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Original Article

Design and Development of a Mobile Application for the Efficient Management and Identification of Solid Waste in North Lima

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Abstract *- This paper presents the design and development of a mobile application for solid waste management in Lima Norte, Peru. The region faces significant waste accumulation, sanitation, and public health challenges due to rapid urbanization and inadequate waste disposal practices. The studio combines design thinking and Lean Startup methodologies to understand user needs, prototype solutions iteratively, and validate them effectively. The app allows users to report waste, identify recyclable materials through image recognition, and make general recommendations on waste management. The survey results of 50 potential users indicate a positive response towards the app, with high usability and usability scores. The image sorting model, trained with Teachable Machine and implemented with TensorFlow Lite, accurately identifies waste types from user-submitted photos. The discussions highlight the app's potential impact on waste management in North Lima, along with recommendations for future improvements and collaborations with local authorities. The study underscores the importance of leveraging mobile technology to address environmental challenges and promote community engagement in waste management efforts.*

Keywords *- Solid waste, Technological innovation, Design thinking, Lean startup, Mobile app.*

1. Introduction

Solid waste management in the North Lima region is a growing concern due to the high population density, accelerated urban growth, and lack of good waste collection and disposal practices among the inhabitants. This problem is reflected in statistics that indicate that the accumulation of waste and public cleanliness occupies the second place, with 34.9%, among the main problems that impact the quality of life in the city of Lima and Callao, specifically, North Lima and South Lima present the highest percentages of problems related to waste management, with 42.0% and 43.1% respectively, compared to other areas such as East Lima, which registers 25.2%. These figures underscore the crucial importance of addressing the problem of public cleanliness in North Lima [1]. On the other hand, it is evident that the coastal region, especially Lima and Callao, faces a significant generation of solid waste. In 2014, daily waste production nationwide reached 13,244 tons, of which Lima and Callao contributed 5,970 tons per day, followed by coastal cities with 3,224 tons per day [2]. These data highlight the urgent need to implement effective solid waste management strategies, especially in densely populated urban areas such as North Lima, where the accumulation of garbage severely affects the quality of life. In this context, [3] poor waste disposal in Peru has multiple negative consequences, including the visual deterioration of streets and public spaces, the generation of unhygienic environments and cost overruns in managing waste transfer and final disposal. In the most severe cases, waste is not collected from the streets, which affects the value of properties and businesses in the area and constitutes a public health hazard by becoming a source of infection. This scenario poses a potential risk to the population and represents an obstacle to sustainable urban development. In addition, the lack of sufficient and strategically placed containers makes it even more difficult to keep the environment clean. This is because most municipalities in the country carry out solid waste management without having crucial information on its characterization and generation. As a direct consequence of this shortage, the population experiences a low quality of services. In addition, the lack of these studies leads to improvisation in the solutions offered, resulting in ineffective waste management [4]. Another worrying aspect is the lack of environmental awareness and the population's scarcity of separation and recycling practices. It is shown that municipalities at the national level have deficiencies in the management of solid waste generated in households due to the lack of adequate sanitary landfills, which results in informal dumps, generating a source of contamination and the spread of diseases. The Environmental Assessment and Control Agency (OEFA) has identified more than 1585 dumps throughout the country, showing the problem's magnitude and the urgency of addressing it [5]. Lack of access to educational programs about recycling and waste reduction contributes to a low rate of waste segregation at source and fewer recyclables recovered. It is mentioned that solid waste management follows a chained process that involves several elements, such as proper waste collection, organized transportation, and trained personnel. In addition, adequate waste disposal systems and fully automated monitoring systems are required, as well as public awareness of appropriate actions in this context [6]. A promising strategy to improve knowledge about recycling, and consequently recycling behaviour in households, is using mobile applications. Therefore, these apps can provide people with up-to-date information to acquire the right knowledge about waste recycling, increasing the likelihood that they will recycle household waste and do it correctly [7]. In this sense, this research aims to design and develop a mobile application that contributes to the efficient management of solid waste in North Lima, promoting environmental awareness and facilitating the community's involvement in the segregation and proper disposal of waste. In this article, the structure is as follows: in Section II, a review of the literature on solid waste management will be carried out, while in Section III, the methodology will be detailed. In Section IV, the results obtained after the implementation of the application will be presented. In Section V, the discussions on the findings and, finally, conclusions and recommendations will be provided in Section VI.

2. Literature Review

In this section, we will examine relevant research that addresses the issue of garbage accumulation, efficiency in waste collection and disposal, and the role of technology, such as mobile applications, in sustainable solid waste management. This review seeks to identify the most effective practices and lessons learned that can be applied to the design and implementation of the proposed mobile application for Lima Norte. According to the authors [8], applying the Design Thinking methodology has proven to be an effective strategy for improving education and awareness about solid waste management. Using this methodology, innovative prototypes designed to meet the needs identified by users and subject matter experts were developed and evaluated, thus establishing a solid foundation for future interventions. Their research highlighted the importance of community and policy engagement in the search for sustainable solutions. In addition, they noted that previous studies have given high scores in usability (86/100) and quality (87/100) to the prototypes developed, indicating the potential of this methodology to address challenges related to solid waste management in urban environments. These findings highlight the need for innovative and collaborative approaches to urban waste management. The application of design thinking provides practical and user-centred solutions and encourages community and government participation in promoting sustainable practices. This integrative approach can be instrumental in driving significant improvements in waste management and ensuring a cleaner future for our cities. The work presented by the authors [9] proposes an IoT-based EcoWaste mobile app to facilitate recycling-as-a-service in developing and emerging countries. This application, developed using Java through the Android Studio Integrated Development Environment, connects to a real-time database (Firebase) and the Google Maps service. In addition, it allows users to request the collection of their waste efficiently and without expensive hardware. The proposal shows considerable potential to improve waste management in resource-limited urban environments. EcoWaste illustrates how technology can be a powerful tool to address social and environmental challenges. This initiative highlights the importance of collaboration between sectors to drive innovative solutions promoting a more sustainable future. On the other hand, the authors [10] focused their research on implementing a prototype mobile application, 'Pilahin', designed to encourage the participation of households, especially housewives, through sorting household waste. The developed app allows users to scan and detect garbage, provide garbage categories to identify and sort, and find nearby garbage banks.

