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Technological Innovation and Circular Economy: Smart Containers and Real-Time Monitoring for Efficient Waste Management

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Abstract: Inefficient municipal solid waste management represents a significant obstacle on the transition towards a circular economy in densely populated urban environments, such as the district of San Juan de Lurigancho, Lima, Peru. This study presents the implementation of advanced technologies, specifically smart containers integrated with sensors and real-time monitoring systems, to optimize waste collection. This resulted in decrements in operating costs and unrecycled waste by 20% and 27%, respectively, whilst increasing citizen engagement by 18% regarding segregation and recycling activities, highlighting positive changes in community behavior. However, the present technological infrastructure, technical training and necessary funds are all insufficient, which presents limitations on the deployment and scalability of these measures. This study thusly indicates the necessity to elaborate public policies, environmental education and engagement strategies to guarantee system stability. These findings both provide a replicable model to address these issues and offer a roadmap for the integration of smart technologies in sustainable city planning, bridging technological innovation and sustainability.

Keywords: circular economy; IoT sensors; waste management

1 INTRODUCTION

One of the greatest challenges in modern cities is proper waste management, only exacerbated by a quick population growth and following overstress of resources. It is estimated in the Global Waste Management Outlook 2024 [1] that municipal solid waste generation will increase from 2.3 billion tons in 2023 to 3.8 billion tons by 2050, being a 65% increase in less than three decades. This necessitates for collection, treatment and disposal infrastructures, especially in densely populated areas. In addition, improper management contributes to 5% of global greenhouse gas emissions, worsening the climate crisis [2]. This makes the implementation of smart technologies an unavoidable solution to mitigate these adverse effects. The integration of advanced sensors, real-time monitoring and route optimization algorithms has proven to better operational efficiency and reduce costs, minimizing environmental footprint. However, structural, financial and regulatory barriers persist, hindering the scalability of these innovations. This study analyzes the impact of these technologies on the sustainability of urban waste management and their role in the transition to an efficient and resilient circular economy.

These obstacles are also present in San Juan de Lurigancho (SJL), the most populous district in Lima with over 1.1 million inhabitants. The district faces a critical waste crisis, where 40% of residents perceive the current management as 'deficient' or 'very deficient'. Despite some environmental awareness, only 25% of the population consistently practices waste segregation at home. Furthermore, the existing infrastructure struggles with traditional collection routes that do not meet the demand of its high density. Addressing these challenges requires a shift from linear models to a circular economy, supported by the technological interventions proposed in this study to improve collection efficiency and community participation.

The circular economy changes the perception of waste management, promoting the reduction, recycling and reuse of materials. According to [3], it seeks to keep the value of materials and products for as long as possible, allowing production systems to reintroduce them to their cycles, generating less waste. To be effective, it should be complemented with smart technologies to optimize waste management, finally encouraging sustainable and efficient practices in densely populated urban areas, such as SJL.

Technological solutions, like smart containers and waste management systems with real-time monitoring, In this study, the system was implemented in San Juan de Lurigancho from March 2024 to February 2025, involving the deployment of 50 smart containers with a capacity of 1,100 liters each. To ensure precise monitoring, these units are equipped with HC-SR04 ultrasonic sensors controlled by an ESP32 microcontroller. The sensors emit high-frequency sound waves to measure the fill level in real-time. This data is transmitted via a GSM/GPRS wireless module using the MQTT protocol to a centralized cloud platform.

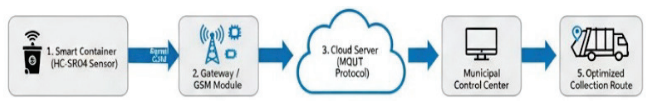

Figure 1 Data communication flow between smart containers and the management system

This architecture allows the system to visualize capacity and generate optimized collection routes based on actual container occupancy, replacing fixed schedules. These technological solutions prove to be effective in various studies. For example, [4] concluded that the use of sensors in containers favors the planning of collection routes and lowers operation costs. Likewise, [5] exposed that these technologies optimize efficiency and improve transparency in waste management, fostering trust and citizen participation.

Recent research [6] found that using Internet of Things (IoT), advanced algorithms and cloud analytics can bring significant improvements. Among these, there was a 32% more efficient routing, 29% less fuel consumption and 33% better performance in waste processing. The wide spectrum of effects these enhancements brought hint at the potential of these technologies to improve the economic, operational and environmental areas of municipal waste management.

A circular economy could also help to build a sustainable and efficient waste management. However, in the context of urban settings like SJL, there are noticeable limitations to their adoption. These include economic and infrastructural constraints, along with limited technical expertise among operators. This commonly happens in developing countries, where the socioeconomic setting can restrict technological progress, requiring for thorough strategies that promote the integration, innovation and strengthening of technologies and institutions [7].

