Helixa: Eco-Technological Systems for Intelligent Recycling with a Gamification and Rewards Platform in Lima, Peru

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Abstract

HELIXA was created, an eco-technological system based on smart recycling aimed at incentivizing and promoting the gathering and collection of plastic waste in university environments in Lima, Peru. The system is enhanced through the use of the Internet of Things applied to HELIXA's smart recycling bin and a responsive web platform working in conjunction. This proposal addresses the growing issue of low citizen participation in recycling, the most significant driver of which is the lack of impact awareness among recyclers and the shortage of mechanisms and motivation that promote environmental sustainability in their surroundings. To address this issue, HELIXA adopted a modified waterfall model organized into six phases, from requirements analysis through prototype deployment and field testing at university events. As a result, a functional prototype was developed integrating an ESP32 microcontroller, an HC-SR04 ultrasonic sensor, an I2C LCD display, and a matrix keypad, connected to a responsive web platform with gamification mechanics for user registration, points, achievements, rankings, and rewards. Validation involved a convenience sample of 80 survey respondents and 65 registered platform users, with 359 bottles collected across two university environmental fairs, evidencing a reduction of plastic waste on campus and a positive preliminary economic analysis using Return on Investment (ROI), Net Present Value (NPV), and Internal Rate of Return (IRR). The results indicated a positive user reception, solid technical feasibility, and potential for scaling to universities, municipalities, and companies with an interest in social and environmental responsibility.

Keywords

Smart Recycling, Internet of Things, Gamification, Sustainability, Plastic Waste

1. Introduction

The increasing generation of municipal solid waste constitutes an environmental, social, and economic problem that demands more effective management solutions [1]. Globally, the poor management of plastic waste continues to increase and has surpassed current mitigation capacity [2], intensifying pressure on existing systems and the costs associated with pollution, public health, and climate change, with forecasts projecting sustained growth of global plastic waste generation toward the year 2050 [3].

In developing countries, municipal solid waste management commonly shows an important gap between waste generation and its effective valorization, a challenge that is intensified in rapidly growing cities with limited institutional capacity [4]. Within Latin America and the Caribbean specifically, governance-related barriers, such as fragmented regulatory frameworks and limited sustained citizen participation, continue to constrain the reinforcement of source segregation, recycling traceability, and long-term user motivation [5]. This situation is particularly relevant in urban contexts, where

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population concentration increases waste generation and demands more efficient separation and recycling mechanisms [4].

In this scenario, several studies have pointed out that circular economy principles applied to solid waste management can contribute to the accomplishment of multiple Sustainable Development Goals (SDGs), particularly when integrated with smart-city strategies [6]. Many countries have promoted circular-economy models supported by Industry 4.0 technologies; in Indonesia, for example, researchers proposed a national waste-management model based on digital integration designed to address structural deficits in collection, transport, and material utilization [7]. Nonetheless, a recent systematic literature review warned that the key performance indicators (KPIs) used to measure this kind of progress still present standardization problems and limitations when translating data into effective citizen-participation outcomes [8].

In a university context in Lima, the frequent consumption of single-use plastic bottles produces a considerable accumulation of waste and hinders adequate separation, largely due to the absence of automated, visible, and motivational mechanisms that could facilitate the task. Traditional awareness campaigns tend to rely on temporary reminders that rarely succeed in consolidating stable recycling habits. Several studies have approached this gap from a technological perspective, showing that the Internet of Things allows the monitoring and automation of waste collection by integrating low-power connectivity and applying artificial intelligence to optimize the classification and operation of smart bins [9, 10, 11, 12].

However, evidence also shows that technical efficiency alone cannot guarantee stable adoption by users [13]. In this gap having a smart infrastructure without a mechanism that sustains human motivation lies the main problem that HELIXA seeks to solve, through the integration of physical infrastructure, digital records, immediate feedback, and rewards that turn recycling into an easy, attractive, and steadfast task.

The present research is justified by the need to design a feasible alternative that promotes environmental participation through direct experience. HELIXA is aligned with Sustainable Development Goals (SDGs) 3, 11, 12, 13, and 15, linking good health and well-being, sustainable cities, responsible consumption and production, climate action, and life on land [6]. Furthermore, the proposal aims to transform recycling behavior through visible KPIs, points, achievements, rankings, and rewards that boost user motivation [14, 15], avoiding a model in which environmental awareness depends solely on public service announcements or feelings of guilt.

The relevance of the project lies in a system that allows individual actions to be registered, collected bottles to be quantified, and participation to be linked to a symbolic gain. In this way, users not only dispose of waste, but also receive feedback about their contribution and can join a growing recycling community. This approach is relevant and attractive for universities, businesses with an interest in social responsibility, municipalities, and public spaces facing waste-organization challenges and seeking to stimulate sustainable habits.

