Selective Collection: App Prototype for Circular Solid Waste Management in the Amazon

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***Abstract*—This paper presents a prototype application designed to address the inefficiency of solid waste management in Amazonian cities, specifically highlighting the city of Marabá-PA, as a case study for this work. Here, an estimated 97% of urban solid waste is sent directly to landfills. The core problem lies in a lack of effective coordination between three critical participants in the recycling chain: producers (waste generators), waste pickers (cooperative or independent collectors), and scrap dealers (recycling plants or resale businesses for recyclable materials). This disconnect hinders recycling efforts and perpetuates an unsustainable waste management model. As a solution, this work introduces a platform that connects these three stakeholders, thereby structuring a circular economy ecosystem. The proposed architecture employs a multi-tier client-server model and integrates external services, including geolocation APIs (Google Maps) and notification systems. Developed as part of a university extension project, the prototype demonstrates scalability potential in the Amazon region and surrounding areas, with the prospect of providing socio-environmental benefits (such as reduced accidents and increased recycling rates) and economic gains (improved logistics and lower operational costs).**

***Keywords*—circular economy; mobile application; waste management.**

I. Introduction

The 2030 Agenda [1] to achieve the SDGs was established by the United Nations (UN) in 2015 [2], with defined goals for global sustainability, including making cities and communities sustainable and ensuring sustainable patterns of production and consumption (SDGs 11 and 12) [3] [4].

Several countries have committed to the SDGs in order to achieve them. However, Brazil faces serious difficulties in aligning itself with these guidelines, despite its main legal instrument for this purpose, which is the National Solid Waste Policy (PNRS) [5], created in 2010.

Recent studies reveal that municipalities — especially smaller and less resourced ones, such as those in the Amazon region — suffer from a lack of investment, inconsistent government actions, and a lack of integration among the involved stakeholders, making the practical application of the law unfeasible [6].

This scenario is worsened by concrete data on waste generation and disposal. In 2023, each Brazilian generated, on average, 1.047 kg of waste per day, totaling 81 million tons annually — equivalent to 221,000 tons discarded daily. Although technical standards such as ABNT NBR 10004 guide safe classification (separating non-hazardous recyclable materials from hazardous ones, such as batteries and chemicals), less than half of this waste receives adequate treatment.

The remainder is sent to dumpsites or uncontrolled landfills, contaminating soil, water, and air, and exposing waste pickers to preventable risks. Furthermore, the Urban Cleaning Sustainability Index (ISLU) confirms this reality: 76% of Brazilian municipalities have unsatisfactory performance, with the Northern region showing the worst indicators (only 22% of waste properly disposed of) [7].

Given this context, the disconnect between laws, regulations, and operational reality becomes evident. The absence of efficient mechanisms to coordinate producers, waste pickers, and recyclers — coupled with low awareness about proper waste separation — perpetuates a cycle of environmental degradation and social exclusion.

It is emphasized that this gap is particularly critical in the Amazon, where precarious logistics and scarce resources intensify the challenges, demanding innovative and accessible solutions to transform legal obligations into concrete actions.

In response to this problem, aligned with the guidelines of the National Solid Waste Policy (Law No. 12.305/2010), this article presents the prototype of a mobile application developed under a university extension project in the Northern region of Brazil, which directly addresses the weaknesses pointed out by Hauenstein and Ismail (2024), such as operational disorganization and the lack of reverse logistics mechanisms.

Studies indicate that in municipalities such as the one analyzed in the state of Pará (omitted for anonymous review), approximately 97% of solid waste is sent to landfills, a scenario directly linked to the lack of coordination among producers (household generators), waste pickers (cooperative or independent), and scrap dealers (recycling facilities).

This fragmentation creates logistical inefficiencies, exposes workers to serious occupational hazards – such as injuries from sharp materials and attacks by venomous animals while scavenging through common waste – and limits access to quality recyclable materials, thereby undermining the economic viability of the sector.

In this work, the proposed system acts as a technological mediator to integrate the three links of the chain, structuring a circular economy ecosystem. The application incorporates a gamification module ("My Garden") that rewards producers for proper waste separation through points, combining real actions and educational challenges, reducing the need for scavenging in general waste and, consequently, mitigating occupational risks for waste pickers.

