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SORTCYCLE: Intelligent Automation System for the Sustainable Management of Solid Waste in Panama

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Abstract

Panama faces significant challenges in solid waste management due to rapid urbanization, population growth, and limitations in waste collection and recycling infrastructure. Although the country generates approximately 4,400 metric tons of municipal solid waste daily, a considerable portion is improperly disposed of in informal dumping sites or reaches rivers, coastal ecosystems, and other natural environments. This inadequate waste management contributes to environmental degradation, public health risks, and the loss of valuable recyclable materials, highlighting the need for intelligent and scalable technological solutions. This work proposes *SortCycle*, a smart waste management system that integrates sensor-based identification, automation, and digital monitoring to improve the classification and traceability of recyclable materials. The proposed system aims to increase classification efficiency, reduce cross contamination, generate real-time operational data, and support informed decision-making. By promoting efficient recycling practices and supporting the principles of a circular economy, *SortCycle* offers a scalable technological approach that contributes to sustainable waste management and innovative development.

Keywords
Waste classification, circular economy, smart waste management, Industry 4.0, Internet of Things (IoT).

1. Introduction
Solid waste management has become one of the most pressing environmental and socioeconomic challenges worldwide. Rapid urbanization, population growth, and increasing consumption patterns have significantly accelerated the generation of municipal solid waste, placing unprecedented pressure on existing collection, treatment, and disposal systems. According to global projections, municipal solid waste generation is expected to increase from approximately 2.1 billion metric tons in 2020 to more than 3.8 billion metric tons by 2050, underscoring the urgent need for innovative, scalable, and sustainable waste management strategies.

This challenge is particularly significant in developing countries, where limitations in infrastructure, technological adoption, and institutional capacity hinder effective waste management. In Panama, municipal solid waste generation is among the highest in Central America, with an estimated per capita production of 1.0–1.2 kg per day. Panama City alone generates more than 2,500 metric tons of solid waste daily, placing considerable strain on collection services and disposal facilities.

Although national initiatives such as Law No. 33 of 2018 (*codenamed* "*Basura Cero", meaning "Zero Trash"*) and Law No. 276 of 2021 have established a regulatory framework for integrated solid waste management, implementation remains constrained by fragmented institutional coordination, limited recycling infrastructure, and low public participation (Buendía et. al). Consequently, a substantial proportion of recyclable materials is either disposed of in

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landfills or improperly discarded in informal dumping sites, rivers, and coastal ecosystems, resulting in environmental degradation, public health risks, and the loss of recoverable resources that could otherwise support a circular economy.

Recent advances in technology provide new opportunities to modernize waste management processes. However, existing waste sorting solutions often overlook the socioeconomic and infrastructural context of developing countries. This technological gap highlights the need for affordable, modular, and scalable systems capable of improving both waste classification efficiency and resource management.

To address these challenges, we propose the development of an intelligent waste management system that integrates sensor-based waste identification, classification, and digital monitoring into a unified platform. The proposed system is designed to improve waste classification accuracy, decrease cross contamination risks, enhance the traceability of recyclable materials, and generate real-time operational data to support informed waste management decisions. By combining intelligent automation with the principles of circular economies and Industry 4.0, *SortCycle* seeks to contribute to more sustainable, efficient, and data-driven waste management practices while providing a scalable technological framework specifically designed to address the operational, infrastructural, and socioeconomic realities of Panama and other Latin American countries.

1.1 Objectives

General Objective

To design, develop, and evaluate an intelligent waste management platform based on automation and digital technologies that improves waste classification, traceability, and recycling efficiency through a scalable and sustainable approach.

Specific Objectives

- Design a retrofit module for existing recycling containers.
- Develop a system for automated material identification and classification.
- Implement an IoT-based monitoring platform for real-time waste traceability.
- Evaluate the technical performance and user acceptance of the proposed system through a pilot deployment.
- Identify opportunities for improving sustainability, scalability, and adaptation to the Panamanian context.

2. Literature Review

2.1 Smart Waste Management and Circular Economy

The increasing generation of municipal solid waste has intensified the need for sustainable waste management strategies that integrate environmental, economic, and social objectives. Circular economy principles have emerged as a key framework for reducing waste generation while maximizing the recovery and reuse of valuable materials. Studies have shown that effective recycling systems not only reduce environmental pollution but also generate measurable socioeconomic benefits through job creation, resource conservation, and improved public services (Gutberlet, J. (2012), Hysa et. al (2020)). Likewise, successful recycling initiatives demonstrate that technological innovation combined with community participation can significantly improve waste recovery rates and promote sustainable urban development.