These results show the need to integrate advanced technologies in solid waste management to enhance sustainability and efficiency. However, the constraints found in places like San Juan de Lurigancho restrict proper implementation. These include reduced budgets, deficient infrastructure and poor operator training, remaining as obstacles to development. To address them, it's needed to procure innovative technologies, stronger institutions and increased community participation.

This article builds upon previous work about smart waste management by evaluating the implementation of modern technologies in densely populated urban areas with infrastructural and economical restraints, as is the case of San Juan de Lurigancho, a district of Lima in Peru. While most other studies focus places with better infrastructure or better funding, this research produces evidence on the integration of technological innovations, along with the participation of local communities, carefully designed education and the addition of supporting policies. With this, the study tends to gaps identified in other works and suggests a scalable approach that can be adapted to other urban settings under similar constraints.

The study's main goal is to assess the situation and suggest technological innovations for better management of solid waste in San Juan de Lurigancho, easing the transition to a circular economy. It focuses on sustainability and modern technologies, along with technical and economic feasibility for the local setting. It also designs strategies to connect innovation, technology, community engagement and institutional strengthening, with their union as a vital component of the circular model's success.

Beyond its practical application, its focus is building a scalable, replicable model that adjusts to other urban settings. With this, it warrants valuable improvements in environmental sustainability, operational efficiency and socioeconomic development, placing the foundations to implement public policies emphasizing an integrated waste management.

This study has a mixed design, with elements both quantitative and qualitative used to understand the environmental, economic and social implications of implementing innovative technologies for solid waste management. This hybrid design produces useful information for better decision making, supporting the optimization of urban waste collection and treatment.

On this research, the quantitative indicators selected for analysis include the reduction of unrecycled waste, advanced algorithms for route optimization and greater involvement of the community in separating and recycling waste. On the qualitative side, it gathers the perceptions and behaviors of local participants to discover opportunities and obstacles to implement these technologies.

The purpose of this design is to evaluate the possible outcomes and explore the interaction between emerging technologies and community dynamics. Municipal solid waste management should be thoroughly addressed by technological tools, environmental education and strategies for social participation [8].

The results of this study will help to design optimized pathways and strategies for more efficient operation for more sustainable and affordable practices. Its final goal is to create a management model that is replicable in other urban contexts, specifically by testing whether IoT-enabled bins can reduce the number of collection trips by 20% within six months and if awareness campaigns can increase the recycling rate by 10 percentage points within a year. These expected outcomes provide a clearer sense of the study's analytical focus, ultimately helping to transition into a circular economy.

Using a qualitative analysis will allow to collect subjective information, like the perspectives of the citizens. This allows us to detect possible practical obstacles and yields detailed information about waste management. With this, the study seeks to improve quality of life, lower negative environmental impacts and increase economic sustainability for San Juan de Lurigancho. This also supports one of the UN's Sustainable Development Goals [9], specifically procuring a sustainable consumption and production, through the design of compliant policies.

Using multi-objective methods to locate waste accumulation can significantly improve the performance of waste collection in actual urban conditions [10]. Similarly, optimizing micro-route sequencing and examining transfer station adequacy prove to be effective in Argentinian cities [11]. Because of this, improving the efficiency of waste management requires strategies that incentivize community engagement and institutional strengthening.

Circular economy policies are essential for optimum resource usage and the mitigation of pollution in developing cities [12]. In fact, this study not only looks for short-term improvements for the San Juan de Lurigancho population, but also sets the groundwork for public policies that can be replicated both nation-wide and internationally. Implementing sustainable waste management strategies has environmental and economic benefits, offering a scalable management model for regions under similar conditions.

2 LITERATURE REVIEW

In this research, there are included theories and procedures that support the connection between technological innovation, the circular economy and an efficient management of municipal solid waste. These are theoretical bases that support digitization, process optimization and adopting emergent technologies as crucial to develop sustainable waste management models. Some relevant factors for understanding include the following.

2.1 Circular Economy

In contrast to the usual linear manufacturing model, the circular economy allows a deep understanding of economic, social and economic sustainability. This model promotes the sustainable production and delivery of goods and services, lessening the negative effects of more traditional management systems while using resources more efficiently throughout their lifecycles [3]. Similarly, it is a structural change in how society views the environment by reducing resource scarcity and enabling sustainable growth via the optimization in the use of materials and their regeneration [13]. Implementing circular approaches is motivated by a persistent lack of raw materials for industry, caused by the overexploitation of resources and poor management.

The implementation of circular economies has effects on different scales. At the smallest level, they encourage sustainable business and consumer practices; at the medium level, they help in coordinating actors for a greater resource efficiency; and at the largest level, they influence national and local policies, enabling closed resource loops that minimize waste and increase industrial performance [14]. As a result, it's an essential component to address the current ecological crisis on a global scale and to develop sustainable and efficient industrial methods.

A central economy has three core principles that seek to transform the global production and consumption models into a regenerative and sustainable system. The first is the preservation and increase of natural capital with the efficient management of renewable resources and supporting technologies with a lower impact on the environment, thus aiding in the recovery of ecosystems and securing essential raw materials on the long term [13]. The second principle is resource optimization through product and process redesigns that comply with circularity criteria.