Simultaneously, it optimizes logistics through geolocation-based routing algorithms and ensures transparency in transactions between waste pickers and scrap dealers via integration with instant payment APIs (Pix).

The solution proposed in this work demonstrates scalability potential for other Amazonian contexts, where partnerships with cooperatives, local companies, and public agencies (such as city halls and SEBRAE) reinforce its operational viability.

The paper is structured as follows. Section II presents the theoretical framework. Section III details the contextual diagnosis. Section IV describes the application architecture. The results are presented in Section V. Finally, Section VI provides the concluding remarks.

II. Theoretical Reference

Solid waste management and the transition towards more sustainable development models are topics of growing global urgency, driven by rapid urbanization, population growth, and consumption patterns [8].

The traditional linear economic model, based on the "take, make, dispose" logic, has proven unsustainable, resulting in serious environmental and public health complications, such as soil, water, and air contamination, the proliferation of diseases, and greenhouse gas emissions. In this context, concepts such as Circular Economy, Industry 4.0 Technologies, and socio-environmental impact metrics emerge as fundamental pillars for a more resilient and equitable future.

A. Circular Economy and Waste Management

The Circular Economy (CE) emerges as an alternative economic model to the linear one, proposing a regenerative and restorative system where materials and products are kept in use for as long as possible, optimizing resource use and eliminating waste [9]. Inspired by nature, the CE aims to ensure that the "waste of one species becomes the food for another," producing and transporting with renewable energy [10]. Its pillars include reduction, reuse, and recycling, aiming for truly sustainable development that operates without waste and with resource savings [11].

The transition to the CE offers various economic, environmental, and social benefits:

Environmentally, it contributes to the reduction of greenhouse gas emissions, protects biodiversity, and limits the excessive use of natural resources, reducing dependence on virgin raw materials. Recycling, for example, reduces the demand for virgin raw materials and the amount of waste in landfills.

Economically, the CE represents a significant opportunity for cost reduction and increased production efficiency, with estimated global savings of up to $ 700 billion per year [12]. It also drives job creation in areas such as remanufacturing, repair, selective collection, and eco-design, and stimulates innovation and the creation of new business models, increasing industrial competitiveness [12].

Socially, the CE promotes productive inclusion, generates income for waste pickers, and improves quality of life, in addition to reducing the population's exposure to hazardous waste and favoring improvements in environmental conditions such as air and water [12].

In Brazil, the National Solid Waste Policy (PNRS, [5]) – Law No. 12,305/2010 is the main legal instrument guiding waste management, establishing shared responsibility among the public sector, companies, and consumers. The PNRS defines a priority order for waste management: non-generation, reduction, reuse, recycling, treatment, and finally, environmentally adequate disposal of waste. One of its crucial instruments is reverse logistics, which aims to enable the collection and return of solid waste to the business sector for reuse or environmentally sound disposal. Brazilian companies such as Eldorado Brasil, JBS, Braskem, EDP Energia, Lojas Renner, and Natura already implement circular economy practices, highlighting the model's potential in the country [13].

ABNT NBR 10.004 is fundamental for the characterization and classification of solid waste, categorizing it into hazardous (Class I) and non-hazardous (Class II A for biodegradable/combustible and Class II B for inert). This classification it is very important for proper handling and safe disposal, avoiding contamination and risks to public health.

Despite the legal framework, Brazil faces challenges in waste management. In 2023, the average generation of municipal solid waste (MSW) per capita was 1.047 kg/day, totaling 81 million tons annually, with less than half receiving adequate treatment [14]. The Urban Cleaning Sustainability Index (ISLU) confirms that 76% of Brazilian municipalities have unsatisfactory performance, with the Northern region showing the worst indicators [14]. The implementation of the PNRS still suffers from a lack of investment, weak public sector performance, lack of infrastructure, disorganization among producers, waste pickers, and recyclers, and low public awareness [14].