The research included tests with 4 target users, which mostly demonstrated satisfactory results and rapid app adoption. This study on the 'Pilahin' app highlights the potential of mobile technologies to promote sustainable practices, such as household waste sorting. However, it is also important to recognize that technological solutions, on their own, are not enough to address environmental challenges fully. Strong policies, continuing education, and changes in human behavior are needed to make a meaningful impact on waste management and environmental preservation. The approach proposed by the authors [11] presents a mobile or web-based system that uses tools such as Android or web apps, a server database, and the Google Maps API. This system called the Location-Based Waste Management System for Smart Cities, facilitates the effective management of the garbage collected daily by the government while offering an improved solution for citizens regarding garbage disposal. The app developed for staff and citizens provides generated routes, bin location, a technologically advanced grievance system, daily waste collection status monitoring, and other incentives to foster a cultural shift in waste segregation. This innovative approach to urban waste management shows the potential of using technology to improve efficiency and sustainability. However, its success will depend on strong collaboration between the government, the community, and tech companies. The Valdivia Clean City project, developed by the authors [12], developed a web and mobile application to address the waste collection challenges of the Municipality of Valdivia in Chile. Based on free and open-source software. Its purpose is to improve communication between users and service providers, and it also offers educational materials on waste management and other environmental issues. It includes a dynamic map viewer, forms for reporting illegal dumping, service status notifications, and educational content. The mobile app, developed with the Ionic and Angular framework, provides functionalities similar to the web interface. The above authors' implementation underscores technology's power to improve solid waste management at the local level. This initiative highlights how mobile and web applications can facilitate communication between the community and the authorities, encouraging citizen participation in environmental protection. It is a reminder of how digital innovation can effectively promote environmentally responsible practices and build cleaner, healthier, and more conscious communities.

Another relevant study in this area is by the authors [13], who propose an intelligent system for solid waste management using the Internet of Things (IoT). Their system includes a smart container with a unique identifier (RFID tag) and an ultrasonic sensor to measure the level of waste in the container. In addition, they developed a mobile app for two types of users: the normal user, who can locate nearby bins, and the garbage collector, who can assess the waste level of the bins remotely. When the bin is full, an alert is sent to the trash collector, and the shortest route to the bin is displayed. They use a genetic algorithm to optimize the path from the user to the smart bin. This model is presented as a cost-effective and efficient alternative to the traditional waste management system, ensuring less time and human effort consumption in the solid waste management process. In another context, the authors [14] investigated motivation, interest and participation in upcycling in Singapore. Using the design thinking methodology, they were able to identify the needs and frustrations of the stakeholders. Based on these findings, they developed and prototyped a mobile app-assisted waste marketplace platform to reduce upcycling barriers by pooling commercially available materials and offering crowdsourced knowledge on upcycling. User testing yielded positive results, indicating that the platform can improve awareness of upcycling and facilitate upcycling through better usability and cultural promotion. Company feedback was also positive, corroborating the viability and potential impact of the platform to promote upcycling in Singapore. This approach demonstrates how user-centred design can increase the acceptance and use of waste management technologies, being adaptable to other cultural and economic contexts.

With the potential environmental and health risks arising from the improper collection and transport of municipal solid waste in open containers, the authors [15] have developed an innovative system based on smart technology called "e-smart", designed to store and transport solid waste efficiently and sustainably. This system uses sensory devices and GPS technology to monitor and control waste filling, collection and transport, thus minimizing environmental pollution and health risks associated with improper waste management. In addition, this system provides substantial economic savings, with estimates showing up to a 40% reduction in total project costs compared to conventional waste management methods. However, despite its advantages, the system initially requires considerable investment, although its operation and maintenance costs are relatively low compared to manual waste collection methods. These findings suggest that the e-smart approach has great potential to improve the efficiency and sustainability of municipal solid waste management systems, thereby promoting a cleaner and healthier environment for urban communities. In solid waste management, the authors [16] propose an innovative IoT-powered system for urban areas and developing countries. This study addresses the problem of lack of planning and resources in densely populated areas by implementing a decentralized solution based on blockchain-enabled ad-hoc Vehicular Networks (VANET). Ultra-High-Frequency (UHF) technology is used with IoT devices to locate waste vehicles in real-time and detect containers. In addition, geo-fencing techniques are applied for monitoring and timely waste collection. Blockchain technology is integrated to ensure machine-to-machine (M2M) communication, ensuring the security and reliability of the system. Experimental results obtained from a pilot project in Karachi, Pakistan, demonstrate the success of this solution in real-time tracking, intelligent container identification, waste weighing, and collection point monitoring. The authors suggest that, in the future, this technology could also be applied to route and fleet management, as well as smart transportation, due to the inherent features of blockchain and IoT.

On the other hand, to reduce the costs associated with sorting, monitoring, and waste collection, the authors [17] proposed a municipal waste management system that uses cloud computing and deep learning to reduce waste sorting, monitoring, and collection costs. This system uses Convolutional Neural Networks (CNNs) to sort recyclable waste into six categories: plastic, glass, paper or cardboard, metal, fabric, etc. MobileNetV3 stood out with 94.26% accuracy, 49.5 MB storage size, and 261.7 ms operation speed. In addition, IoT devices allow the exchange of information between the waste containers and the waste management centre, facilitating real-time monitoring of the waste volume and the containers' operational status using gas and ultrasound sensors. This innovative approach not only improves the efficiency of the waste management system but also encourages citizens to sort waste at the source, contributing to the conservation of the environment. Regarding the search for innovative solutions to address the problem of environmental pollution, a study was conducted where the development of a mobile application was proposed as the main tool. This initiative, led by the authors [18], consists of implementing cutting-edge technologies, such as Android Studio and Firebase, to store user data in the cloud and facilitate its access in real-time. The app promotes recycling practices and environmental awareness, offering tangible incentives to users through prizes or points in collaboration with brands and sponsors committed to preserving the environment.