2.2 Technological Advances in Intelligent Recycling Systems

Recent developments in intelligent waste management have incorporated embedded systems, Internet of Things (IoT) technologies, sensors, and artificial intelligence to automate waste classification and improve operational efficiency. Smart recycling stations equipped with material recognition capabilities and automated decision-making mechanisms have demonstrated the potential to reduce human error during waste separation while generating valuable operational data for monitoring recycling activities (Lakhouit, A. (2025)). These technologies contribute to the digital transformation of waste management by enabling real-time monitoring, traceability, and data-driven decision-making, providing a foundation for future smart city applications.

2.3 User Behavior and Public Participation

Technological solutions alone are insufficient to improve recycling performance without considering user behavior and public engagement. Research conducted in Panama highlights that recycling habits remain limited due to insufficient environmental awareness, lack of incentives, and inadequate infrastructure for waste separation (Lasso,

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S. (2024)). Similarly, Chang, I. (2014) emphasizes that behavioral models incorporating incentives can significantly increase citizens' willingness to separate waste at the source, creating opportunities for both environmental improvement and entrepreneurial initiatives. Educational campaigns and community-based programs, such as those promoted by educational and environmental institutions, further demonstrate that public participation plays a critical role in the long-term success of recycling initiatives by fostering environmental responsibility and encouraging sustainable practices.

2.4 Research Gap

Although previous studies have explored the environmental benefits of recycling, behavioral factors influencing waste separation, and recent advances in intelligent recycling technologies, relatively few efforts integrate these components into a unified platform specifically designed for the operational and socioeconomic context of Panama and other Latin American countries. This gap highlights the need for affordable and adaptable intelligent waste management systems capable of improving both operational efficiency and citizen participation.

3. Methods

This research follows a **Design Science Research (DSR)** methodology, focused on the iterative design, development, implementation, and evaluation of an intelligent waste management system. The study aims to develop a technological solution that improves waste classification, minimizes cross-contamination between recyclable materials, and enables digital traceability throughout the waste collection process. The proposed system is intended to be accessible, user-friendly, environmentally sustainable, and scalable for deployment in educational institutions and other public or private environments within Panama and Latin America.

The first prototype for the proposed solution consists of retrofitting existing recycling containers with an embedded sensing and automation module capable of assisting users during waste disposal. The prototype integrates proximity sensors to detect user interaction, material identification sensors to classify incoming waste, and a decision system that determines whether the deposited item corresponds to the designated recycling category. Depending on the classification result, the system either accepts or rejects the material while providing immediate educational feedback through positive and informative messages that encourage correct recycling practices.

To support digital transformation and data-driven waste management, each smart container incorporates a monitoring subsystem capable of recording the quantity and type of materials collected, container fill levels, collection and emptying events, and other operational metrics. This data is then transmitted through a low-power communication network to a digital platform, allowing real-time visualization, historical analysis, and operational traceability of the recycling process. The system architecture is expected to operate using renewable energy sources whenever feasible, reducing operational costs and improving long-term sustainability.

The initial pilot implementation will be conducted at Universidad Latina de Panamá through the retrofit of existing recycling bins. This pilot environment provides a controlled setting to evaluate both the technical performance and user interaction with the proposed system before larger-scale deployment (Figure 1).

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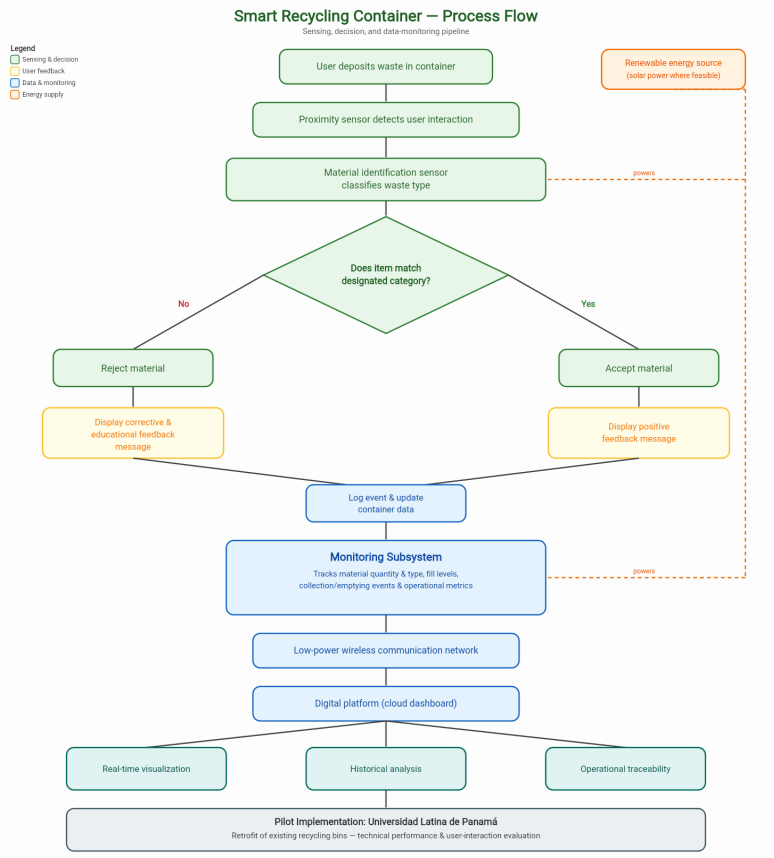