An eco-technological system was developed that incentivizes the recycling of plastic bottles through the integration of a smart bin and a web platform with gamification mechanisms, beginning in controlled environments and with projections for scaling toward communities, municipalities, and businesses.

Based on the problem described above, this research addresses the following research question: to what extent can the integration of a low-cost IoT-based smart recycling bin with a gamified web platform improve recycling participation among university users, while remaining technically reliable, socially accepted, and financially viable for future scaling? To answer this question, the study pursued the following specific objectives:

1. Technical objective: to design, implement, and validate a functional prototype integrating an ESP32 microcontroller, an HC-SR04 ultrasonic sensor, an I2C LCD display, and a matrix keypad with a responsive web platform, and to assess its operational reliability under real usage conditions.
2. Social objective: to evaluate user perception, motivation, and participation associated with the gamification mechanisms of HELIXA (points, achievements, rankings, and rewards) through a survey and field validation at university environmental fairs.

3. Financial objective: to assess the preliminary financial feasibility of the HELIXA system by estimating its investment cost and projected revenue streams, and by calculating standard economic indicators (NPV, IRR, and ROI).

This article is organized as follows: Section 2 presents the literature review; Section 3 describes the methodology; Section 4 reports the technical, social, and financial results; Section 5 discusses the findings and limitations; and Section 6 presents the conclusions.

2. Literature Review

Sharma et al. [16] analyzed the application of the circular economy in solid waste management with the aim of determining how this approach could contribute to post-COVID-19 pandemic recovery and accelerate the fulfilment of the Sustainable Development Goals. Their methodology consisted of an analytical review of scientific literature and institutional and policy reports related to the economic, social, and environmental effects of the pandemic, as well as the management of food, plastic, electronic, biomedical, and construction waste. The results showed that circular-economy and sustainable waste-management principles were directly related to public health, resource use, environmental protection, and economic development, and could contribute to 12 of the 17 SDGs.

The authors concluded that waste management based on the circular economy should be incorporated as a priority in economic recovery strategies, through decentralization policies, strengthening of local supply chains, environmental education, information exchange, and international cooperation.

Fatimah et al. [7] studied solid waste management in Indonesia with the aim of identifying its main problems and opportunities, determining the maturity level of existing systems, and designing a smart and sustainable national model based on Industry 4.0 technologies. The methodology combined a systematic review of more than 40 studies, direct observation of collection, treatment, and final disposal centers, interviews, discussions with specialists, and semi-structured questionnaires applied to 78 participants linked to municipalities, recycling companies, collectors, informal recyclers, and communities in four Indonesian cities. The results showed that the four cities remained at a "common" maturity level, with their greatest deficiencies in the technological and environmental dimensions due to the low use of automation, IoT, and integrated information systems. Based on these findings, the authors developed a multidimensional model integrating governance, economy, society, environment, and technology, placing ICT and IoT at the center of the management chain.

Tundjungsari et al. [17] developed Circonomy with the aim of integrating an IoT-based smart bin, semantic web technologies, and gamification mechanisms within a circular management model geared toward Indonesian community waste banks. The research used the Design Science Research Methodology, organized into problem identification, solution proposal, prototyping, evaluation, learning extraction, and communication. A prototype was implemented with an ESP32, a load cell, an ultrasonic sensor, a servomotor, a mobile application, a web platform, and a server through a REST API. The technical evaluation considered sensor accuracy, response time, and data transmission, while user experience was evaluated with ten participants between 18 and 60 years old. The results showed a minimum accuracy of 80% in estimating capacity and data transmission, lid opening in under five seconds for 90% of the tests, perceived ease of use by 80% of participants, and motivation associated with gamification reported by 100% of them. The authors concluded that Circonomy presented acceptable performance for an initial prototype, with potential for scalability and low cost, although they recommended improving sensor placement, incorporating multiple measurement devices, and expanding the platform's challenges and rewards.

Vishnu et al. [18] proposed an IoT-enabled waste-management system aimed at the real-time monitoring of the fill level and location of containers installed in both public spaces and residential areas. The methodology included the design of a hybrid architecture with two types of nodes: PBLMU units for public containers, communicated through LoRaWAN, and HBLMU units for domestic containers, connected by Wi-Fi. The devices incorporated ultrasonic sensors, geolocation modules, energy-management systems, and MQTT communication, while a central graphical interface allowed the visualization of the data received. Validation was carried out with eight public and eight residential containers filled with paper, cardboard, bottles, and garments at different levels; consumption in active and standby modes was also measured to estimate the autonomy of the public node. The results showed that container fill levels could be transmitted and visualized on the platform, while the PBLMU node presented an average consumption of 1.5 mA and an estimated autonomy of approximately 70 days under hypothetical conditions. The authors concluded that the hybrid architecture was suitable for remote container monitoring in smart cities and proposed incorporating GIS systems and machine-learning algorithms to optimize collection routes.