B. Technologies 4.0 (Gamification, Geolocation)

Industry 4.0 (I4.0) represents a new technological revolution that integrates various innovations to optimize production processes and promote sustainability. Digital technologies of I4.0, such as the Internet of Things (IoT), cloud computing, Big Data, Artificial Intelligence (AI), robotics, and digital twins, are fundamental to increasing productivity, efficiency, and innovating business models. The integration of I4.0 technologies with the principles of the Circular Economy (CE) can enhance innovation and profitability across various sectors, creating a value scale based on the economic, social, and environmental tripod.

In the context of waste management and sustainability, specific I4.0 technologies play crucial roles:

Internet of Things (IoT): It is an enabling technology of I4.0 that, through sensors, allows the integrated collection and transmission of information about consumption habits and production processes. In waste management, IoT can enhance collection monitoring and optimize flows, contributing to more effective management.

Gamification: Defined as the application of game elements in non-playful activities to motivate and engage people. It is an effective tool for Environmental Education, especially for children, making learning about sustainability playful and interactive. Gamified applications such as EkoPlay or the ”My Garden” module of Selective Collection 4.0 demonstrate the potential to influence behavioral changes and increase awareness about proper waste separation, reducing risks for waste pickers. Despite its benefits, the integration of apps into lesson plans and monitoring screen time are challenges to be considered.

Geolocation: Geolocation technology is vital for optimizing logistics and the accessibility of waste collection points. Studies, such as the one in Manaus, demonstrate the georeferencing of Voluntary Delivery Points (PEVs) for recyclable waste, identifying their distribution and highlighting the need to create new points in strategic areas for greater population coverage. Providing information about the location and types of waste accepted at PEVs through popular tools like Google Maps facilitates proper disposal and promotes environmental education.

C. Social Return on Investment (SROI) and Socio-Environmental Impact Metrics

Due to the impossibility of quantifying certain metrics (environmental, economic, financial, social, and cultural) in the data sources, this work employed the Social Return on Investment (SROI) approach hypothetically. Despite this limitation, the choice of this methodology is justified by its ability to measure and evaluate socio-environmental benefits and impacts, reflecting the concern to transcend a purely financial perspective.

Specialized literature emphasizes the relevance of robust indicators to assess both efficiency and progress toward urban sustainability and circularity. Notwithstanding the inherent challenges of data collection and methodological standardization, the analysis of appropriate metrics proves crucial to persuade different social actors—including policymakers, communities, and companies—about the feasibility and advisability of investments in sustainable models.

In the environmental sphere, metrics range from quantitative parameters of waste separation and recycling to more complex indicators such as the reduction of the ecological footprint and decreased environmental pollution. The economic-financial domain encompasses savings in the public sector and reduced operational costs, as well as the generation of new economic opportunities and the creation of green jobs. In the socio-cultural dimension, indicators related to improved quality of life, levels of environmental awareness among the population, and the valorization of waste pickers’ work stand out.

The integrated analysis of these indicators constitutes a fundamental tool for urban planning, enabling more efficient resource allocation and the effective promotion of environmental sustainability. The convergence between the concepts of Smart City and Circular Economy, articulated with the technical standardization of ABNT, can potentiate the development of cities that are simultaneously more technological and environmentally responsible. The adoption of a balanced and multidimensional approach, which transcends fragmented evaluation through isolated indicators, proves essential for an accurate assessment of impacts and for guiding public policies and strategic decisions toward more resilient and environmentally sustainable cities.

III. REGIONAL CONTEXT AND DIAGNOSIS

A. City Characterization

The city of Marabá, located in southeastern Pará, constitutes the focus of the case study presented. A geographical analysis of municipal distribution, conducted based on Google Maps data, reveals a concentration of scrapyards in two of its five urban nuclei (highlighted in green and blue, identified as 1 and 2, respectively), as demonstrated by Figure 1. Thus, the field efforts of this study were directed to these regions, which feature such establishments in both central and peripheral areas.

Fig. 1. Distribution of urban cores

B. Collection Flow

Selective collection activities in the studied municipality, represented by Figure 2, begin with the Producer, who disposes of solid materials without proper guidance, resulting in the contamination of other materials and the mixture of non-recyclable items. The absence of a technical distinction between what is recognized as trash and what is classified as reject can compromise the rate of waste that could enter the recycling cycle and strengthen collection activities in the region.