Recirculating material within biological and technical loops, through reuse and recycling, is vital to reduce waste and lengthen product lifetimes [14]. This reduces demand for virgin inputs and lowers the energy and environmental burdens of extraction and processing. The third principle emphasizes system-wide efficiency by limiting the social and environmental harms of economic activity, from reducing toxic substances and emissions to improving mobility, food, and health systems [13]. Applying these principles both quickens the transition to a more sustainable economy also allows innovation, investment and technological development that bolster urban resilience to emerging environmental and socioeconomic risks.

The circular economy has broad benefits across economic, environmental, business, and social dimensions. As noted in [3], it spurs growth by optimizing resource use, lowering production costs, and innovating areas like reverse logistics and energy efficiency. It also creates jobs in small and medium industrial enterprises, reinforcing resilience and competitiveness. Environmentally, circular strategies can cut CO_2 emissions by up to 50% by 2030, decrease raw-material extraction, and help mitigate climate change [3].

For firms, the model reduces supply chain upsets, lowers costs by recycling input, and deepens customer loyalty through engagement and responsible consumption [14]. For citizens, this model improves quality of life by extending product durability and discouraging planned obsolescence [13]. Beyond these general benefits, empirical studies in Latin America, such as those conducted in Argentinian and Peruvian urban centers, demonstrate that successful implementation depends on integrating local data with specific micro-route sequencing and community participation methodologies [11].

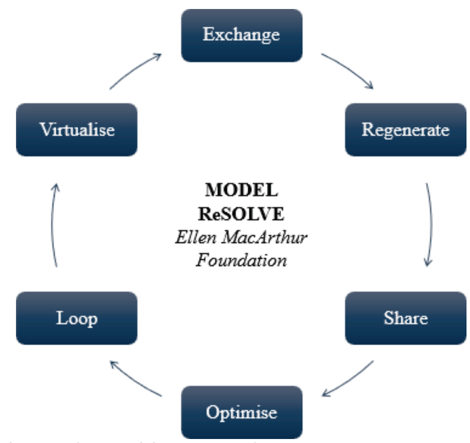

Figure 2 Stages of the ReSOLVE model for the transition to a circular economy, including strategies for regeneration, sharing, optimization, looping, virtualizing, and exchanging. Source: Ellen MacArthur Foundation [15]. Author's elaboration**.**

The ReSOLVE model, as designed by the Ellen MacArthur Foundation [3], has six core strategies to implement a circular economy, regenerating resources, optimizing processes and achieving digital transformation. The first one, regeneration, increases the use of renewable energies and the restoration of ecosystems by reintroducing biodegradable matter into natural cycles, increasing environmental resilience and limiting dependence on finite resources [14]. At the same time, sharing and optimizing strategies could promote a better management of assets and materials by placing reusability and long product lifespans as priorities to reduce waste.

Remanufacture and recycling, core elements of closed loop strategies, are critical for a continued circulation of materials and lowering the demand of raw input [13]. In the same way, digitalization transformed the management of consumption and waste by virtualizing services and processes, improving operational efficiency [3]. Lastly, phasing obsolete materials for more advanced options boosts innovation and business sustainability. As Mauricio Canu (in [3]) emphasizes, successful application of ReSOLVE hinges on integrating corporate social responsibility, eco-design, and adaptation to innovative processes, yielding a more efficient, sustainable, and competitive production model.

2.2 Efficient Waste Management Technology Solutions

Advanced technologies reshaped waste management by optimizing collection, treatment, and final disposal. Innovations span from end-to-end digitization to automated systems that polish operations for greater efficiency and sustainability. For example, smart sensors enable real-time tracking of container fill levels, improving route planning and cutting operating costs and collection-related emissions. In parallel, applying artificial intelligence (AI) to sorting has increased the accuracy of identifying recyclables, raising recovery rate and reducing landfill disposal [7].

Automation in treatment facilities through robots and high-precision sorting has boosted processing efficiency, reduced human intervention and errors. Beyond operational gains, these tools support the shift to a circular economy, where waste becomes a resource that reenters production cycles. Adopting such technologies is critical to meet current environmental challenges and advance sustainable management practices [7].

Integrating technological solutions has also modernized core practices by creating more efficient and sustainable approaches. In collection and transport, sensors installed in containers permit live monitoring of fill levels, which optimizes routes and lowers both operating costs and CO_2 emissions. The use of electric and automated vehicles further improves efficiency and lessens environmental impacts. In treatment, anaerobic digestion facilities convert organic waste into biogas, generating renewable energy and reducing the volume of organics sent for disposal [16].