Figure 1. Process flow diagram of recycling operation.

4. Data Collection

During the pilot phase, two categories of data will be collected. The first comprises technical and operational data, including material classification accuracy, quantities of recyclable materials deposited, fill-level evolution, collection frequency, and system reliability. The second includes user-related information, such as acceptance of the proposed interaction model, frequency of correct and incorrect disposal attempts, and behavioral trends observed among students, faculty, and administrative personnel. This data will support subsequent iterations of system refinement and optimization.

The development process follows an iterative prototyping approach in which each implementation cycle incorporates the analysis of collected data, identification of system limitations, and integration of hardware and software improvements. This methodology seeks to progressively evolve the prototype into a fully functional, intelligent, and sustainable waste management platform adapted to the operational and socioeconomic context of the institution, while maintaining the flexibility required for future expansion across the country (Figure 2).

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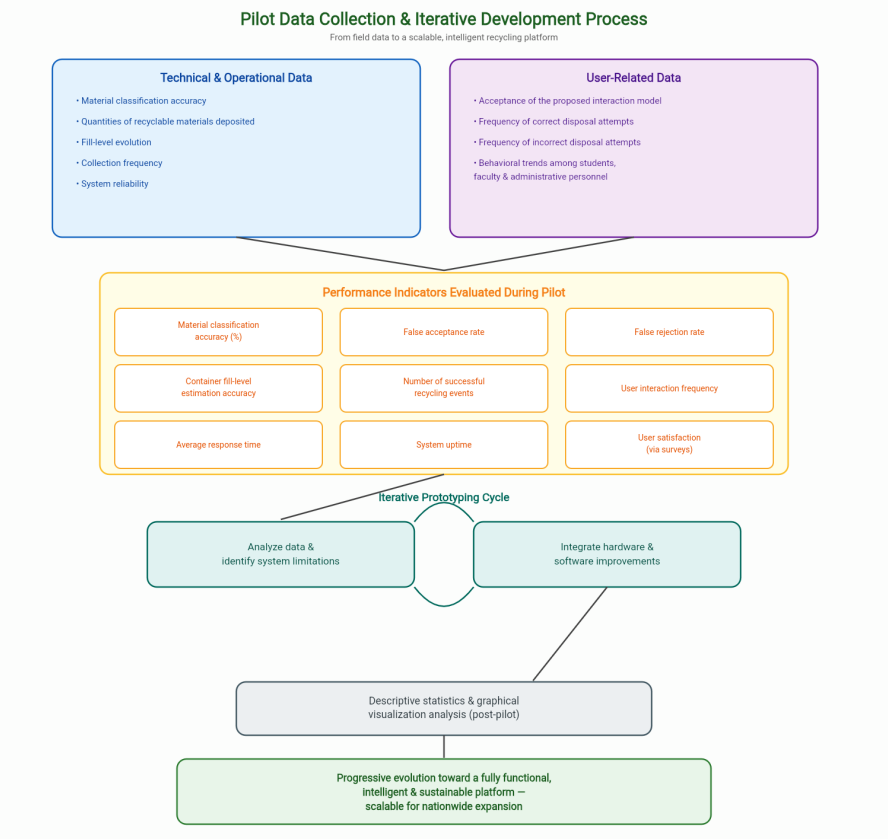


Figure 2. Diagram of proposed data collection and analysis techniques.

5. Results and Discussion

5.1 Expected Outcomes

The proposed pilot implementation is expected to demonstrate the feasibility of integrating user interaction, sensor-based classification, and digital monitoring into a unified smart recycling platform. Specifically, the system is expected to:

- Improve the accuracy of waste separation.
- Reduce cross-contamination between recyclable materials.
- Increase user awareness through real-time educational feedback.
- Generate reliable operational data for waste management.
- Demonstrate the feasibility of retrofitting existing recycling infrastructure.