With this deficiency at the origin of the process, the activities of Waste Pickers, besides requiring greater attention due to the inadequacy of the material, present potential safety risks. The harmful characteristics of certain wastes (physical, chemical, and biological risks), combined with the lack of personal protective equipment (PPE), make this layer of the flow the most vulnerable in the process.

This dynamic exposes waste pickers to significant occupational risks, such as accidents with sharp materials and contact with hospital waste, amplifying their condition of vulnerability and compromising their dignity as workers. Furthermore, the need to travel to scrapyards to sell the collected materials imposes an additional burden on them, both in terms of time and physical effort, accentuating the precariousness of their labor activity.

At the end of the process, scrapyard logistics face the challenge of dealing with the problems inherited from the aforementioned actors. Operational costs increase as a consequence of the inferior quality of the received material (cardboard, for example, loses its commercial value when moistened), resulting from the irregularity in the receipt flow.

Fig. 2. Selective Waste Collection Flow

IV. TECHNICAL ARCHITECTURE

The tool's architecture, as outlined, was designed as a multi-tier client-server model, intrinsically seeking modularity, scalability, and efficiency in communication between the various system components: user interfaces, business logic, and data storage. This robust structure enables the integration of complex functionalities and smooth interaction with essential external services.

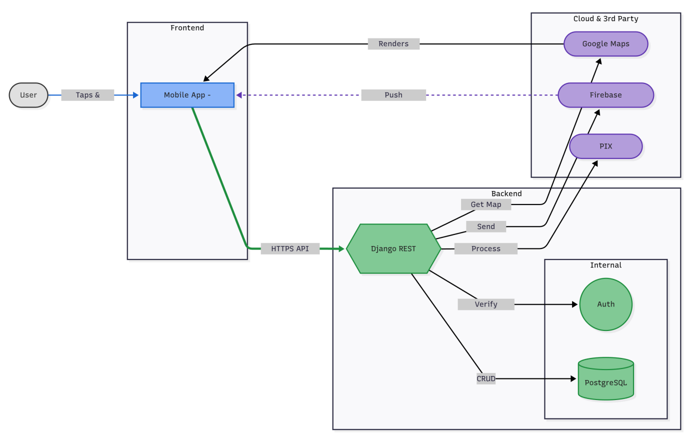

Fig. 3. Software Architecture

A. Client Tier (Frontend)

This tier as shown in Figure 3, constitutes the direct interface with the end user, encompassing profiles such as waste pickers, collectors, and scrapyard operators, who interact with the system through a graphical user interface (GUI). Its primary function is the visual presentation of data, capturing user actions, and sending requests to the server. For the development of this tier, Flutter technology was chosen, a cross-platform UI development framework that allows the creation of native applications for iOS and Android from a single codebase, significantly optimizing development time and cost, in addition to offering high performance for the application.

The functionalities provided to users, regardless of age, education, or gender, are designed to capitalize on the strong motivator of environmental protection that encourages engagement in selective collection campaigns. For waste producers, gamification screens ("My Garden"), geolocation maps, collection scheduling forms, transaction viewing, and analytical dashboards with socio-environmental indicators are available. The "My Garden" gamification module rewards producers for proper waste separation through points, combining real actions and educational challenges, which helps reduce the need for scavenging in general waste and mitigate occupational risks for waste pickers. Gamification is recognized as an effective tool for promoting sustainable behaviors in educational and awareness environments, as elements such as point gains for rewards in application games are rated more positively by users than methods that provide information in isolation, due to greater psychological involvement.

B. Server Tier (Backend)

Considered the "brain" of the application, the Backend tier as shown in Figure 3, is responsible for processing business logic, managing data access, and coordinating communication with external services. The tool was developed using Django, a high-level Python web framework, known for promoting fast, clean, pragmatic, and secure development, being ideal for complex applications that demand robustness and scalability.

Within the Backend tier, the following modules stand out:

API Gateway / Controller: Acts as the entry point for all requests coming from the Frontend. It is responsible for routing to the appropriate Backend modules, initial data validation, and formatting responses to be sent back to the client, ensuring standardized and secure communication between the client and the server.