Furthermore, thermal technologies, like pyrolysis and gasification, break down solid waste for energy production while notably reducing the amount to be finally discarded. Using AI and robotics aided systems on recycling operations helps to efficiently sort materials, increasing resource recovery. By using specific procedures to recover valuable metals and treat hazardous components appropriately, e-waste recycling also evolved, minimizing environmental risks. When combined, these technologies have the potential to improve management systems and promote ecologically conscious behavior [16].

Using waste management technologies enhances the social, economic and environmental areas. This saves expenses and operating times by increasing efficiency at every step of waste-related operations, from collection to final treatment [17]. For instance, using sensors to track container fill levels enables effective route planning and lowers CO_2 emissions from transport. This shows that these solutions promote sustainability by reducing negative environmental effects, lessening waste generation and easing the transition to a circular economy.

Since these systems can be implemented in a variety of conditions, such as urban and rural areas as well as other nations, regardless of development, another perceived advantage of the circular economy is its adaptability [18]. Therefore, aside of increasing resource efficiency by promoting reuse and recycling, it minimizes environmental risks through the efficient treatment and recycling of waste, lessening pollution in soil, air and water. This also benefits public health because proper management avoids needless exposure to hazardous waste and reduces the risks of inadequate practices. Overall, integrating emerging technologies improves operations and has a significant positive impact on society and the environment [18].

2.3 Technological Solutions in a Circular Economy

Integrating innovative technology to enable a thorough use of resources through reuse and recycling is crucial for a shift from linear production models to a circular economy. This implies creating recyclable goods and materials and implementing intelligent systems for resource optimization and waste management. Incorporating sensors and IoT into products and infrastructure allows to accurately track and monitor materials, aiding in process optimization and improving decision making in circular models.

Additionally, gathering and analyzing large datasets can yield useful knowledge to improve resource management and decision making in circular systems. Data on trends, chances to improve and greater resource efficiency can be obtained through a thorough study, leading in cost savings and waste reductions [19]. Beyond process enhancements, these technologies support the development of new business models that adhere to sustainability and environmental responsibility, both principles of the circular economy.

Adopting innovative technologies in many areas is essential to transition into a circular economy. On this regard, eco-design revolves around designing things with consideration for their whole lifecycle, from material selection to recycling and reuse, lowering their environmental impact from the start. A known example is 3D printing, which is a critical tool for environmentally friendly construction, creating structures with recycled materials and noticeably cutting down on waste. Overall, these technologies contribute to a more sustainable and efficient production process while also encouraging innovation in business models that follow circular economic principles, fostering a more responsible resource management and reducing their environmental impact [20].

2.4 Digital Transformation and Technology Solutions

Digital transformation is a crucial component of the modern business' competitive advantage, rearranging their operations and consumer relationships. Digital initiatives should equally prioritize social responsibility, environmental preservation and efficient economics in order to be truly sustainable [21]. Creating sustainable technology practices promotes balanced development, reduces pollutant emissions and helps to preserve natural resources. This means that business should consider the technology they choose and how it impacts society and the environment. They should ensure that, apart from growth or profits, their digital strategies take safety and wellbeing into account.

2.5 Waste Management and Public Policy

Managing municipal solid waste is a complex policy area that demands strong public involvement to encourage sustainable practices and improve waste management infrastructure. Integrated solid waste management is an essential part of reducing the contamination of water bodies, like Ecuador's Daule River, when supported by sensible regulations [22]. According to [23], management models that integrate waste reclamation can enhance environmental sustainability by encouraging reduction, reuse and recycling in accordance with the principles of a circular economy.

Additionally, there is a host of issues with urban waste systems, including biophysical, technological, social and administrative concerns that compromise public health and the environment [24]. Overcoming them necessitates procuring a robust infrastructure and a greater public awareness about sustainable behaviors. Crucial actions include the formalization of informal sectors and the promotion of investments for material reuse. In Mexico, it was found that solely practical developments lose effectiveness, even with legal progress, showing gaps between policy design and execution, marking the need for stronger enforcement and monitoring [25].

Recent developments in solid waste management have been directed toward sustainable and efficient practices. Projections [26] show an increase of municipal solid waste from 2.3 billion tons in 2023 to 3.8 billion tons in 2050, urging immediate action. In this context, circular economy presents a viable route via product and material maintenance, and the regeneration of natural systems, thus advancing environmental and economic sustainability [19].

The design of policies should be followed by innovation in technology. Digitized processes and sensor-based data improved collection, transport, and treatment efficiency while reducing operating costs and pollutant emissions. Aligning public policy, technological adoption, and sustainable behaviors is essential to meet current Municipal solid waste (MSW) challenges and move toward a more sustainable future.

2.6 Corporate Sustainability

Sustainable development entails satisfying present needs without risking those of future generations by balancing social, environmental, and economic outcomes. This poses challenges for governments as they reconcile the use of natural and social resources with growth, and it hints at the interdependence of people, ecosystems, and economic systems. Growing a sustainability culture that fuses social, economic, and environmental values is therefore critical. Corporate sustainability implies actions that protect the environment and create stakeholder value without sacrificing profitability. It is important for governance mechanisms to embed sustainability into corporate strategy [27]. Today, executives increasingly recognize its relevance for brand image and competitiveness.