3. Methodology

The research adopted a waterfall-based methodology because the development process required a sequential approach, progressing from problem identification to prototype validation. This methodology allowed the project to be organized into well-defined phases with specific outcomes, where each stage provided the necessary inputs for the subsequent one [19]. For the development of the HELIXA system, the waterfall approach was adapted into six phases: Requirements Analysis, System Design, Implementation, Testing, Deployment, and Maintenance. This structure facilitated the progressive integration of the hardware prototype, web platform, user evaluation, and field-validation activities, as shown in Figure 1.

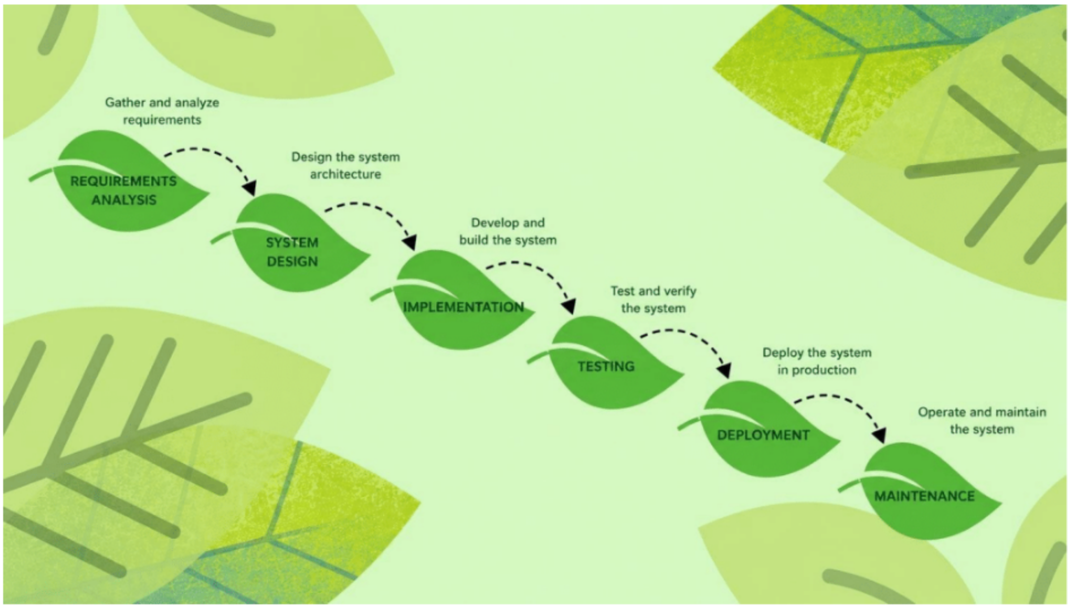

Figure 1: Waterfall methodology applied to the development of the HELIXA project.

3.1. Phase 1: Requirements Analysis

During this phase, information was collected through a review of the literature on solid waste management, recycling behavior, and gamification strategies, complemented by an anonymous survey administered to a non-probabilistic convenience sample of 80 participants from Universidad de Ciencias y Humanidades. The survey was conducted to identify users' recycling habits, perceptions, and motivational factors related to recycling,

and included items assessing the frequency of recycling, the perceived attractiveness of the proposed HELIXA platform, and the factors that could encourage more consistent recycling behavior, such as points, rewards, environmental information, and challenges. It should be noted that the 80 survey respondents and the 65 users who later registered on the HELIXA platform constitute two distinct, partially overlapping convenience samples: not every survey respondent went on to register on the platform, and some registered users joined directly at the field events without completing the initial survey. The collected data were analyzed to characterize the initial perceptions of the target community and to support the design decisions adopted in the subsequent phase.

Because the platform relies on the Peruvian national identity document number (DNI) as a unique key for identifying users in the MySQL database, specific data-privacy safeguards were adopted. Access to the DNI field was restricted to the system administrator through role-based credentials, all transmission between the client and the server occurred over encrypted HTTPS/TLS connections, and the DNI value was used strictly for user de-duplication and reward-redemption verification, consistent with the principles of data minimization and purpose limitation established under Peru's Personal Data Protection Law (Law No. 29733) and its regulations. No DNI data was shared with third parties, and users were informed of this use during the registration process.

3.2. Phase 2: System Design

During this phase, the architecture of the HELIXA system was designed to integrate both the physical prototype and the web platform. The proposed architecture consisted of two layers: a physical layer, composed of the smart recycling bin, an ESP32 microcontroller, an HC-SR04 ultrasonic sensor, an I2C LCD display, and a matrix keypad; and a digital layer, consisting of a responsive web platform responsible for user registration, point management, rankings, rewards, and the visualization of recycling metrics. The overall client–server architecture is presented in Figure 2.