Business Module: Contains the core logic of the application. This includes algorithms for gamification (point calculation, "My Garden" progression), collection scheduling management, route optimization for waste pickers, processing and validation of material transactions, and generation of environmental impact reports. It is where the system's business rules are implemented, addressing the weaknesses in operational articulation and the lack of reverse logistics mechanisms.

Authentication Service: Manages user registration, login, and authentication, being responsible for system access security and data protection. It implements access control mechanisms based on profiles (producer, waste picker, scrapyard operator), fundamental for system coherence.

C. Database Tier

This tier is dedicated to the persistent and structured storage of all system information as displayed in Figure 3. It stores user data (profiles, gamification points), material records (types, volumes, prices), collection schedules, transaction history, scrapyard and cooperative information, and geographical data. The main technology adopted is PostgreSQL, chosen for its robustness, scalability, support for geospatial data (via PostGIS, if necessary), and ability to handle large volumes of complex data efficiently and securely.

D. External Services Tier

This tier as demonstrated in Figure 3 enables the integration of the Backend with third-party APIs and services, which provide specialized functionalities not developed internally. Some of the main services employed in this prototype include:

Geolocation API: Provides map data, route optimization, and geocoding/reverse geocoding services. This service is crucial to enable waste pickers to visualize producers and scrapyards on the map, plan the best collection routes, and make precise scheduling. The Geocoding API is used to transform producer addresses into geographic coordinates (latitude/longitude) and vice versa. In turn, the Directions API calculates routes between multiple points, providing distances, times, and detailed paths, being used to generate optimized routes and calculate Estimated Times of Arrival (ETAs) for waste pickers and recyclers. Geolocation is a direct response to the difficulty faced by residents of cities like Manaus in disposing of their recyclable waste due to not knowing the location of Voluntary Delivery Points (PEVs) and the types of waste accepted. Research in Manaus, for example, revealed that PEVs are insufficient and not inclusive, especially in areas with higher population density, making information about their location even more critical.

• Pix Payment API (Charge): A service that generates dynamic QR Codes to enable immediate or scheduled payments, with the possibility of including interest, fines, or discounts. This service is crucial for formalizing transactions between waste pickers and scrapyards/recyclers, ensuring fast, secure payments and promoting financial transparency in the recycling chain. The formalization of transactions via Pix contributes to income generation for waste pickers and the valorization of their work.

• Notification Service (Firebase Cloud Messaging - FCM): Used to send push notifications directly to the user's mobile application. It is responsible for sending alerts and important communications, such as scheduling confirmations, collection status updates, transaction messages, and gamification reminders.

• SendGrid: Used for sending registration confirmation emails and environmental impact reports.

E. Alignment with Sustainability Models and Waste Management

V. Results and Alignment with Sustainability and Waste Management Models

This architecture is intrinsically aligned with the principles of the Circular Economy (CE), which presents itself as a promising strategy for sustainable development by promoting the reuse, recycling, and regeneration of materials, breaking with the linear logic of "take, make, and dispose" The platform, by integrating producers, waste pickers, and recyclers, acts as a technological mediator to structure a circular economy ecosystem. Logistics optimization through geolocation-based routing algorithms and transaction transparency via Pix are mechanisms that directly respond to the weaknesses of operational disorganization and the lack of reverse logistics.

Furthermore, the implementation of this system contributes to the National Solid Waste Policy (PNRS) (Law No. 12,305/2010), which, despite being a key legal instrument, still faces critical implementation challenges in Brazilian municipalities, especially in the Amazon region, due to scarce financial resources, governmental fragility, and lack of integration among actors. By providing efficient mechanisms for articulation and awareness about proper waste separation, the tool supports the reduction of waste sent to landfills and the valorization of recyclable materials.

The system aligns with the Sustainable Development Goals (SDGs) of the UN 2030 Agenda, particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production), which encourage the efficient use of natural resources, waste reduction, and the promotion of responsible consumption practices. The application's ability to optimize routes and formalize transactions represents an advance in intelligent waste management, fundamental for cities seeking more sustainable and efficient models, using Industry 4.0 technologies.