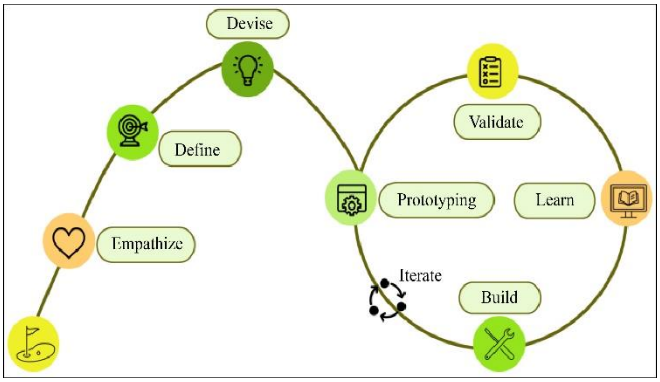


Fig. 1 Diagram of the design thinking + lean startup methodology

In addition, the studio adopts the Scrum methodology, which is recognized for its ability to adapt and respond quickly to changes, thus guaranteeing customer satisfaction and continuous product improvement. This research highlights the importance of feedback from users, whose participation has contributed significantly to the optimization of the application, allowing the inclusion of key functionalities such as the identification of less polluted areas, the location of recycling points and the generation of efficient routes, all aimed at providing a comprehensive and valuable experience for the inhabitants of the Los Olivos district.

3. Methodology

This section details the methodological approach used to develop the mobile application to improve solid waste management in northern Lima. We have decided to combine design thinking and lean startup approaches. This combination provides a comprehensive framework that allows for a deep understanding of user needs, agile prototyping of solutions, and continuous validation in the market. Through this methodology, the aim is to create an effective, user-centric application with a focus on innovation and efficiency.

3.1. Design Thinking + Lean Startup

This combined methodology between Design Thinking and Lean Startup provides a comprehensive framework covering the process's different stages, from understanding the user's needs to the continuous validation of solutions in the market. It will leverage the synergy between Design Thinking, which prioritizes empathy and creativity, and Lean Startup, which focuses on rapid iteration and validation, to ensure efficient and user-centric development. In this context, the key phases of this combined methodology are presented in Figure 1, highlighting the sequence of activities and workflow for successfully creating the mobile application.

3.1.1. Empathize

In this phase, the goal is to understand users' needs, wants, and experiences to identify opportunities for improvement. According to [19], it seeks to fully understand the needs and experiences of the user in order to create solutions that adapt to their context.

3.1.2. Define

The information collected in the empathy phase is analyzed and synthesized to precisely define the problem to be solved and establish specific objectives.

According to [20], compares, decides, and selects between possible solutions in a more structured environment.

3.1.3. Devise

Creative ideas are generated, and possible solutions to the defined problem are explored. According to [21], the necessary resources are provided to create prototypes and generate innovative solutions, encouraging the acceptance of all ideas.

3.1.4. Prototyping

Low-fidelity prototypes are developed to test and refine proposed solutions. According to [22], a solution is developed that encompasses a selection of the features requested by the user, allowing them to experience it.

3.1.5. Validate

The prototype is tested realistically to assess its effectiveness and feasibility. According to [23], surveys are developed as data collection tools.

3.1.6. Learn

Test results are reflected upon, and key lessons are drawn to inform the development process. According to [24], the viability of the business is evaluated, and it is decided whether to continue or pivot based on the results.

3.1.7. Build

The final version of the mobile application is developed based on what was learned during the previous phases. According to [25], a Minimum Viable Product (MVP) is developed that we use to validate or invalidate hypotheses.

3.2. Flowchart

This section shows the flowchart presenting the complete process of the mobile application for solid waste management in North Lima. Figure 2 shows that the process starts with the option to register or log in, depending on the user's situation.

Once inside, a panel of options encompassing various functions, such as reporting waste or accessing educational resources on environmental management, are displayed.

If you report waste, you are guided through the process, followed by the option to view incidents or the reporting/recycling map. Alternatively, if you opt for environmental education, you are presented with relevant information and recommendations on waste management. Finally, the option to log out to conclude the interaction is offered.