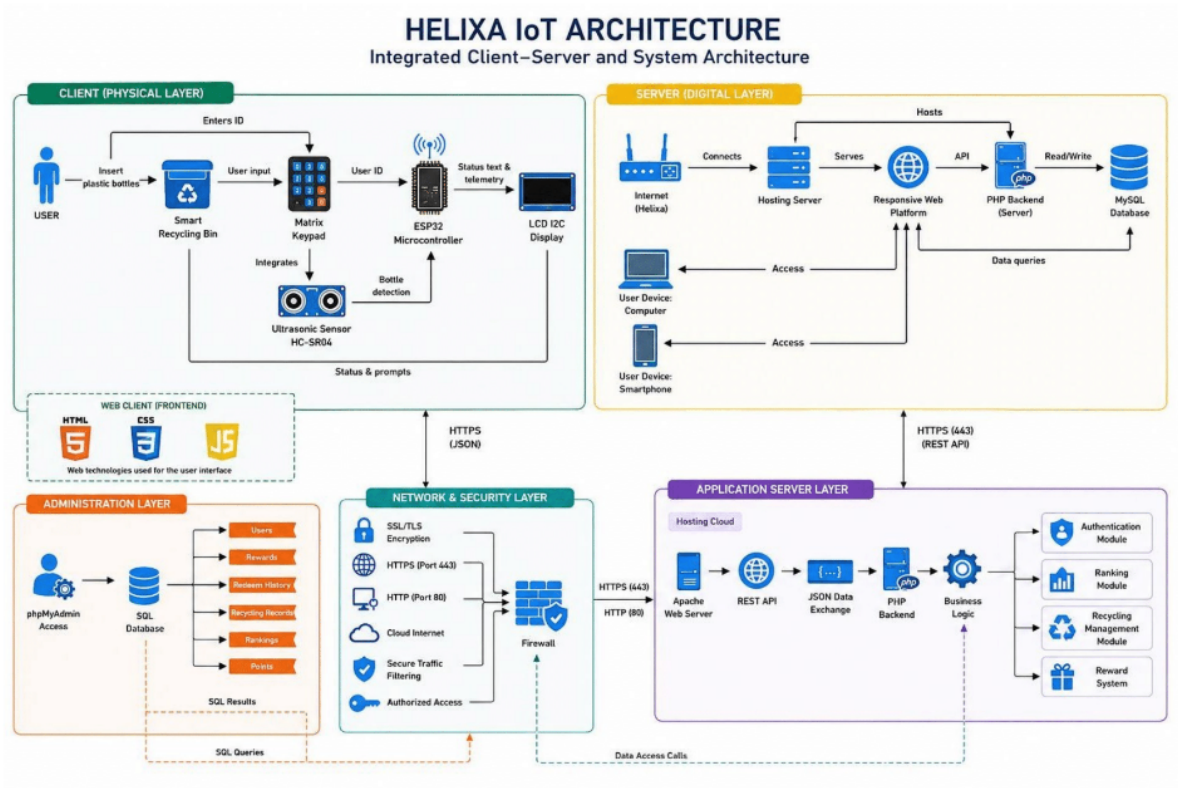

Figure 2: Overall client–server architecture of the HELIXA system.

The hardware configuration of the prototype was defined by selecting the electronic components required for bottle detection, user interaction, data processing, and communication with the web platform. Table 1 summarizes the main hardware components and their respective functions, while the physical interconnection of these components is illustrated in Figure 3.

Table 1
Main Components of the HELIXA Prototype.

Component	Function
ESP32	Control and communication
HC-SR04	Bottle detection
LCD I2C	User feedback display
Keypad	DNI/ID input
Bin (Tacho)	Physical collection
Mounting	Mounting and isolation