A. Prototype Design

The application development process required an integrated vision that combined technology, usability, and socio-environmental impact. To ensure that different user profiles

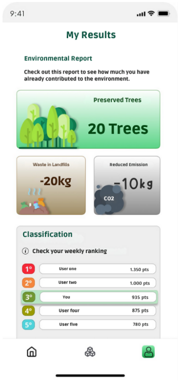

Fig. 4. Gamification results screen

could use the tool in an accessible and efficient manner, high-fidelity wireframes were created. These visual prototypes were essential to anticipate screen layout, validate navigation flows, and align the user experience with the project's objectives.

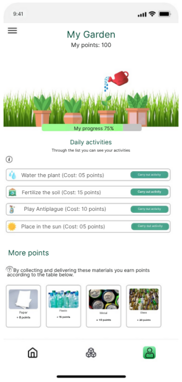

Fig. 5. Gamification activity screen

The screens were structured around three main perspectives. The first corresponds to the producer, who is responsible for registering, as shown in Figure 6 and in Figure 7, and for scheduling the collection of generated waste, as shown in Figure 8, detailing location, volume, and material types. This profile plays a central role in data input and is fundamental to initiating the selective collection cycle. The second profile is that of the waste picker, who receives requests and organizes optimized collection routes. This interface was designed for simplicity and objectivity, considering that many users may have limited digital access. Finally, the third profile corresponds to the scrap dealer, who acts as the receiving and purchasing point for collected waste, closing the loop of the circular economy.

In addition to visual representation through wireframes, an

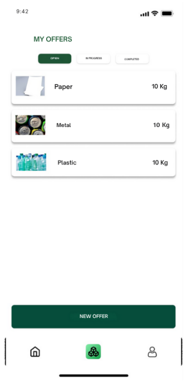

Fig. 6. My offers screen

articulated operational flow was designed, clearly organizing interactions among different system actors. This flow consists of three fundamental stages: (i) scheduling, when the producer registers the need for collection in the application, providing detailed waste information; (ii) collection, carried out by the waste picker based on system-preorganized routes validated through georeferencing; and (iii) payment, executed via integration with the Pix API, ensuring speed, security, and transparency in financial transactions.

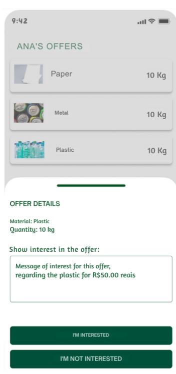

Fig. 7. Offers screen

The operational flow is not limited to a sequence of technical actions. It also represents an effort to formalize trust relationships among producers, waste pickers, and scrap dealers. Historically, the selective collection sector has high informality rates, which hinders fair valuation of waste pickers' work and limits the socio-environmental reach of recycling practices. By structuring a clear digital flow, the application helps legitimize these relationships, ensuring traceability, reliability, and more consistent gains for all involved.

Another relevant aspect is that using an articulated operational flow brings logistical efficiency to the collection process. Optimized routes reduce displacement costs and execution time, in addition to lowering carbon emissions associated with transportation. For the Amazon region, where geographical distances and infrastructure limitations pose significant challenges, this operational gain is even more meaningful. Thus, the application presents itself not only as a technological tool but also as an instrument for sustainable territorial management.

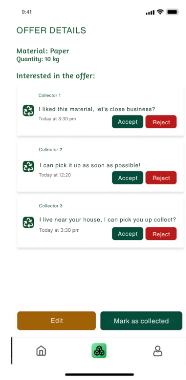

Fig. 8. Scheduling details screen

In addition to the screen design and the definition of the operational flow, a scoring and rewards system was designed to enhance user motivation and engagement as demonstrated in Figure 4 and Figure 5. This logic was formalized through Formula 1:

$$PT = RW + GP$$

Where PT represents the user's total score, RW corresponds to the quantity of waste effectively and correctly forwarded (Real World), and GP refers to gains from gamified activities (Game Points). Thus, the formula integrates both real-world impact and the application's playful elements.

