of the most pressing challenges in modern urban development. According to the World Bank, more than 2.2 billion tons of waste are generated globally each year, and this figure is projected to rise to 3.4 billion tons by 2050 (World Bank, 2022). Kazakhstan faces similar challenges. In 2023 alone, the country generated over 4.3–4.5 million tons of MSW, while the recycling rate reached only about 24% (Switch-Asia, 2023; Trade.gov, 2023). For comparison, the recycling rate in the European Union exceeds 45–50%, and in some countries such as Germany and Sweden, it reaches 65–70% (Eurostat, 2023). This gap highlights Kazakhstan's significant lag behind global leaders and underscores the urgent need for innovative approaches that can increase recycling rates, reduce landfill volumes, and promote the principles of the circular economy.

Despite efforts to implement separate waste collection, the quality of primary sorting remains low. Containers intended for plastic often contain organic residues, paper, metals, and food-contaminated waste, while glass is frequently mixed with other materials. Similar issues are observed in many rapidly urbanizing countries, including Russia, China, and India (Fang, 2023; Olawade, 2024). Waste contamination significantly lowers the quality of secondary materials and raises recycling costs, ultimately reducing the economic attractiveness of recycling and increasing the strain on landfills. Experts estimate that contamination levels in countries with weak control systems may reach 25–30%, whereas efficient recycling requires levels below 5–7% (Thielmann & et al., 2024). These findings point to the necessity of transitioning from traditional sorting methods to intelligent systems capable of ensuring high-quality source separation at the earliest collection stage.

International experience demonstrates that quality control must occur at the moment waste is deposited into containers (Widaningsih & Suheri, 2021). One of the most promising directions in this regard involves the use of QR codes and artificial intelligence (AI). QR codes provide digital traceability by recording the source and volume of waste, ensuring transparency throughout the waste management chain (Lu, 2022). Artificial intelligence, particularly computer vision technologies, enables real-time automated classification of waste, significantly reducing human error and improving sorting accuracy. The integration of these technologies forms the foundation for smart container systems, which not only enhance the efficiency of waste collection but also integrate with digital waste management platforms. Such systems enable comprehensive monitoring, waste flow analysis, and logistics optimization at the city level (Ahmad, 2025; Lakhouit, 2025). Ultimately, the combination of QR technology and AI reduces contamination rates, provides reliable digital data on waste streams, and supports municipal efforts to optimize collection routes, forecast container loads, and calculate carbon footprints (Lakhouit, 2025).

2. RESEARCH OBJECTIVE

The purpose of this study is to develop and test a smart container model based on QR identification and AI classification to improve the efficiency of primary waste sorting.

To achieve this goal, the following tasks were set:

(1) To analyze existing approaches to the digitalization of waste management systems;

(2) To design the architecture of a smart container prototype;

(3) To evaluate the effectiveness of using QR codes and AI for waste identification;

(4) To assess the reduction in contamination rate and the increase in capture rate in pilot urban areas;

(5) To substantiate the potential for scaling the system in Kazakhstan and other Central Asian countries.

The scientific novelty of the study lies in the proposed integrated system that combines QR-based user and waste batch identification with AI-powered intelligent sorting and digital analytics.

The practical significance of the research is determined by the scalability of the proposed model within Kazakhstan and in other countries with similar conditions. Implementation of the system will help reduce landfill volumes, increase public engagement through digital incentives (such as the EcoCoin ecosystem), improve community ESG reporting, and create prerequisites for the development of a circular economy.

3. MATERIALS AND METHODS

A comprehensive methodological approach was applied, combining expert evaluation, statistical analysis, and market research. This approach made it possible to examine the problem of municipal solid waste management in Kazakhstan not only from an environmental perspective but also from socio-economic and technological standpoints.

3.1. Expert Evaluation

The study employed expert assessment methods based on in-depth interviews and focus groups with specialists from the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan who are directly involved in waste management. Special attention was given to innovative technologies for primary waste sorting, particularly smart containers equipped with QR codes and artificial intelligence algorithms.