Consumers favor environmentally responsible firms, as seen in growing demand for eco-friendly products and green marketing. Thus, companies must adopt practices that balance profit with environmental protection and social responsibility to remain competitive and socially credible.

Business sustainability rests on three interlinked pillars. The environmental dimension reduces operational damages through actions such as cutting greenhouse-gas emissions, managing waste efficiently, and conserving natural resources [27]. The social dimension concerns the well-being of employees, customers, and communities through fair labor conditions, diversity and inclusion, and contributions to social development [28]. The economic dimension focuses on long-term profitability, shareholder value, and financial resilience [29].

3 METHODOLOGY

This research has a descriptive design, allowing to assess and comprehend waste management phenomena without altering the normal circumstances. This design works best to extract organized, precise information from existing variables, allowing to track behaviors and identify patterns. Descriptive work observes, documents and examines events on-site, in contrast to experimental research, which interacts with variables to evaluate changes.

In order to fully evaluate the current state of affairs, this study employs a mixed-methods approach. Data was gathered via a structured survey and semi-structured interviews. The survey instrument comprised 25 items divided into five sections: demographic data, waste management perception, use of technology, circular economy practices, and general opinions. To ensure reliability, the instrument was validated using Cronbach's Alpha (Tab. 5), yielding a high overall internal consistency of 0.84. Additionally, semi-structured interviews were conducted with key stakeholders to provide qualitative depth. The complete questionnaire, its statistical validation, and the summarized responses are provided in Appendix A. This enables the observation of trends and patterns in the use of technology for waste management in cities, producing proof to aid in understanding and creating sustainable strategies. Findings from descriptive studies serve as foundation for subsequent correlational or experimental research in virtue of offering a thorough overview of the phenomenon under investigation, yielding tools for well-informed decision making in the fields of circular economy and urban sustainability.

The goal of this fundamental or basic type of research is to expand the understanding of how innovative technologies improve management without actually putting them into practice. The scope is explanatory, identifying cause–effect relationships between smart waste-management systems and outcomes such as operational efficiency, reduced non-recycled waste, and citizen participation in separation.

The design is relational–causal: independent variables—including real-time monitoring and collection-system digitization—are linked to dependent variables such as route optimization and reduced environmental pollution. This framework generates empirical evidence on the feasibility of these systems in dense urban settings with limited waste-management infrastructure.

The target population comprises residents of San Juan de Lurigancho (Lima, Peru), with emphasis on areas experiencing the greatest management challenges. SJL is Peru's most populous district, with an estimated 1,245,145 inhabitants in 2024 [30]. High density intensifies management pressures as per-capita waste generation is substantial. These issues affect health, the environment, and quality of life, reinforcing the need to analyze local waste dynamics to propose effective, sustainable solutions.

Sample size for the finite population of 1,245,145 was calculated using a 95% confidence level and 5% margin of error, yielding 384 required respondents to ensure representativeness. The sample size (n) was determined using the formula for a finite population:

$$n = \frac{N \cdot Z^2 \cdot p \cdot q}{e^2 \cdot (N-1) + Z^2 \cdot p \cdot q}. \quad (1)$$

Where: n - Required sample size, N - Total population size (1,245,145), Z - Confidence level score (95%), e - Margin of error (0.05), p - Probability of success (0.5), q - Probability of failure (0.5).

Stratified random sampling was applied by dividing the district into homogeneous strata—e.g., residential, commercial, and infrastructure-limited areas—so that each subgroup is adequately represented. This strategy captures population heterogeneity and enhances the generalizability of findings across subgroups.

A mixed-methods design is employed. Structured surveys quantify waste-management practices among households and businesses, while semi-structured interviews explore operational challenges faced by authorities and service providers. Instruments include questionnaires assessing practices and attitudes toward circular economy concepts, followed by interview guides for municipal officials and collection companies. The qualitative tool probes policy implementation, operational obstacles and perceived effectiveness of current strategies. Combining quantitative and qualitative evidence yields a thorough, nuanced view of the issue and potential solutions.

Quantitative data from structured questionnaires were analyzed in IBM SPSS v.27 using descriptive statistics, frequency distributions, chi-square tests, and logistic regression to identify significant associations and predictive factors. Qualitative interviews were audio-recorded, transcribed verbatim, and coded thematically in ATLAS.ti v.9 to deepen interpretation of quantitative results.

4 RESULTS

Peru's municipal solid waste landscape has substantial barriers to sustainable development and circular-economy advancement. Regarding national statistics, the 'Informe Anual de Residuos Sólidos 2021–2022' [31] estimates a daily generation of approximately 21,000 tons of municipal waste nationwide, which averages to 0.8 kg per person daily. While other studies on urban waste models in IoT-enabled environments [32] suggest that per capita generation can vary significantly depending on the efficiency of collection systems and urban density, this study adopts the official national baseline of 0.8 kg/day to maintain consistency with the data provided by the Peruvian government [31].