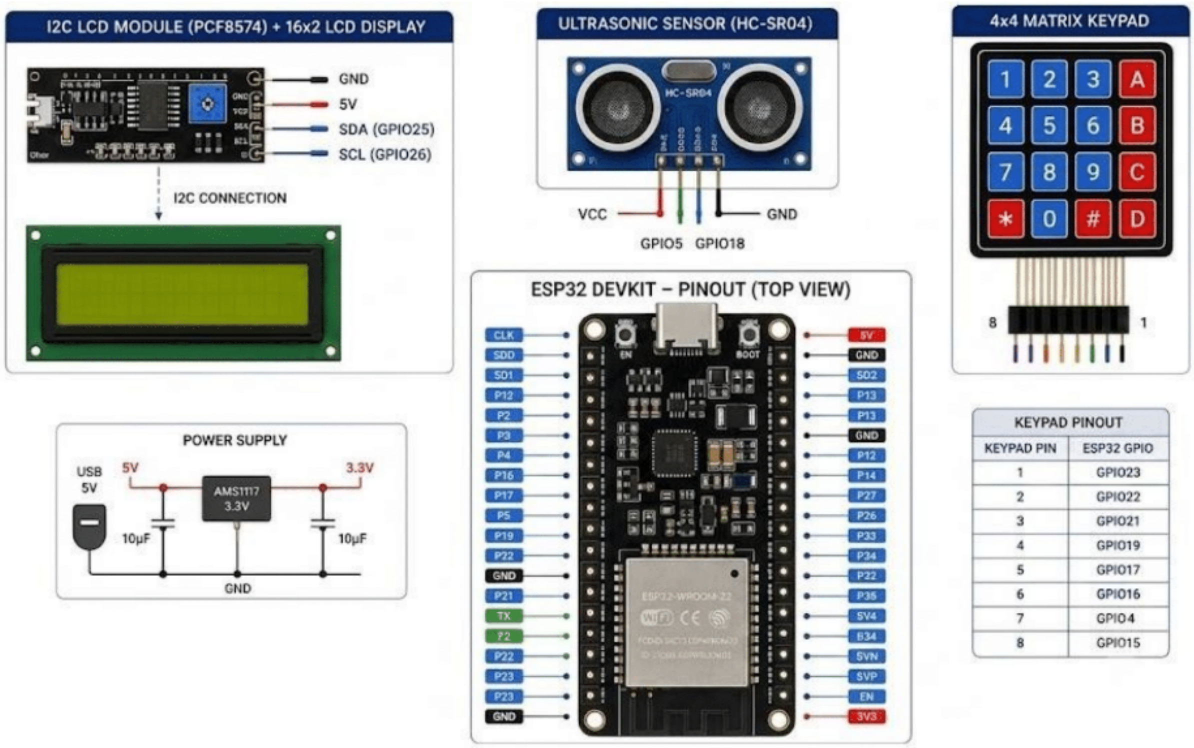

Figure 3: Pictorial diagram of the HELIXA electronic prototype.

3.3. Phase 3: Implementation

During this phase, the HELIXA prototype was implemented by integrating the physical components and the digital platform. The physical prototype was assembled on a plastic recycling bin with dimensions of 1.20 m × 0.60 m. The ultrasonic sensor was configured to detect the presence of bottles, while the ESP32 microcontroller processed the input data and managed the interaction between hardware components. The I2C LCD display provided real-time feedback to users, and the numeric keypad enabled user identification through DNI/ID input.

The electronic components were integrated through wiring, soldering, and internal fixation using low-cost materials to ensure a compact and functional assembly. In parallel, the responsive web platform was implemented to manage user records, points, rankings, rewards, and recycling statistics. The communication between the physical prototype and the digital platform allowed the registration of recycling actions and the visualization of user-participation metrics.

3.4. Phase 4: Testing

During this phase, functional tests were performed to validate the correct operation of the HELIXA system and the integration between its hardware and software components. The user-identification module was evaluated through different DNI/ID input scenarios: first, a valid simulated DNI verified the registration process; subsequently, invalid inputs with an incorrect number of digits were introduced to evaluate the system's input-validation mechanism; then, real DNI numbers from the development team were used to verify user registration and data management; finally, real users were registered on the platform to validate the account-creation process under normal operating conditions.

Figure 4: Physical prototype of HELIXA during hardware–software integration tests.

The hardware components were also tested by introducing different bottles into the smart bin to verify the detection capability of the ultrasonic sensor and the correct response of the system during the recycling process. The interaction between the sensor, the ESP32 microcontroller, the LCD display, and the user-input module was evaluated to ensure the proper operation of the prototype, as shown in Figure 4.

3.5. Phase 5: Deployment

During this phase, the HELIXA web platform was deployed as a functional and responsive system focused on promoting recycling behavior through gamification mechanisms. The deployed platform included modules for user authentication, personalized dashboards, bottle counting, accumulated points, rankings, a rewards catalog, and progress visualization. The interface was designed with an eco-technological, user-friendly, and intuitive approach to encourage continuous interaction and facilitate access to recycling-performance indicators.

The deployment process allowed users to access their personal information, monitor their recycling contributions, and interact with the gamification elements integrated into the platform. Figure 5 shows the user dashboard of the HELIXA web platform, including the main participation metrics.

3.6. Phase 6: Maintenance

During this phase, the HELIXA prototype was monitored after deployment through real-world testing activities conducted at Universidad de Ciencias y Humanidades (UCH). The evaluation was carried out during two environmental events: the Activación Ambiental Reciclatón, held on 28/05/2026, and the Feria de Emprendimientos Ambientales, held on 05/06/2026. During these activities, user interaction with the prototype was observed, bottle-collection processes were evaluated, and the integration between the smart bin, the web platform, and the reward system was verified. The system operated under real usage conditions, allowing the identification of possible improvement opportunities related

Figure 5: Web platform user dashboard with engagement metrics.

to usability and user experience. No corrective maintenance actions or modifications to the hardware or software components were required during this evaluation period. Figure 6 shows the HELIXA prototype during field-evaluation activities at an environmental fair.