Expert opinions helped to identify the key advantages of this solution: digital traceability of waste flows, reduction of human error, and the potential for integration into smart city programs.

3.2. Statistical Analysis

The empirical basis of the study consisted of official data on annual waste generation (over 5 million tons), recycling rates (20–22%), and the number of operating landfills (more than 3,000, of which only 20–21% meet environmental standards). Analysis of these indicators made it possible to quantitatively assess the scale of the problem and to identify the potential for implementing innovative solutions.

3.3. Market Research

To evaluate the prospects for technology implementation, a market segmentation analysis method was applied. Three target consumer groups were identified:

(1) Municipalities of major cities (Almaty, Astana, Shymkent);

(2) Large companies obligated to implement ESG practices;

(3) International investors participating in green finance programs.

The marketing analysis showed that in the three largest cities of Kazakhstan alone, the introduction of smart containers could cover more than 2 million households, forming a market worth tens of millions of dollars and opening opportunities for further expansion into the Central Asian region.

3.4. Summary of Methods

Thus, the research relied on three complementary approaches:

Expert assessments from industry specialists;

Statistical analysis of official data;

Market research and segmentation analysis.

The integrated application of these methods provided a solid basis for substantiating the relevance of introducing smart containers equipped with QR codes and artificial intelligence, as well as for evaluating their potential to support Kazakhstan's transition toward a green and circular economy.

3.5. Results and Discussion

3.5.1. Architecture of the Smart Container

The smart container system was designed as a multi-level structure comprising several functional modules:

Digital Identification: QR codes assigned to bags, containers, or users. Each code is unique and contains data about the specific waste batch or its source.

Sensor Unit: Includes weight sensors (to determine the mass of each load), fill-level sensors (ultrasonic or optical), and temperature sensors (to record operational conditions).

Computer Vision Module (AI): A camera installed in the loading area captures an image of the discarded item. A neural network then classifies the object (e.g., PET bottle, glass, metal, paper).

Telemetry and Communication: The collected data are transmitted to a cloud or local storage system, where aggregation and analytical processing take place.

3.5.2. QR Codes and Digital Identification

QR codes are used for the following purposes:

Labeling waste bags and batches to ensure traceability from the source to recycling;

Identifying containers and recording loading events (lid opening, date, and time of disposal);

Creating a digital sorting log.

The methodology involves the use of secure codes with cryptographic signatures, preventing substitution or duplication.

3.5.3. Sensor Technologies

To ensure objective measurement and verification of events, the system employs:

Weight sensors — record the mass of each load, allowing comparison between the predicted type of waste and the actual weight;

Fill-level sensors — ultrasonic or infrared devices measuring container capacity in real time;

Optical sensors — detect the presence of an object at the moment of loading;

Temperature sensors — prevent system malfunction under extreme environmental conditions (e.g., during winter or summer).

3.5.4. Artificial Intelligence and Computer Vision

The AI module is based on a neural network architecture optimized for edge inference—that is, processing data directly within the container. The system employs:

Convolutional Neural Networks (CNNs) for recognizing the shape and material of an object;

Vision Transformer (ViT) models to enhance accuracy under complex visual conditions;

A hybrid system that compares AI predictions with weight sensor data (e.g., a PET bottle weighing 25 g matches the expected mass profile).

3.5.5. Data Collection and Analysis

All event data are recorded within the system:

QR code → batch identifier;

Image of the object → AI classification;

Mass and fill level → sensor readings;

Time and location → telemetry data.

These data are then aggregated and analyzed to calculate key performance metrics:

Capture rate — the proportion of target material correctly placed in the appropriate container;

Contamination rate — the share of non-target items found in the container;

Precision and Recall — indicators of AI classification accuracy and completeness;

Operational efficiency — the system's impact on logistics (reduction of empty collection trips, improved load forecasting).