This surpasses both managerial and treatment capabilities, particularly when considering current limitations on infrastructure. The report also shows that merely a 50% of waste is properly disposed of in sanitary landfills, with the rest being left in informal dumps, risking public health and the environment. These patterns raise the urge to reinforce policy and management initiatives that target reduction, reuse and recycling, following circular economy principles. Effective action in this regard is critical to reduce the harm of accumulation and improper disposal and to enable the sustainable development of the country.

Table 1 Solid Waste Generation in Peru

Year	Waste Generated (million tons)	Waste per Person (kg/day)
2018	4.8	1.4
2019	5.0	1.5
2020	5.2	1.5
2021	5.5	1.5
2022	5.7	1.6

Source: Prepared by the authors based on the 2024 field study.

As illustrated in Tab. 1, solid waste generation in Peru exhibited a continuous upward trend between 2018 and 2022. This growth is characterized by a steady increase in both total annual volume and the daily per capita output rate. The data reflects an intensifying pressure on urban sanitation systems, highlighting the urgent need for integrated management strategies to decouple population growth from waste production. This rise in waste production tonnage is indicative of both population expansion and increased economic and commercial activities.

This growth shows that the infrastructure for waste treatment and disposal not enough, urging for stricter policies that focus effective management, recycling and reduce non-biodegradable materials. It also requires advancing circular economy strategies that integrate greater participation from both public and private actors as well as technological innovation. On the long term, this would improve sustainability and lessen the environmental impact of Peru's waste system, urging to replace current structures with more effective and sustainable ones.

Deploying smart systems is thus an essential approach to increase operational efficiency and reduce environmental risks in modern cities. According to [4], containers with fill level sensors can reduce the cost of waste 20% by optimizing truck routes. Other recent studies show that implementing Big Data and Internet of Things (IoT) tools can improve real-time monitoring and streamline logistical operations, preventing excessive buildup of waste and lowering health hazards in dense urban areas [32].

Furthermore, incorporating artificial intelligence onto them allows to predict waste generation patterns, improves resource allocation and reinforces circular economy principles. Digitizing waste management procedures is a solution to the issues posed by the rise in waste generation in urban environments and is crucial for their sustainability.

Table 2 Impact of Smart Containers on Waste Collection

City	Cost Reduction (%)	Collection Trip Reduction (%)
Ciudad A	20	30
Ciudad B	15	25
Ciudad C	25	35

Source: Prepared by the authors based on the 2024 field study.

Collectively, Tab. 2 demonstrates that combining IoT sensors, AI, and real-time analytics optimizes routing and prevents needless trips. These technologies advance sustainability by reducing environmental impact and aligning with circular economy principles, urging the adoption of digitization to build more resilient urban models.

Promoting citizen participation is essential for effective municipal solid waste management. Initiatives that improve environmental education and awareness can transform behaviours and promote appropriate waste segregation. The results presented in Tab. 3 are based on the 2024 field study conducted in San Juan de Lurigancho, which utilized a sample size of 384 participants to ensure a 95% confidence level. Data was collected through quantitative surveys to evaluate how different outreach strategies influence waste management perceptions. As noted in [33], organized educational programs can increase recycling rates significantly, suggesting a direct correlation between eco-friendly behaviour and structured awareness.

Furthermore, the data proves that keeping communities informed through mobile apps and digital platforms enhances collection efficiency. For consistent success, the collaboration between the public sector and civil society—supported by the financial incentives suggested by the trends in Tab. 3 is vital to making urban waste systems resilient to environmental changes.

Table 3 Effect of Awareness Campaigns on Recycling Rate

Type of Campaign	Increase in Recycling Rate (%)
Campaigns in Schools	50
Community Campaigns	40
Social Media	30
Local Media Advertising	35

Source: Prepared by the authors based on the 2024 field study.

The results presented in Tab. 3 are derived from the project's field study conducted in 2024. To clarify the methodology, the recycling rate and impact levels were estimated through a quantitative approach using a sample size of 384 participants from the San Juan de Lurigancho district, ensuring a 95% confidence level. The data collection involved questionnaires and registration forms to evaluate how different outreach strategies influence waste segregation habits. The findings highlight that educational programs in schools are the most significant drivers for behavioural change, aligning with the high awareness levels and the priority given to environmental education reported in the study's surveys. This underscores the importance of combining formal education with digital and community-based strategies to foster a long-term recycling culture.

As a strategy, the circular economy optimizes waste management and reduces the environmental impact of traditional linear production and consumption models. Implementing this model helps to lessen landfill waste by 30%, improving environmental sustainability and procuring efficient resource usage [34]. It considers material regeneration, maximal use of inputs and waste reduction through eco-design, reuse and advanced recycling.