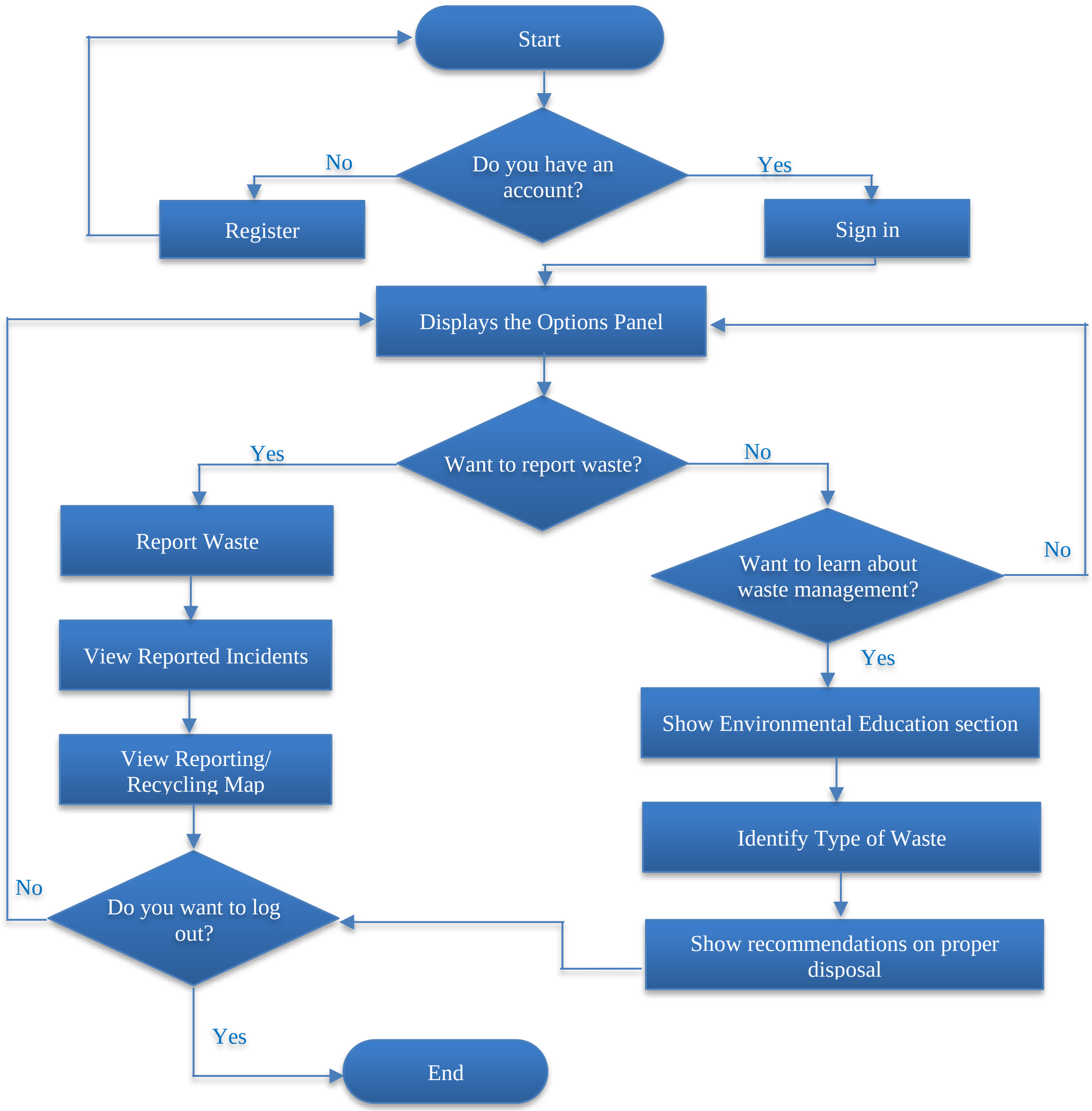


Fig. 2 Mobile app flowchart

According to the visual presentation provided in Figure 2, the process approach includes the following:

a) Sign In: This process allows registered users to access the mobile app using their created login credentials. By logging in, users can access all the application functionalities, such as reporting waste, accessing the map of reports and recycling, and participating in environmental education activities. A user authentication system will be implemented using Firebase Authentication for this functionality. Users can log in using their pre-registered email address and password.

b) Report Waste: This functionality allows users to report solid waste in specific areas of North Lima. This process helps to create a visual record of garbage accumulation points and facilitates their subsequent collection and management by the relevant authorities. Users can capture and submit photos of the waste and provide additional information, such as the exact location and type of waste. Users can take photos when reporting waste using their mobile devices' cameras. These images will be uploaded and stored in Firebase Storage for later viewing and management.

c) Report & Recycling Map: This section of the flowchart shows how users can visualize on an interactive map the waste reports made by other users and the location of available recycling points in North Lima. Users can explore the map to identify areas with high waste concentration and find nearby recycling points to dispose of their waste properly. The waste reports and recycling points will be visualised through the integration of Google Maps API.

d) Environmental Education: This process shows a unique functionality that will allow users to identify the type of waste through the capture of photographs. The app will automatically process the image using artificial intelligence algorithms and image recognition techniques to determine the type of waste. Once the type of waste is identified, the app will provide personalized recommendations on properly handling that type of waste.

3.3. Software Architecture

Figure 3 illustrates the software architecture, which focuses on a mobile application that interacts with a variety of cloud services through a centralized API. A user operates the mobile application at the client layer, designed with an intuitive interface, which communicates with external services through API requests. This API is managed by Ktor, a lightweight and efficient Kotlin framework for building asynchronous web applications and microservices. The API interacts with multiple technology services on the server side:

Firebase for user authentication and Firebase Cloud Storage for file storage. In addition, it integrates with Google Cloud's Firestore for database management and Teachable Machine to incorporate machine learning capabilities, along with TensorFlow Lite for image classification. This design allows for clear and efficient segregation between UI logic and data processing and takes advantage of the scalability and security offered by cloud services.

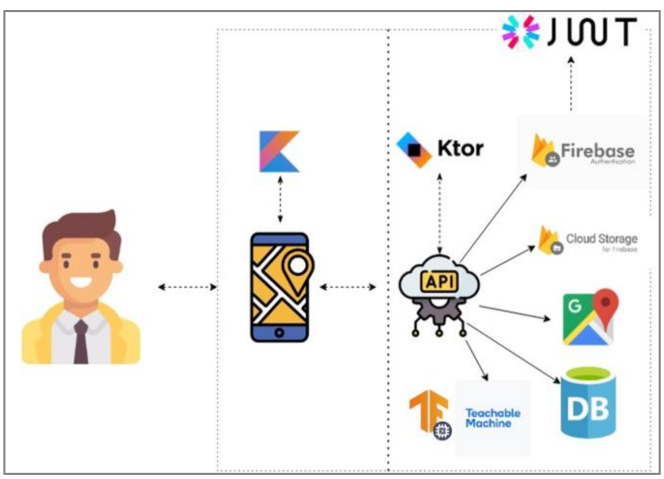


Fig. 3 Mobile application software architecture

3.4. Target Population

The target population for implementing the solid waste management mobile application in North Lima includes residents of this region, municipal authorities responsible for waste collection and management, and community organizations involved in environmental initiatives. The selection of the North Lima sector as the study area is based on statistics indicating a high concentration of solid waste management problems compared to other areas of Lima. This approach will make it possible to evaluate the effectiveness of the application in a densely populated urban environment with critical needs for improvement in waste management.

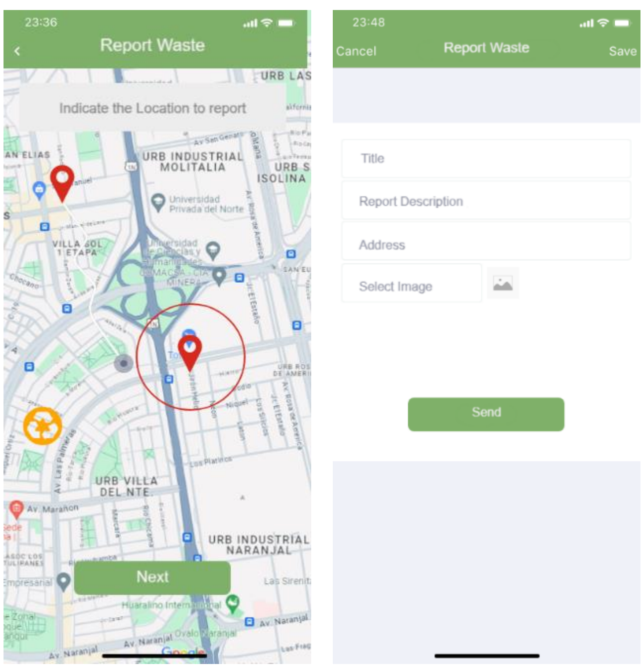
3.5. Prototype Development

In this phase of the research, the design and creation of functional prototypes of the mobile application was carried out, following the Design Thinking methodology combined with Lean Startup. The main objective was to develop a solution that meets the specific needs of users in North Lima and optimize the user experience through rapid iterations based on user feedback.