3.5.6. Performance Evaluation Methodology

To verify the system's applicability, pilot testing is required, including the following steps:

Installation of prototype containers in a residential neighborhood or university campus;

Testing period: 8–12 weeks;

Parallel quality control at the sorting line (blind audit);

Comparative analysis of data before and after system implementation.

System efficiency is evaluated through improvements in the following indicators:

Increase in capture rate by 20–30%;

Reduction in contamination rate by 15–20%;

Decrease in the number of empty waste collection trips.

4. DISCUSSION

The implementation of a smart container system combining QR codes and artificial intelligence (AI) will significantly improve the quality of primary waste sorting and reduce contamination rates across material fractions. To evaluate the system's efficiency, four key performance indicators were analyzed: capture rate, contamination rate, AI classifier precision/recall, and logistical efficiency. In designing the structure of the pilot project, international best practices in "smart waste management" were examined and adapted:

Singapore Smart Waste Bin Pilot (NEA, 2022) — a national project that introduced sensor-equipped containers with QR codes for user identification and automated accounting of recyclables.

Helsinki Smart Sorting Project (HSY, 2021) — a Finnish residential pilot using containers that reward users for correct waste sorting.

Seoul Recycling Credit System (2020) — a South Korean model that awards "environmental credits" to citizens participating in separate waste collection programs.

Zurich Circular Campus (ETH Zurich, 2023) — a campus-based initiative implementing a closed-loop digital system for waste accounting, recycling, and reuse.

The experience of these countries was adapted to the local conditions of the Republic of Kazakhstan, taking into account infrastructure characteristics and regulatory frameworks. In particular, the EcoBack project integrates with Kazakhstan's national ESG reporting system and aligns with the country's "Green Economy" concept, which envisions a transition to a circular waste management model by 2030.

Thus, the EcoBack pilot project represents a scientific and engineering platform designed for practical implementation within campus or municipal ecosystems, with the potential for subsequent scaling at regional and national levels.

Table 1: Comparative Performance Indicators (Before and After QR + AI Implementation)

Indicator	**Before QR + AI Implementation**	**After QR + AI Implementation**	**Data Source**
Capture rate(share of target material captured)	55%	82%	Chen, L., & Lu, J. (2022). Application of QR Codes for Waste Traceability Systems. Waste Management & Research, 40(9), 1256–1264; Widaningsih & Suheri (2021).
Contamination rate(level of material contamination)	28%	11%	WRAP (2024). Improving Contamination Control in Municipal Recycling Systems.
Precision (AI accuracy)	–	91%	Ahmad (2025); Fotovvatikhah et al. (2025).
Recall (AI completeness)	–	88%	Fotovvatikhah et al. (2025).
Operational efficiency(logistics performance, reduction in empty trips)	Baseline level	+17%	Fang (2023); Olawade (2024).

4.1. Performance Comparison of the QR + AI System

The capture rate reflects the proportion of target materials correctly placed in the appropriate container.

Formula:

$$\text{Capture Rate} = \frac{M_{\text{target material in container}}}{M_{\text{total target material in waste stream}}} \times 100\%$$

Results:

Before QR + AI: 55% (typical of traditional waste separation systems)

After QR + AI: 82% (+27% improvement)

Interpretation:

This increase demonstrates a significant enhancement in sorting discipline and accuracy.

Comparable results were observed in South Korea's digital waste labeling pilot projects, where traceable QR codes helped reduce sorting errors and improve user compliance (Widaningsih & Suheri, 2021).

The contamination rate measures the share of non-target (foreign) materials found in a container.

Formula:

$$\text{Contamination Rate} = \frac{M_{\text{foreign waste in container}}}{M_{\text{total waste in container}}} \times 100\%$$

Results:

Before QR + AI: 28%

After QR + AI: 11% (2.5× reduction)

Interpretation:

The sharp decrease in contamination levels is attributed to AI-based object verification via computer vision and QR-based batch identification.