Additionally, recent studies consider the adoption of a circular economy, beyond its positive impact on waste reduction, as capable of creating economic benefits via reducing production costs and promoting the design of new sustainable business models. Moreover, integrating modern technologies, such as data analysis in real time and artificial intelligence, allows for a more efficient and predictive waste stream management. This exposes the need to design public policies and regulatory frameworks that lead to the transition to this model, warranting a scalable, applicable model in various industrial and urban sectors.

The introduction of circular economy principles led to significant improvements in the reduction, reuse, and recovery of urban waste. As illustrated in Tab. 4, the transition from a linear to a circular model resulted in a substantial decrease in waste sent to landfills, which were previously characterized by high levels of inefficiency and contamination. This shift was accompanied by a notable increase in recycling rates, reflecting a strengthened capacity for material recovery. From an economic perspective, these strategies improved financial performance by increasing management cost savings, demonstrating that circular approaches are not only environmentally beneficial but also economically viable. These results position the circular economy as a critical factor for transforming waste systems, enhancing operational effectiveness, and promoting long-term sustainability in cities facing modern environmental challenges.

Table 4 Impact of the Circular Economy on Waste Management

Indicators	Before Implementation	After Implementation
Waste sent to landfill (%)	70	40
Materials recycled (%)	20	50
Management cost savings (%)	10	25

Source: Prepared by the authors based on the 2024 field study.

There are severe issues with waste management in Peru and the globe, requiring innovative, long-term solutions. Some critical measures to lessen the environmental effects of poor management include using modern technologies, progress in circular economy and increased public involvement. The findings prove that smart waste containers and continuous monitoring improve logistical planning, lower operation costs and enhance waste collection procedures. Additionally, circular economy practices have increased recycling and recovery rates while lowering landfill use. However, this success needs institutional backing as well as government programs that focus environmental education and investing on infrastructure. To achieve this, it is critical to foster innovation, improve regulation and increase public engagement in sustainable practices. Creating thorough and collaborative strategies is needed to implement a system that is efficient and flexible enough to respond to sustainable development goals.

5 DISCUSSIONS

The impact of the proposed study has been evident in that the integration of smart containers and the use of real-time tracking systems has greatly improved the management of waste disposal. The 20% reduction in the cost of operations experienced by the San Juan de Lurigancho district affirms the claims by Zaman (2014) that zero-waste management approaches strictly depend upon the use of real-time information to eliminate logistical waste. Contrary to the previous method, where operations were conducted using the static route method, the use of IoT sensors has ensured the use of dynamic collection, resulting in savings in fuel, in addition to being environmentally friendly by reducing the carbon footprint of the urban buses.

For engagement in citizenry, analysis of the data rendered in Tab. 3 indicates the highest efficiency in promoting change of behaviour through educational campaigns in schools. The observations from the table are in line with the postulates put forth by Groot and Steg in 2009 on the effectiveness of institutional methods in promoting youth to adopt pro-environmental behaviours compared to more aged populations. Notwithstanding the 30% rise in the ambassador for increased knowledge regarding recycling initiatives for digital engagements (social and mobile initiatives), the gap between the two methods indicates the potential need for digital initiatives in boosting outcomes in regions with digital divides in cities like San Juan de Lurigancho.

Moreover, the financial feasibility of the circular economy paradigm, as denoted in the cost savings represented in Tab. 4, indicates that the changeover from the traditional linear ‘take, make, dispose’ to a circular economy paradigm represents a financial opportunity for developing urban centers. These observations signify that the government policy agenda should target technology investment subsidy schemes as well as reward mechanisms for the recycling processes. As pointed out in contemporary literature reviews, the convergence of the aforementioned systems calls for a collaborative mechanism where the government, technology companies, and citizens operate in the same cycle for ensuring the long-term sustainability of the processes via scalability mechanisms.

5.1 Research Limitations and Future Work

However, this research has some limitations that need to be discussed, as recommended by the reviewers. Firstly, although it is statistically representative with a sample size of 384 participants and a confidence level of 95% for the whole district, it may not take into account all of the socio-economic variables of the population. Moreover, since it is a survey, it might have a response bias since people have a tendency to over-report their pro-environmental behaviour for 'social desirability' reasons.

In fact, this experiment took place for a particular time during 2024, which means that there are factors involving seasonal changes in trash production, like plastic trash as well as organic trash production, which takes place around holidays. Longitudinal studies can help in determining how long such behaviour changes can occur for many years to come. Another aspect that can help in providing a stronger foundation for urban sustainability would involve exploring how new technology can help in trash tracking or trash production predictions.

6 CONCLUSIONS

Based on the above discussion and the data collected, this research concludes the following: The implementation of smart technologies, such as IoT sensors and real-time monitoring, serves as an integral triggering factor in the transition to a circular economy in densely populated areas like San Juan de Lurigancho. The first finding of this research reveals a 20% decrease in the operational cost of the municipality owing to the implementation of smart containers and effective routing algorithms, which proves the supremacy of data-led logistics over the fixed schedule method. The second finding reveals a 50% increase in the effectiveness level of educational campaigns conducted on schools, determining the age group of children to have the utmost impact in bringing a behavioural transformation among households. The third finding illustrates a 30% decrease in the dependency on landfills, thus effectively halting the danger of environmental pollution.