Figure 4 shows the initial screen, where users can register with their details or log in if they already have an account. This functionality is crucial to ensure that only registered users can access the application's functionalities, guaranteeing the security and personalization of the services offered. Once logged in, in Figure 5, users are directed to the main dashboard that acts as the app's operations center. From there, they can access various functions such as Report Waste, view the report map, and access the educational section on waste management.

Fig. 4 Prototype registration and login

Fig. 5 App dashboard prototype



(a) **(b)**

Fig. 6 Prototype of the report map section (a) Map to select the location to be reported, (b) Recording of the other data to be reported

In Figure 6, users can view an interactive map to report the location of accumulated solid waste. Using integration with Google Maps, this functionality allows users to mark exact points on the map, making it easier for authorities to collect and manage waste. After selecting the location on the map, users are guided to a screen where they can enter additional details about the report, such as the title, description of the waste and/or any relevant observations, and the address and the option to upload an image. In Figure 7, the screen shows a list of all the user's reports.

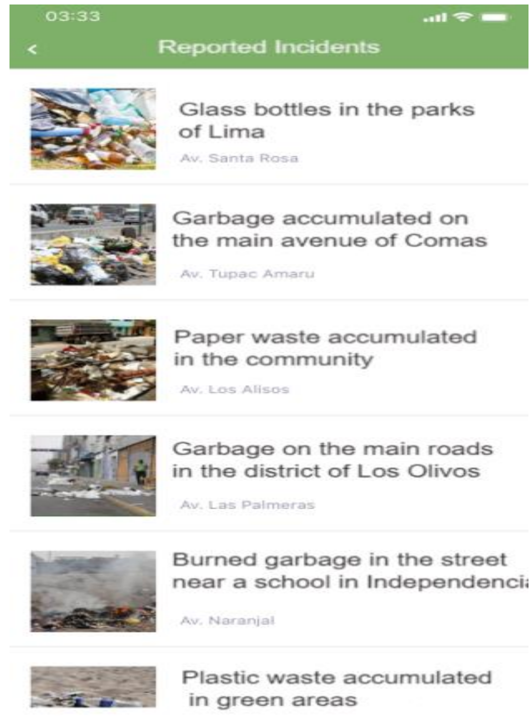


Fig. 7 Prototype list of registered reports

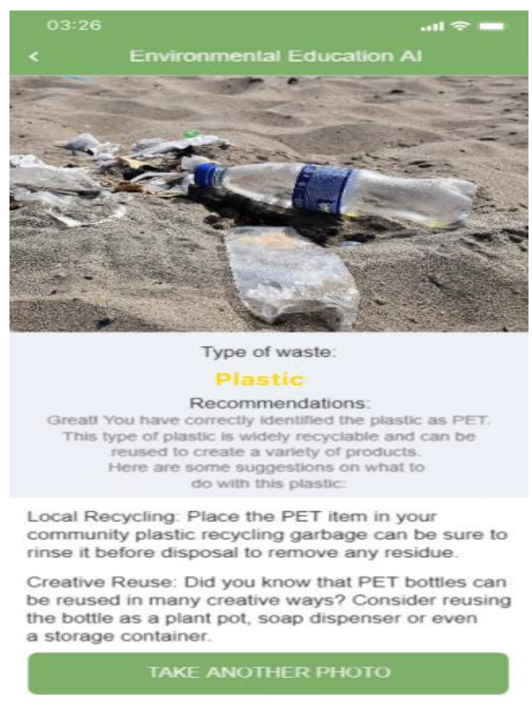


Fig. 8 Waste identification prototype

It provides an organized and accessible view of the user's contributions, allowing easy and transparent tracking of their reports. Figure 8 shows an advanced application functionality: the ability to identify the type of waste through a photograph taken by the user. Using image recognition and machine learning algorithms, the app processes the image and provides specific recommendations on handling the type of waste appropriately identified. This educational feature promotes correct segregation and recycling practices.

4. Results

In this section, the results obtained during the implementation of the mobile application in North Lima will be presented. The survey results, the training of the image classification model, and the implementation results will be detailed.

4.1. Evaluation of the Survey

To evaluate and validate the perception of the prototype of the mobile application for solid waste management, a survey structured in four main dimensions was designed: Demographics, Perception of the Mobile Application, Functionalities of the Mobile Application, Expectations and Disposition and Open Comments. Table 1 summarises the questions included in the survey, organized by dimension. The survey was answered by 50 potential users in Table 2, of which 48% were women and 52% were men. Most of the respondents were aged 25 to 40 years old and resided in different districts of North Lima.

Table 1. Survey dimensions and questions

Dimension	Question
Demographic	What is your age range?
	What is your gender?
	What district of North Lima do you live in?
Perception of the Mobile App	How would you rate the user-friendliness of the prototype's user interface?
	How intuitive do you find the prototype design?
Functionalities of the Mobile App	How useful are the following features of the prototype?
	How accurate do you expect waste identification through photography to be?
Expectations & Disposition	What do you hope to achieve with the use of this app?
	How often would you use this app once it becomes available?
	Would you recommend this app to others if it were available?
Open Comments	Do you have any comments or suggestions about the app prototype?

Table 2. Survey participants

Participants	Age	Sex
50 People Surveyed	18-24 years (32%)	Female (44%)
	25-40 years (45%)	Male (50%)
	41-60 years (13%)	Other (4%)
	Over 60 years old (10%)	I would rather not say (2%)

Figure 9 shows the results obtained based on the question How would you rate the user-friendliness of the prototype UI? the majority of respondents found the prototype UI easy and very easy to use, with 40% and 36%, successively, which is a positive indicator of the usability of the mobile app. Figure 10 shows the results obtained with the question, How accurate do you expect waste identification by photograph to be? many respondents answered very accurately, 60% and 30% accurately. On the other hand, Figure 11 shows the figures obtained based on the question How often do you think you would use this application once it is available? the answer obtained from most respondents was several times a week, with 30% and only 20% daily.