The adoption of this gamification logic was inspired by practices already established in other sectors but adapted to the socio-environmental context. The goal is not only to reward users for their actions but to create a continuous incentive system in which each completed collection or challenge generates digital rewards. These rewards may take the form of prizes, badges, or progression in educational modules, such as the feature called "My Garden," which transforms environmental achievements into visual elements of a digital space cultivated by the user.

This scoring model strengthens the sense of belonging and engagement, especially among producers and waste pickers. For waste pickers, each collection represents not only an economic gain but also digital recognition of their socio-environmental contributions. For producers, each correct disposal is converted into points that reinforce their environmental responsibility. For scrap dealers, the scoring system offers greater control over processed volumes and a clear view of the collective impact generated by the network.

The integration of wireframes, operational flow, and gamification makes the application more than just a waste management system. It stands as an innovative circular economy solution that combines user-centered design, cutting-edge technology, and motivational strategies. Every component of the prototype was designed to address regional challenges in the Amazon while responding to global sustainability demands.

Thus, the application prototype demonstrates that technology can be used as an instrument of social and environmental transformation. By formalizing relationships among producers, waste pickers, and scrap dealers, optimizing collection logistics, and stimulating participation through gamification, the proposed solution creates a virtuous cycle that contributes to waste valorization, the social inclusion of waste pickers, and the strengthening of collective environmental awareness.

VI. Concluding Remarks

This study presents the technical and operational feasibility of a selective waste collection application as an innovative solution to solid waste management challenges in Amazonian contexts. The proposed architecture, based on a multi-layer client-server model, proves capable of efficiently integrating the different actors in the recycling chain - producers, waste pickers, and scrap dealers - overcoming the coordination limitations identified in the regional diagnosis.

The implementation of geolocation, gamification, and digital transaction features via Pix directly addresses the operational and financial weaknesses that have historically hindered the effective implementation of the National Solid Waste Policy in the region. The system's scalability is demonstrated through its modular design and the use of open-source technologies, allowing for its adaptation to other municipal contexts with similar challenges.

As future work, we propose expanding pilot tests to other locations in the Amazon, incorporating artificial intelligence for automated waste classification, and establishing strategic partnerships with cooperatives and public agencies to ensure the long-term sustainability of the initiative.

It is crucial to emphasize that the system presented in this paper is a conceptual framework and a technical feasibility study; the platform is not yet in operational use. The results obtained thus far are confined to the validation of the proposed architecture and its theoretical potential to address the identified challenges. Consequently, this study has not yet been tested in the field, and we do not yet have empirical tests or controlled pilots that demonstrate concrete metrics regarding user adoption, recycling rate increases, or economic impact. Such quantitative evaluation remains a primary objective for the next phase of the project.

Furthermore, a critical analysis reveals several limitations and challenges that must be addressed for successful implementation. Significant barriers may include adoption difficulties among users with low digital literacy, a challenge that requires intuitive design and community-based training programs. The system's effectiveness is also heavily dependent on reliable internet and GPS connectivity, which can be inconsistent in remote Amazonian areas. Finally, long-term financial viability depends on managing ongoing server maintenance and technical support costs, which will require a sustainable business model beyond the initial implementation phase.

Regarding the future implementation of artificial intelligence for automated classification, the methodological plan will involve developing a computer vision model, likely based on Convolutional Neural Networks (CNNs). This would require the creation of a comprehensive, region-specific database consisting of thousands of annotated images of waste materials commonly found in Amazonian households and businesses. The model would be trained to accurately distinguish between different types of plastics, papers, metals, and glass, with the goal of reducing human error in the sorting process and increasing the value of collected materials.

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References

[1] "Agenda 2030 para o desenvolvimento sustentável," Organização das Nações Unidas, 2015, acesso em: 24 jul. 2025. [Online]. Available: https://brasil.un.org/pt-br/91863-agenda-2030-para-o-desenvolvimento-sustentvel

[2] Escritório das Nações Unidas sobre Drogas e Crime, "A agenda 2030 para o desenvolvimento sustentável," 2015, acesso em: 24 jul. 2025. [Online]. Available: https://www.unodc.org/lpo-brazil/pt/crime/embaixadores-da-juventude/conhea-mais/a-agenda-2030-para-o-desenvolvimento-sustentvel.html