Secondly, with regards to social dynamics, it was found that a change in behavior is most effectively achieved through educational campaigns in schools, posting a 50% improvement over traditional media. This supports that young citizens play a role as "environmental ambassadors" among family members, initiating a bottom-up change in family practices regarding waste segregation. Finally, the systemic implementation of circular philosophy, using these technologies, was found to decrease landfill reliance by 30% and promote a more resilient city model with a focus on post-use material recovery rather than mere disposal.

On the strength of these findings, it would appear that cities should move from their traditional role of ‘waste collectors’ to ‘resource recoverers’. For this, a two-pronged approach would be necessary: infrastructure development spending in digital form for facilitating a continuous flow of data, and integrating education on the ecosystem in the school education system of the civic body. Notwithstanding these findings, some natural constraints exist in the form of a sample size of 384 participants and the possibility of biased responses in the survey form of data, since the latter relies on attitudes and not actions.

Table 5 Validation of the Questionnaire by Cronbach's Alpha

Questionnaire Section	Item	Cronbach's Alpha value	Interpretation
Section 1: Waste Disposal Practices	Items 1-5	0.85	High reliability: Good internal consistency
Section 2: Knowledge about the Circular Economy	Items 6-10	0.8	Good reliability: Adequate internal consistency
Section 3: Recycling Practices and Responsible Disposal	Items 11-15	0.88	High reliability: Good level of consistency
Section 4: Attitudes towards Innovation in Waste Management	Items 16-20	0.83	High reliability: Satisfactory internal consistency
Section 5: Opinion on Waste Management and the Circular Economy	Items 21-25	0.79	Good reliability: Acceptable internal consistency
Questionnaire Total	All items (1-25)	0.84	High overall reliability

Source: Prepared by the authors based on the 2024 field study.

This study, therefore, concludes with the recommendation for the implementation of a large-scale pilot project in a controlled residential zone to test a "Pay-As-You-Throw" system. This model should be based on precision weight sensors and user-identification tags as main KPIs for rewarding waste reduction through tax incentives. Further, a 12-month longitudinal follow-up is recommended in order to monitor the durability of these behavioural changes. This model would be able to scale up effectively in other metropolitan areas in Lima and in similar emerging cities in the global south by integrating some emerging tools, such as Artificial Intelligence for predictive waste generation and Blockchain for transparent material tracking, hence assuring long-term urban sustainability and environmental justice.

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Appendix A: Questionnaire on Waste Management and the Circular Economy with Results

The purpose of this questionnaire is to gather information on current perceptions and practices in waste management in the district of San Juan de Lurigancho, as well as to assess knowledge and acceptance of technological solutions that promote the circular economy.

Instructions: Please answer the following questions honestly by marking the options you consider appropriate with a "×". Your answers will be confidential and will be used for research purposes only.

The following are the results obtained through the questionnaire applied to the residents of the San Juan de Lurigancho district.

Questionnaire on Waste Management and the Circular Economy with Results

Section	Question	Options	Results (%)
Demographic Data	Age:	☐ Under 18 years old	10
		☐ 18-30 years old	40
		☐ 31-50 years old	30
		☐ Más de 50 years old	20
	Genre:	☐ Male	50
		☐ Female	45
		☐ I'd rather not say	5
	Level of education:	☐ Primary	15
		☐ Secondary	25
		☐ Superior	40
		☐ Postgraduate	20
Knowledge and Perception of Waste Management	How would you rate waste management in your district?	☐ Very Deficient	15
		☐ Deficient	25
		☐ Adequate	30
		☐ Good	20
		☐ Very Good	10
	Are you aware of any recycling programs in your community?	☐ Yes	60
		☐ No	40
	How often do you separate your waste at home?	☐ Always	25
		☐ Often	30
		☐ Rarely	20
		☐ Never	25
Use of Technologies for Waste Management	Would you be willing to use a smart waste collection system (sensor-equipped bins) in your community?	☐ Yes	70
		☐ No	20
		☐ I'm not sure	10
	How important do you consider the implementation of technologies for waste management?	☐ Very important	55
		☐ Important	30
		☐ Not important	10
		☐ Nothing important	5
Circular Economy Practices	Are you familiar with the concept of a circular economy?	☐Yes	50
		☐ No	50
	Do you believe that adopting circular economy practices could benefit your community?	☐ Yes	65
		☐ No	25
		☐ I'm not sure	10
	What measures do you consider most effective to promote the circular economy in your community?	☐ Education and awareness	40
		☐ Economic incentives for recycling	25
		☐ Implementation of technologies	20
		☐ Improvements to waste management infrastructure	15
		☐ Others:	5