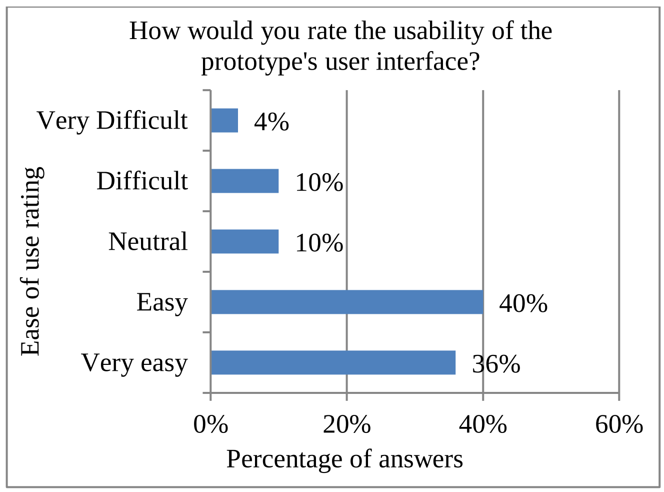


Fig. 9 User interface results

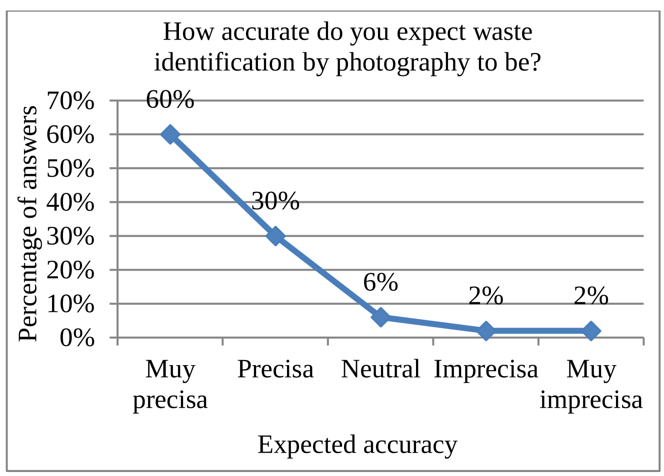


Fig. 10 Results on waste identification

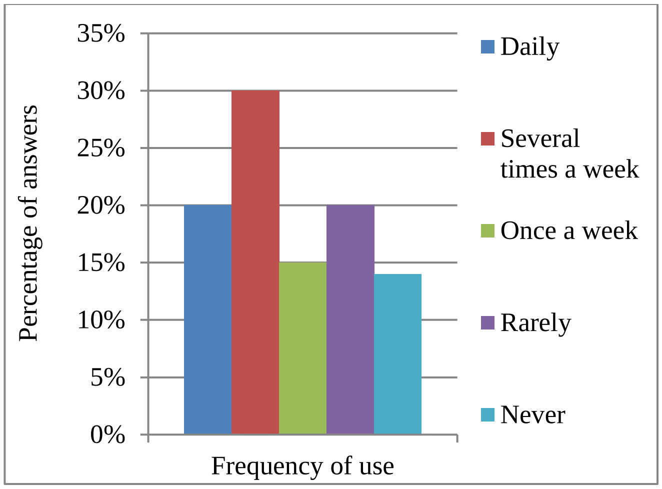


Fig. 11 Results on willingness to use the app

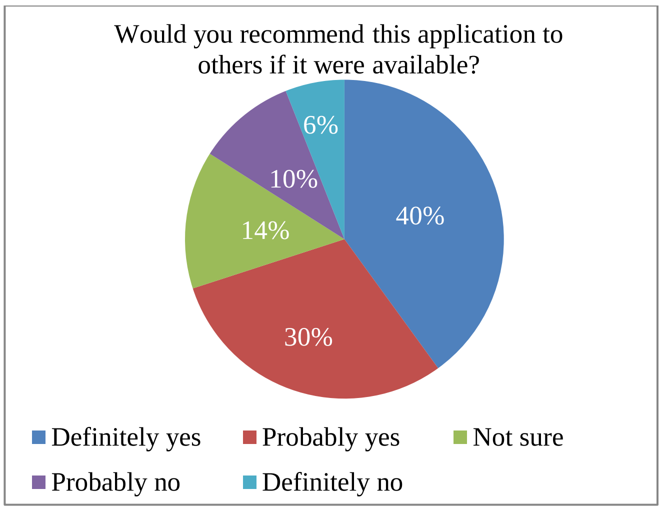


Fig. 12 Results of application recommendation

Therefore, Figure 12 visualizes the results to the question, would you recommend this application to others if it were available? respondents indicated definitely yes with 40% and probably yes with 30%. In this way, Table 3 shows the proposed functionalities of the prototype of the mobile app, which were well received, with high ratings in terms of usefulness. The evaluation of the proposed functionalities of the mobile application prototype revealed the respondents' high level of acceptance and perceived usefulness.

On a scale of 1 to 5, where 1 is "Not at all helpful" and 5 is "Very helpful." The photo waste identification function received special attention with a 4.5 Average Utility. These results indicate that users perceive the waste identification functionalities and recommendations provided by the app to be particularly useful, suggesting that these key features could be decisive for the success and adoption of the prototype. Finally, do you have any comments or suggestions about the app prototype? It allowed respondents to express their opinions and suggestions about the app prototype.

Table 3. Mobile app features

Functionality	Average Utility
Registration & Login	4.0
App Dashboard	4.2
Map to report on	3.5
Reported Location Data Log	3.8
List of Registered Reports	3.9
Identification of the type of waste and recommendations	4.5

Table 4. Comments and suggestions from participants

Category	Comments and Suggestions
Suggestions for Improvement	Several respondents said they would like a notification feature to alert them about trash collection events. Some suggested incorporating an initial tutorial explaining how to use the app and a more intuitive user interface, especially for older users.
Positive Feedback	Many participants praised the initiative, and the photo waste identification functionality was very well received.
Concerns	Some respondents expressed concerns about the accuracy of waste identification and the privacy and security of the data collected by the app.

Table 4 presents the main observations and recommendations provided by the participants. The survey results indicate a positive response towards the mobile app prototype. The suggestions and feedback received provide valuable guidance for future improvements and refinements prior to final implementation. The high willingness to use and recommend the application indicates a potential positive impact on solid waste management in North Lima.