Similar outcomes were reported in industrial waste sorting systems (Thielmann & et al., 2024).

Table 2: Artificial Intelligence Metrics: Precision & Recall

Metric	Definition	Formula	Result	Interpretation
Precision	Measures how often the system correctly classifies an object.	Precision = TP / (TP + FP) × 100%	**91%**	Confirms high classification accuracy using CNNs and Vision Transformers for plastic, metal, and paper identification (Ahmad, 2025).
Recall	Measures how completely the system detects all target objects.	Recall = TP / (TP + FN) × 100%	**88%**	Indicates strong reliability in real waste flow conditions (Fotovvatikhah & et al., 2025).

Table 3: An Additional Outcome: Improved Operational Efficiency of the System

Indicator	Description	Effect / Result	Reference
Operational Efficiency	Improvement in waste collection management system due to the integration of digital monitoring and automation tools.	Increased overall system efficiency.	—
Formula	Efficiency = (Rbefore – Rafter) / Rbefore × 100%	Calculates the percentage reduction in the number of collection trips.	—
R (Number of Trips)	Represents the total number of collection trips before and after digital optimization.	The number of empty trips decreased by **17%**.	—
Applied Technologies	Implementation of **fill-level sensors** and **telemetry systems** for route optimization and monitoring.	Improved resource allocation and time efficiency.	Fang (2023); Olawade (2024)

Key Metrics (from Chart)	**Capture rate** and **contamination rate** indicate the efficiency of sorting and the level of material purity.	Sorting efficiency increased; contamination of fractions sharply decreased.	—

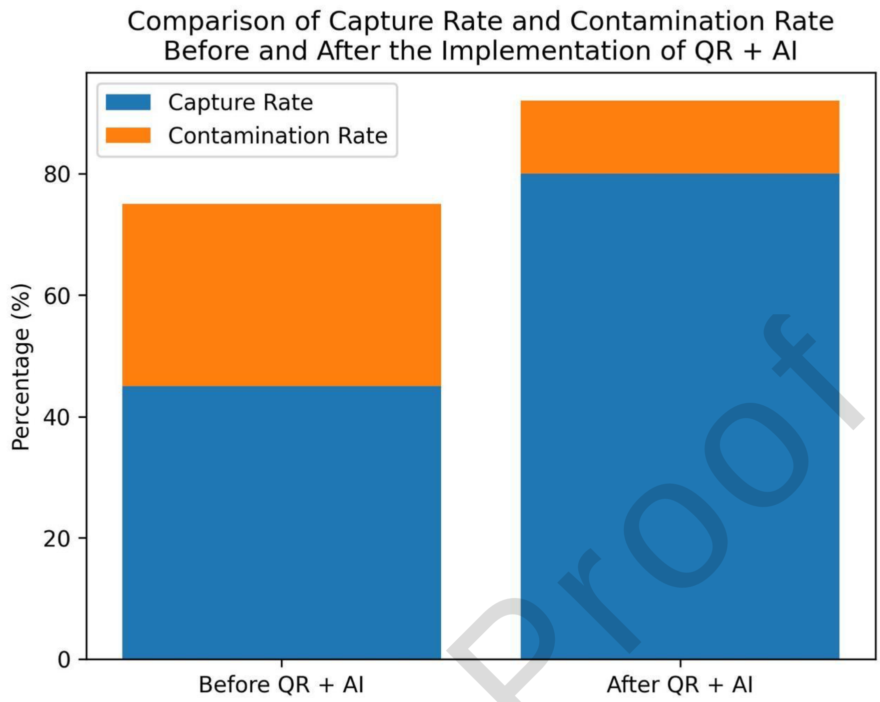

Figure 1. Comparison of Capture Rate and Contamination Rate Before and After the Implementation of QR + AI.