Figure 6: Field evaluation of the HELIXA prototype during an environmental fair.

4. Results

4.1. Smart Bin Hardware Prototype

A functional prototype of a smart bin (see Figure 7) was obtained, capable of recording recycling actions through user interaction with the keypad, bottle detection through the ultrasonic sensor, and process confirmation through the LCD screen. The integration of the ESP32 microcontroller, the HC-SR04 ultrasonic sensor, the I2C LCD display, and the matrix keypad enabled the recycling-log flow to execute correctly. The use of accessible, low-cost components demonstrated the feasibility of implementing the proposed solution in educational settings with limited resources.

Figure 7: HELIXA system prototype during field operation at an environmental fair.

Regarding hardware reliability, throughout the two field events the ESP32 microcontroller operated continuously without restarts or communication interruptions with the web platform. The HC-SR04 ultrasonic sensor achieved consistent bottle-detection triggering when bottles were inserted within its effective detection cone, although placements at extreme lateral angles occasionally required a second insertion attempt. The matrix keypad handled all 359 bottle-deposit confirmations together with the identification inputs of the 65 registered users without any reported key failure, and no corrective hardware maintenance was required throughout the evaluation period (see Phase 6). While these observations are preliminary and based on a short field-testing window rather than an instrumented reliability study, they provide an initial positive indicator of component robustness under real usage conditions. A more rigorous quantitative assessment of detection accuracy and response latency, following protocols similar to those used in comparable IoT-based recycling systems [17, 18], is identified as future work.

4.2. Web Platform - HELIXA

Figure 8: Rewards module available on the HELIXA platform.

The HELIXA web platform was developed and implemented as a digital component aimed at monitoring and motivating users' recycling activities. The system made it possible to manage users, record individual progress, and visualize participation indicators through an interactive dashboard. The integration of gamification elements accumulated points, achievements, rankings, and rewards, transformed the recycling process into a more dynamic, motivating, and interactive experience. The ranking and reward modules were designed to promote both individual and collective participation, as shown in Figure 8.

4.3. Survey Results

The survey applied to the convenience sample of 80 participants showed a positive reception toward the proposal. On the question of attraction to HELIXA, most participants selected the highest values of the scale, indicating an initial acceptance of the system, as shown in Figure 9. The results on motivation suggest that recycling points, rewards, achievements, environmental information, and challenges could increase the frequency of recycling, as shown in Figure 10.

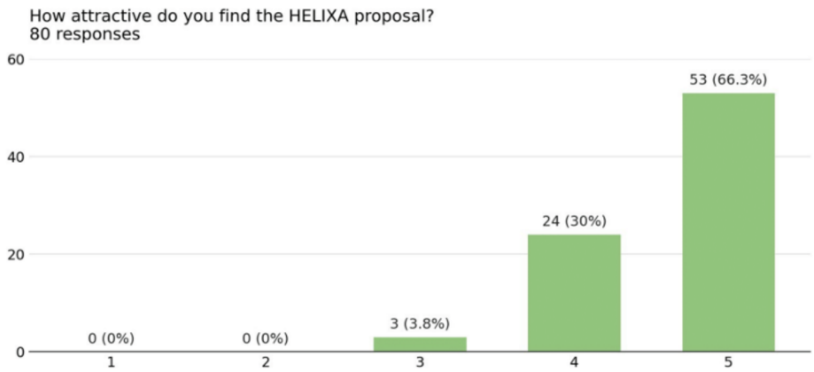

Figure 9: Result of perception on how attractive the HELIXA proposal was.

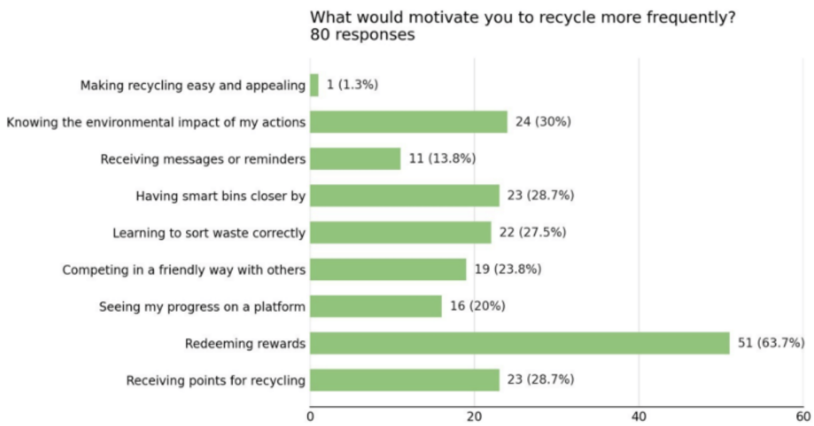

Figure 10: Factors that would motivate recycling more frequently.