4.2. Results of the Survey

Training the image classification model is a crucial stage to ensure the accuracy and effectiveness of the mobile application in identifying solid waste types. This process was carried out using the Teachable Machine platform, which simplifies the creation of machine learning models in an accessible and effective way. Figure 13 shows the image classification model. For training, images of different types of waste were used, classified such as plastic, paper and cardboard, organics, glass, metal, and garbage in general.

4.2.1. Preparing the Dataset

A dataset was collected that includes images of various types of solid waste common in North Lima to train the model. These images were classified into several categories, such as:

- Plastic waste
- Organic waste

- Paper and Cardboard waste
- Glass waste
- Metal waste
- Mixed waste

Each category contains at least 100 images to ensure representativeness and diversity within the dataset.

4.2.2. Training Setup

The Teachable Machine platform configured the image classification model. The process began with uploading classified images to the platform and assigning them to their respective categories. Subsequently, the number of epochs and the rate of learning were determined.

Finally, the model was trained using the uploaded data, adjusting its internal weights and biases during this process to minimize errors in image classification.

4.2.3. Training Results

The model was evaluated for precision, accuracy, and generalizability from a validation dataset. Table 3 shows the results of the precision by class training. The accuracy of each of the trained classes is 1, indicating that the model did not make any errors during the tests performed in training.

Similarly, the confusion matrix in Figure 14 summarizes the accuracy of the predictions. This matrix allows you to identify which classes are confusing for your model.

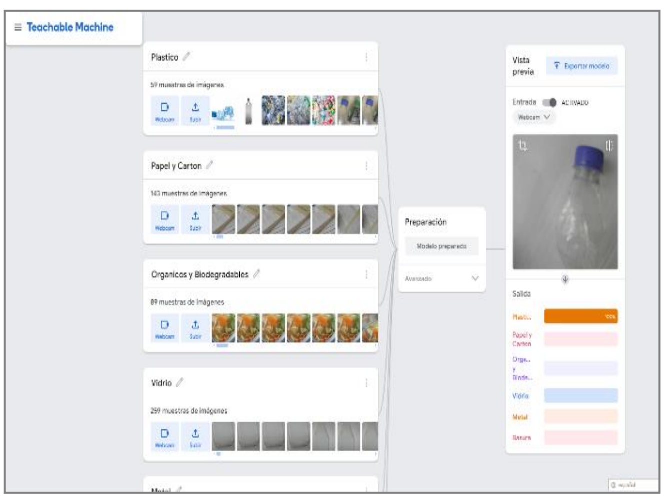


Fig. 13 Image classification model training

Table 3. Accuracy model performance by class

Accuracy by class		
CLASS	**ACCURACY**	**#SAMPLES**
Plastic	1.00	9
Paper and Cardboard	1.00	22
Organic and Biodeg..	1.00	14
Glass	1.00	39
Metal	1.00	50
Garbage	1.00	26

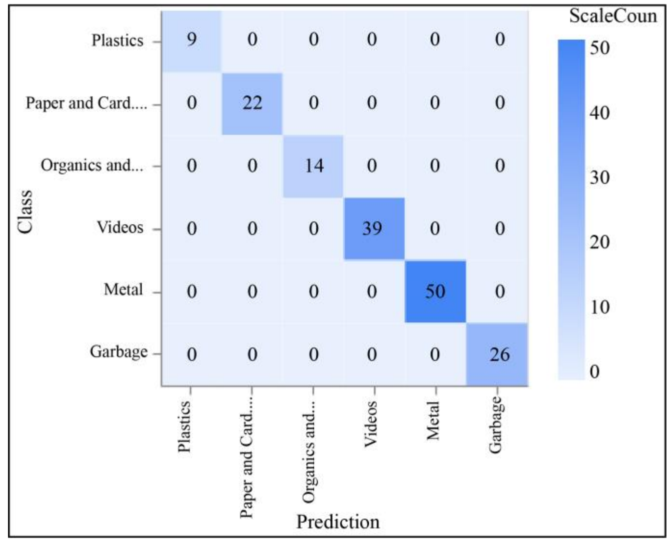


Fig. 14 Confusion matrix

In the confusion matrix, you can check whether the precision of a class causes an error. Therefore, the trained model has predicted each of the classes correctly. These results indicate that the model can correctly classify most solid waste images with high accuracy.

4.2.4. In-App Deployment

Once the model was trained and validated, it was implemented in the mobile application using TensorFlow Lite. This technology makes it possible to efficiently run machine learning models on mobile devices. The model was integrated into the Android Studio development environment, using Kotlin as the main programming language.

4.2.5. Initial Testing

Initial tests of the mobile app with the integrated sorting model demonstrated good performance in identifying waste from photographs captured by users. The user interface displays recommendations based on waste sorting, making it easier for users to manage and properly handle waste.

4.3. Mobile App Results

The development of the mobile application based on the survey results has been a crucial step in implementing solutions for efficient solid waste management in North Lima. The mobile application was developed following the guidelines established in the methodology, prioritizing usability, functionality, and effectiveness in solid waste management.

Selected tools and technologies were used for image classification model integration, including Android Studio, Kotlin, Firebase Services, Teachable Machine, and TensorFlow Lite. Figure 15 shows the first screen of the application, where it shows the Registration and Login, which allows users to create an account and log in to access all the features of the application.

Fig. 15 Registration and login app

Figure 16 shows the app's dashboard, providing an intuitive interface for exploring the various sections of the app and accessing key functionality. Figure 17 shows the map for reporting. The feature in this section allows users to locate points of interest and report the presence of solid waste in specific areas.