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5.2 Planned Evaluation Metrics

During the pilot deployment, the following performance indicators will be evaluated:

- Material classification accuracy (%)
- False acceptance rate
- False rejection rate
- Container fill-level estimation accuracy
- Number of successful recycling events
- User interaction frequency
- Average response time
- System uptime
- User satisfaction (through surveys)

These metrics will be analyzed using descriptive statistics and graphical visualizations following completion of the pilot study.

5.3 Proposed Improvements

Future development of *SortCycle* will focus on expanding the system into a comprehensive intelligent waste management platform through iterative improvements in sensing, automation, and data analytics. Planned enhancements include the integration of computer vision and machine learning algorithms to improve material identification accuracy, the implementation of predictive analytics for optimizing waste collection schedules and resource allocation, and the adoption of low-power wide-area communication technologies and renewable energy sources to increase autonomy and scalability.

Additional research will explore user-centered features such as gamification, mobile applications, and incentive mechanisms to encourage proper recycling behavior and strengthen community participation. Furthermore, the platform will be designed to support interoperability with smart city infrastructures, enabling municipalities and organizations to leverage real-time data for evidence-based environmental decision-making. These developments aim to establish *SortCycle* as a scalable, sustainable, and adaptable solution tailored to the operational and socioeconomic context of Panama, with the potential for deployment throughout Latin America.

5.4 Validation

The proposed system will be validated through a pilot implementation at Universidad Latina de Panamá. Validation will include both technical and user-centered evaluation. Technical validation will assess classification accuracy, system reliability, communication performance, and operational stability. User-centered validation will be conducted through surveys and observational studies to evaluate usability, accessibility, and user acceptance.
Statistical analyses, including descriptive statistics and hypothesis testing where appropriate, will be performed once sufficient operational data has been collected.

6. Conclusion

This paper presented the conceptual design and research methodology of *SortCycle*, an intelligent waste management platform that combines principles of automation, traceability, and digital technologies to address current challenges in municipal waste classification and recycling.

Rather than replacing existing waste management infrastructure, the proposed approach seeks to enhance it through the retrofit of conventional recycling containers with intelligent classification capabilities, automated decision-making, and real-time monitoring capabilities. The planned pilot implementation at Universidad Latina de Panamá will provide the foundation for evaluating the system's technical performance, usability, and scalability while generating valuable operational and behavioral data to guide future improvements.

By integrating the principles of Industry 4.0, the Internet of Things, and the circular economy, *SortCycle* has the potential to contribute to more sustainable, data-driven waste management practices tailored to the needs of Panama and adaptable to other Latin American contexts.

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Biographies
Ana Freitez is a Mechatronics Engineering student at Universidad Latina de Panamá with a multidisciplinary focus that bridges engineering, creativity, and human-centered design. As President of the IEEE Robotics and Automation Society (RAS) Student Chapter at her university, Ana has led technical initiatives, engineering events, and collaborative projects that encourage innovation and knowledge sharing among students. Her academic interests span robotics, IoT, machine learning, industrial automation, and sustainability, with a growing emphasis on research and scientific communication in the development of projects such as SortCycle. Driven by curiosity and the principle of lifelong learning, Ana aspires to become a multidisciplinary professional whose work integrates engineering excellence with creativity to develop innovative technologies that address meaningful global challenges.

Cristell Cedeño is a Mechatronics Engineering student at Universidad Latina de Panamá, where she has focused her education on integrating programming and automation to develop innovative technological solutions. She is currently in the early stages of developing the project SortCycle, an automated waste classification system she is building in collaboration with her project partner Ana Freitez, through which she has strengthened her skills in teamwork, analysis, research, and problem-solving. Alongside her academic training, she has actively participated in engineering student organizations, such as her institution's IEEE Student Branch, contributing to the planning and execution of academic and technological activities aimed at promoting learning and innovation among students. These experiences have helped her develop leadership, organizational, and communication skills. Her main areas of interest include robotics, applied artificial intelligence, the Internet of Things (IoT), and the development of technologies aimed at improving quality of life and sustainability. She considers scientific research an essential tool for generating knowledge and proposing solutions to society's current challenges. Her professional goal is to contribute to the

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development of innovative technologies with a positive impact on industry and society, participating in research projects that advance scientific and technological progress both in Panama and internationally.

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