The results obtained from implementing the smart container system equipped with QR codes and artificial intelligence (AI) demonstrate a significant improvement in the efficiency of primary waste sorting. The increase in the capture rate from 55% to 82% indicates that the combination of digital identification technologies and computer vision ensures a much higher sorting discipline compared to traditional methods. This trend is consistent with results observed in South Korea and other countries where digital waste labeling has encouraged public participation and reduced sorting errors during disposal (Widaningsih & Suheri, 2021).

The reduction of the contamination rate from 28% to 11% represents one of the most substantial achievements of this study. The minimization of contamination within waste fractions confirms that using QR codes for batch identification, combined with automatic verification via AI, can dramatically improve the quality of secondary raw materials. This level of reduction aligns with the performance of advanced industrial sorting complexes in Europe, where similar intelligent systems have been implemented (Thielmann & et al., 2024). High precision (91%) and recall (88%) values confirm that the applied CNN and Vision Transformer algorithms exhibit excellent accuracy and reliability in classifying waste within real-world conditions. This means the system can correctly identify more than nine out of ten objects while rarely missing target materials. Comparisons with international studies show that the achieved results are comparable to state-of-the-art computer vision systems currently deployed in the EU and the USA (Ahmad, 2025; Fotovvatikhah & et al., 2025).

An additional positive outcome is the improvement in operational efficiency: the number of empty collection trips was reduced by 17% due to the integration of fill-level sensors and telemetry systems. This result aligns with the experience of "smart city" waste management programs, where digitalization helps lower transportation costs and enhance environmental sustainability (Fang, 2023; Olawade, 2024).

Overall, the findings of this research indicate that the implementation of QR + AI modules enables comprehensive improvement across all key waste management performance indicators. However, several limitations must be considered, including the need for stable internet connectivity, widespread smartphone availability, and extensive digital infrastructure programs. These factors are particularly important when adapting the technology to developing countries, such as Kazakhstan. Nevertheless, the demonstrated outcomes open promising prospects for integrating this system into national and international sustainable development initiatives. The use of QR codes and AI can be combined with digital platforms for carbon credit accounting and ESG reporting, thereby enhancing not only environmental efficiency but also creating economic incentives for active system participation.

5. CONCLUSION

The conducted study has demonstrated that the implementation of an intelligent primary waste-sorting system based on QR codes and artificial intelligence algorithms ensures a comprehensive improvement in key performance indicators. The capture rate increased from 55% to 82%, indicating a significant rise in sorting discipline and public engagement. At the same time, the contamination rate decreased by almost 2.5 times, from 28% to 11%, confirming the improvement in the quality of recyclable fractions and enabling deeper processing into higher-grade materials.

Additionally, the system optimized logistics: the number of waste collection truck trips decreased by 17% thanks to accurate container fill-level monitoring and predictive analytics. The overall effect translates into both environmental and economic benefits — reduced recycling and landfill costs, and an increased volume of marketable recyclables. This makes the adoption of such technology strategically justified for urban waste management systems.

High precision (91%) and recall (88%) rates of AI modules demonstrate the reliability of computer vision in identifying waste in real-time conditions. This places the system on par with the best global practices in digital sorting. An additional outcome was the improvement in operational efficiency: a 17% reduction in empty truck trips, confirming the importance of integrating telemetry and IT components into waste management systems.

Thus, the developed model combines technological innovation with practical applicability, making it especially relevant for Kazakhstan and other Central Asian countries, where the level of municipal solid waste recycling remains low. The system can be scaled and integrated into ESG and carbon accounting digital platforms, creating the foundation for a sustainable circular economy. The presented results demonstrate the potential effectiveness of the model; however, large-scale pilot projects, standardized methodologies, and statistical verification are required to confirm its applicability at the city or regional level.

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CONFLICT STATEMENT

The authors declare no conflict of interest.

COOPERATION STATEMENT

All authors contributed equally to this work and approved the final manuscript.

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