Fig. 16 App dashboard

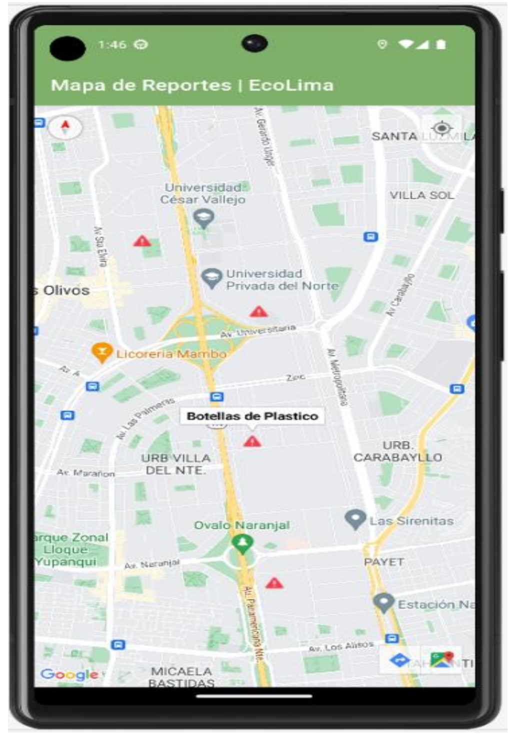


Fig. 17 App reporting map

Following the flow of the previous screen, Figure 18 shows the screen where users can provide additional details about the reported location. Figure 19 shows a list showing the history of the reports made by the user, including the title and location of the report.

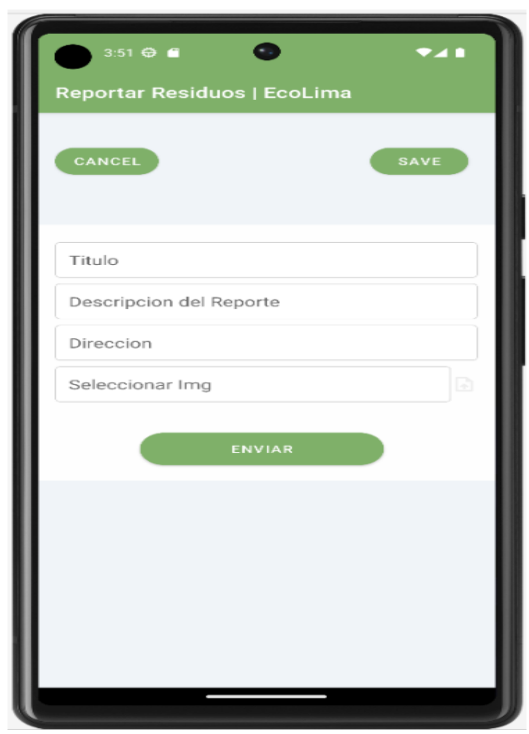


Fig. 18 Waste reporting app registration

Fig. 19 List of reports registered in the app

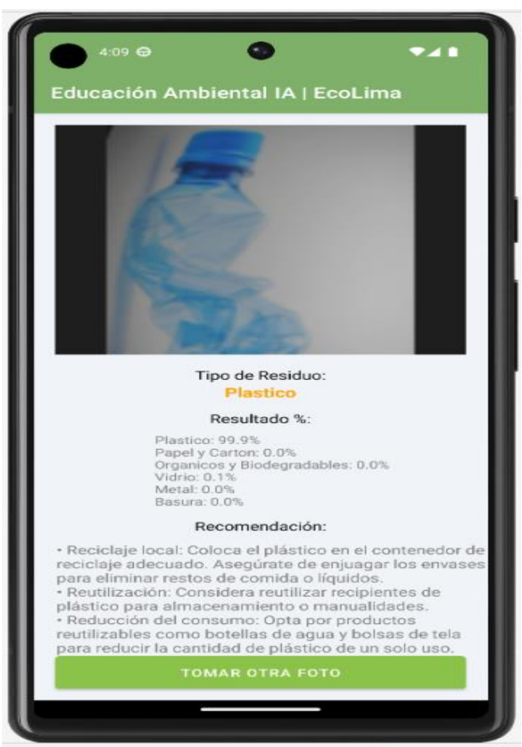


Fig. 20 Identification of waste type and recommendations

Finally, Figure 20 presents an image classification model based on deep learning to identify the type of waste from a photograph taken by the user, offering recommendations on its proper management.

5. Discussions

The demographic profile of the respondents shows an equal distribution between genders, and most of them are in the age range of 25-40 years and reside mainly in Comas and Los Olivos. This reflects a significant interest in this geographical area. On the other hand, the perception of the prototype is positive, as most users rate the interface as easy and intuitive. This result is crucial for the acceptance and continued use of the application. In addition, the image classification model showed high accuracy, as it was trained with a Teachable Machine and implemented in the application with TensorFlow Lite. This performance suggests the model can significantly improve waste management by automating waste identification and sorting. In terms of technological implementation, using TensorFlow Lite enabled the efficient integration of the image classification model on mobile devices, and using Android Studio and Kotlin provided a robust and flexible development environment. However, more in-depth training in these technologies is recommended to optimize the application further and add future functionalities.

However, it is important to recognize the limitations of the study. Although a working app version was developed and implemented, the evaluation was mainly based on prototypes. In the same way, the sample size was made with a limited number, which may not represent the entire population of North Lima. Lack of familiarity with the technologies used was another limitation, as it may have limited the development of more advanced features. However, the application was developed using the Minimum Viable Product (MVP) in its final version, which can be constantly improved. Based on these findings, it is recommended that a user feedback feature be integrated into future iterations of the application, extensive field testing be conducted to evaluate its performance in real-world environments, and collaborations with municipalities be explored to promote its use. These potential improvements could increase the effectiveness and acceptance of the application, contributing significantly to solid waste management in North Lima.

6. Conclusion

The design and development of the mobile application for solid waste management in North Lima represents a significant step towards solving an urgent environmental problem in the region. Through the combination of agile methodologies such as Design Thinking and Lean Startup, it was possible to design a tool that effectively addresses the community's needs and concerns. The survey results demonstrate a positive reception by users, highlighting the ease of use and perceived usefulness of the mobile app. The intuitive interface and well-integrated functionalities facilitate identifying and reporting waste, encouraging ongoing community involvement in solid waste management. Implementing the image classification model has proven to be a valuable tool for improving the efficiency of the waste management process. The ability to quickly identify the type of waste through user photographs streamlines waste collection and sorting, resulting in more effective and sustainable management. Although the study has certain limitations, such as sample size and familiarity with the technologies used, the findings suggest significant potential to address solid waste management challenges in North Lima. It is recommended to continue exploring new ways to improve and expand the app and seek collaborations with local authorities and community organizations to promote its adoption and continued use. In summary, the mobile application offers an innovative and practical solution to improve solid waste management in the Lima Norte area, with the potential to positively impact both the environment and the quality of life of its residents.

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