[3] Organização das Nações Unidas no Brasil, "Objetivo de desenvolvimento sustentável 11: Cidades e comunidades sustentáveis," 2020, acesso em: 24 jul. 2025. [Online]. Available: https://brasil.un.org/pt-br/sdgs/11

[4] ——, "Objetivo de desenvolvimento sustentável 12: Consumo e produção responsáveis," 2020, acesso em: 24 jul. 2025. [Online]. Available: https://brasil.un.org/pt-br/sdgs/12

[5] Brasil, “Política nacional de resíduos sólidos,” Lei nº 12.305, de 2 de agosto de 2010. Disponível em: https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm, Presidência da República, ago. 2010, acesso em: 15 out. 2023, versão atualizada em 29 jul. 2023.

[6] A. G. Corrêa, T. Vargas, L. Aldrighi, and D. Leandro, “Diagnóstico da gestão de resíduos sólidos urbanos no brasil: enfoque nas regiões com disposição inadequada,” *Anais - 7º Congresso Sul-Americano de Resíduos Sólidos e Sustentabilidade*, 2024. [Online]. Available: https://api.semanticscholar.org/CorpusID:269397674

[7] Sindicato das Empresas de Limpeza Urbana (SELUR), “Índice de sustentabilidade da limpeza urbana,” SELUR, Brasil, Tech. Rep., 2016. [Online]. Available: https://www.selur.com.br/wp-content/uploads/2016/08/SELUR-ISLU-2016-ACESSIBILIZADO.pdf

[8] M. d. S. Alves and Á. L. Viana, “Proposal for geolocation of voluntary delivery points of recyclable waste in the city of manaus,” 2023.

[9] F. H. B. Mainardi, I. Mendes, S. D. d. Silva, G. F. Marsoli, E. A. d. Oliveira, and E. R. Tagliaferro, “A economia circular como estratÉgia para o desenvolvimento sustentÁvel no brasil,” *Revista Ibero-Americana de Humanidades, Ciências e Educação*, vol. 11, no. 6, p. 3127–3142, jun. 2025. [Online]. Available: https://periodicorease.pro.br/rease/article/view/19876

[10] A. N. S. dos Santos, D. d. S. Soares, H. F. da Silva, C. C. Veloso, R. G. Furtado, I. F. Nascimento, D. A. da Silva, A. S. C. Recuero, A. C. d. S. Taumaturgo, R. Silva, A. F. Guimarães, K. R. d. O. Pereira, I. D. Assunção, L. T. Dezem, J. N. d. O. Felippe, and R. Rasia, “ResÍduos sÓlidos e design sustentÁvel – uma anÁlise da reciclagem na “economia circular” À luz da agenda 2030,” *ARACÊ*, vol. 7, no. 2, p. 7365–7391, fev. 2025. [Online]. Available: https://periodicos.newsciencepubl.com/arace/article/view/3335

[11] R. C. Conterno, A. Morgan, J. J. Kleinubing, C. L. d. Silva, and G. D. Santos, “Comparação entre indicadores de gestão de resíduos na perspectiva das cidades inteligentes e economia circular,” *Fronteira: Journal of Social, Technological and Environmental Science*, vol. 14, no. 2, p. 285–298, jun. 2025. [Online]. Available: https://periodicos.unievangelica.edu.br/index.php/fronteiras/article/view/7882

[12] H. K. Mohajan, “Circular economy can provide a sustainable global society,” *Journal of Economic Development Environment and People*, 2020. [Online]. Available: https://doi.org/10.26458/jedep.v9i3.670

[13] F. H. B. Mainardi, I. Mendes, S. D. da Silva, G. F. Marsoli, E. A. de Oliveira, and E. R. Tagliaferro, “A economia circular como estratégia para o desenvolvimento sustentável no brasil,” *Revista Ibero-Americana de Humanidades, Ciências e Educação — REASE*, 2025. [Online]. Available: https://periodicorease.pro.br/rease/article/view/19876

[14] [Online]. Available: https://www.abrema.org.br/2024/12/11/mais-de-41-dos-residuos-urbanos-tiveram-destinacao-inadequada-em-2023/