4.4. Tests at Face-to-Face Fairs

In the validation events, a total of 359 bottles were collected. The first fair registered 103 bottles in 1 h 30 min, and the second fair registered 256 bottles in a similar time span, an additional 153 bottles, confirming a considerable increase in participation and visibility of the HELIXA system between the two events (Table 2).

Table 2
Data Collection at In-Person Trade Fairs.

Event	Bottles	Result
First fair	103	Initial validation.
Second fair	256	Increased participation.
Difference	+153	Significant growth.

4.5. Budgetary and Financial Indicators

The total investment of the project amounted to S/ 4,290.36, considering hardware materials, development of the web platform, and estimated labor. The cost of software accounted for the largest proportion of the investment, including UI/UX design, front end, back end, integration, testing, domain, hosting, and maintenance.

Table 3
Projected Revenue Flows.

Period	Projected income (S/)	Discount factor(12%)	Present value (S/)
Year 1	S/ 800.00	1.1200	S/ 714.29
Year 2	S/ 1,200.00	1.2544	S/ 956.63
Year 3	S/ 1,600.00	1.4049	S/ 1,138.85
Year 4	S/ 2,000.00	1.5735	S/ 1,271.04
Year 5	S/ 2,400.00	1.7623	S/ 1,361.82
Total revenue	S/ 8,000.00	–	–

Table 4
Financial Indicators.

Indicator	Value	Reading	Conclusion
NPV	S/ 1,152.27	Present value of future cash flows discounted at 12%, minus the initial investment.	Positive NPV: the project generates value. Viable.
IRR	20.57%	Rate at which NPV equals zero; compared against the discount rate (12%).	IRR (20.57%) > discount rate (12%): acceptable return.
ROI	86.46%	Percentage of profit on the total investment after 5 years.	Positive ROI (86.46%): the investment is recovered and generates profit.

The projected revenue flows presented in Table 3 originate from three complementary sources identified during the financial feasibility analysis: (i) the sale of the collected recyclable material (PET plastic bottles) to recycling companies and formal collection intermediaries; (ii) institutional sponsorships from businesses interested in supporting social and environmental responsibility initiatives in exchange for visibility within the HELIXA platform and at campus events; and (iii) municipal convenio (cooperation agreement) arrangements with local government entities interested in extending the HELIXA model to public spaces. Each revenue stream was projected conservatively, assuming a gradual increase in scale over the five-year horizon shown in Table 4.

As shown, the financial indicators suggest initial viability, especially since the project can operate with accessible materials and a reusable platform. However, profitability will depend on the scale of implementation, maintenance, partnerships for rewards, and the sustainability of user participation over time.

5. Discussion

In relation to Sharma et al. [16], HELIXA agrees that the transition to a circular economy requires combining recycling infrastructure, citizen participation, and socio-economic benefits. While that study addressed waste management from a broad review aimed at public policy, the creation of green jobs, the formalization of recyclers, and compliance with the SDGs, HELIXA transferred these principles to a concrete intervention within a university environment. In this way, the system made it possible to visualize and reward individual recycling actions, providing a practical, small-scale application. However, HELIXA has not yet completely closed the circular cycle, since the subsequent traceability of the bottles and their formal articulation with recyclers or recovery companies was not documented. Likewise, while the projected NPV, IRR, and ROI suggested initial economic viability, these indicators should be complemented by operating costs and environmental benefits measured over extended periods.

This need to integrate different actors was also identified by Fatimah et al. [7], who formulated a nationwide IoT-based smart management system and assessed the waste chain through observations and consultations with 78 participants from four Indonesian cities. Unlike this multidimensional model, which incorporated governance, transport, treatment, resource recovery, and the participation of municipalities, companies, and recyclers, HELIXA focused on the initial segregation of bottles and user motivation within a controlled space. Its main advantage was materializing the interaction between hardware, digital platform, and user through a functional prototype; however, its institutional scope was narrower. Therefore, scaling up HELIXA will require defining responsibilities for the collection, storage, transport, and recovery of bottles, in addition to incorporating environmental and operational indicators that allow the system's maturity to be evaluated beyond the number of registered deposits.

The most direct comparison occurred with Circonomy, developed by Tundjungsari et al. [17], since both systems used an ESP32, ultrasonic sensors, digital platforms, and gamification mechanisms based on points, rankings, and rewards. However, Circonomy incorporated a load cell, automatic opening, QR-code identification, a mobile application, and semantic web technologies, in addition to quantitatively evaluating its technical performance, achieving at least 80% accuracy in measurement and data transmission, a response time under five seconds in 90% of tests, and full acceptance of gamification among its ten participants. HELIXA, in contrast, presented a simpler architecture based on a keypad, an LCD, and a web platform, but was exposed to a larger number of users across two face-to-face activities, in which 359 bottles were collected. Circonomy therefore showed more detailed technical validation, while HELIXA provided more evidence of interaction in a real university context. In both cases, the short evaluation period makes it impossible to determine whether user motivation will be sustained once the novelty effect diminishes.

From the perspective of technological scalability, Vishnu et al. [18] developed a hybrid architecture to monitor eight public containers using LoRaWAN and eight residential containers using Wi-Fi, incorporating geolocation, centralized visualization, and energy management, achieving an average consumption of 1.5 mA and an estimated autonomy of 70 days. A comparable multiagent-simulation approach for IoT-enabled smart city waste-management models, proposed by Hussain et al. [20], likewise emphasized the importance of coordinating multiple collection nodes at scale. In contrast, HELIXA prioritized user identification and the modification of the recycling experience, but did not evaluate energy consumption, autonomy, continuous fill level, or communication between multiple bins. These approaches are complementary: HELIXA addressed human participation, while Vishnu et al. and Hussain et al. focused on logistics and network efficiency. A future expansion could combine HELIXA's gamification with remote monitoring, capacity alerts, and long-range connectivity to facilitate implementation across different university venues. Overall, HELIXA's main contribution was to demonstrate the initial feasibility of integrating accessible technologies with a gamified recycling experience in a Peruvian university. To strengthen the evidence, it will be necessary to measure detection accuracy, recording errors, communication availability, the number of recurring users, and the recycling rate before and after the intervention. Longitudinal evaluations and verifiable traceability of the collected material are also required to determine whether the system generates sustained changes and measurable environmental benefits beyond the initial acceptance observed during the fairs.

5.1. Limitations

Several limitations should be considered when interpreting these results. First, the evaluation period was short, consisting of two university fairs held within a few weeks of each other, which does not allow conclusions about the sustainability of user motivation over months or academic terms. Second, the growth observed between the two events from 103 to 256 bottles, for a total of 359 is consistent with a novelty effect: attendance, curiosity, and event-driven visibility likely contributed to participation at least as much as the gamification mechanics themselves, and it remains unclear how much of this increase would persist under routine, non-event conditions. Prior evidence on citizen engagement in recycling suggests that well-designed incentive structures, rather than novelty alone, are what sustain participation over time [21], which reinforces the need for longitudinal follow-up once the initial novelty has faded. Third, both the survey (80 respondents) and the registered-user sample (65 users) were obtained through convenience sampling within a single university, which limits the generalizability of the findings to other institutions, age groups, or socioeconomic contexts; a probabilistic or multi-site sample would be required before extrapolating these results to municipalities or companies. Finally, the financial indicators (NPV, IRR, and ROI) rely on projected, rather than realized, revenue and should be revisited once recurring institutional sponsorships and municipal agreements are formally established.

6. Conclusion

HELIXA was developed and validated as an eco-technological recycling system that integrates a smart bin and a gamified web platform to encourage the recycling of plastic bottles in a university environment, demonstrating that digital registration, points, achievements, rankings, and rewards can turn an everyday environmental action into a participatory and motivating experience. The waterfall methodology organized the work into phases of diagnostic survey, design, hardware and software development, implementation, and testing, which allowed the integration of physical and digital components and the validation of the system under real conditions.

The validation involved 80 survey respondents, 65 registered users, two face-to-face events, and 359 bottles collected, with growth from 103 to 256 bottles between fairs. These results confirmed a favorable reception, although the short evaluation period did not allow a determination of whether motivation will be sustained beyond the novelty effect.

The financial analysis showed an investment of S/ 4,290.36, an NPV of S/ 1,152.27, an IRR of 20.57%, and an ROI of 86.46% over five years indicators that suggest initial viability conditioned on the strengthening of alliances and the traceability of recycled material.

As future work, HELIXA will be implemented in additional organizations and expanded to other institutions; sensors will be improved and automatic classification by artificial vision incorporated; energy consumption and long-range connectivity for the remote monitoring of multiple bins will be evaluated; a native mobile application with real-time notifications will be developed; and alliances with recyclers and sustainable companies will be established to document the traceability of the material and expand the rewards catalog, in addition to conducting longitudinal evaluations that measure the recycling rate and user retention beyond the initial acceptance.

Declaration on Generative AI

During the preparation of this manuscript, the authors authored all original text, scientific content, methodology, data analysis, and conclusions entirely through human effort. Generative artificial intelligence tools were employed exclusively for low-level English-language polishing, grammar correction, and typographical refinement of the text previously drafted by the authors. No AI tools were used to generate original ideas, scientific data, technical analysis, or conclusions. The authors personally wrote, reviewed, and edited every section of this publication, and they assume full and sole responsibility for the final content.

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