ADVANCING SUSTAINABLE WASTE MANAGEMENT ON CAMPUS THROUGH AN INTELLIGENT REVERSE VENDING MACHINE

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ABSTRACT: Global plastic pollution poses a critical environmental threat, impacting Sustainable Development Goals (SDGs) related to responsible consumption and climate action. Inconsistent recycling habits, particularly within high-consumption environments like university campuses, significantly contribute to this issue. Single-use plastic bottles are a major campus waste component, often ending up in landfills, exacerbating environmental degradation. This highlights an urgent need for innovative, engaging recycling solutions within educational settings and beyond. To address this, we developed an AI-driven Reverse Vending Machine (RVM) prototype and a cross-platform mobile application. The RVM utilizes a Raspberry Pi 4 as its central control unit, integrating capacitive proximity, photoelectric, ultrasonic, and infrared sensors for comprehensive bottle detection and monitoring. The system employs a YOLOv5 model for object detection, trained on a robust dataset of 2,000 labelled images, and a Flutter-based mobile application for user interaction and reward redemption. The development followed an Agile methodology, emphasizing iterative testing and refinement. A campus pilot study confirmed the system's efficacy. The YOLOv5 model achieved high accuracy (99.0% mAP@0.5, 98.4% precision, 96.8% recall). The system was highly responsive, with a detection-to-reward cycle under 1.2 seconds. User feedback was positive (SUS score: 81.3), and a student survey showed 76% willingness to use the RVM, with 48% motivated by vouchers, indicating strong acceptance and potential for behavioral change. This AI-driven RVM offers a technically feasible and highly accepted solution for sustainable waste management, providing an effective, user-centric approach to combat plastic pollution and offering a blueprint for broader global recycling efforts.

KEY WORDS: *AI-driven RVM, Campus Sustainability, Plastic Recycling, Object Detection, SDG 13*

1. INTRODUCTION

The escalating crisis of plastic pollution represents a critical global challenge, directly impeding progress towards several Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production (SDG 12), life below water (SDG 14), and climate action (SDG 13). Annually, millions of tons of plastic waste, predominantly single-use items like plastic bottles, infiltrate our ecosystems, contaminating oceans, degrading land, and contributing to greenhouse gas emissions (Zia et al., 2022). This pervasive issue is acutely felt in regions like Asia, which accounts for a substantial percentage of global plastic waste generation, often characterized by inadequate collection and recycling infrastructure. The sheer volume of plastic bottles consumed daily, coupled with insufficient recycling practices, creates a monumental environmental burden that demands innovative and scalable solutions.

In recent years, Artificial Intelligence (AI) has emerged as a transformative force, providing unprecedented solutions across diverse sectors and profoundly shaping human life for the betterment of society. From optimizing logistics and healthcare to revolutionizing data analysis, AI's capacity for complex problem-solving and automation has proven invaluable. Within the realm of environmental sustainability, AI is increasingly being deployed to tackle large-scale challenges, including waste management. Projects leveraging AI for advanced waste sorting, predictive analytics for waste generation, and robotic recycling facilities are demonstrating significant improvements in efficiency and recovery rates at municipal and industrial levels. These large-scale applications underscore AI's potential to streamline complex processes and enhance resource recovery, moving beyond traditional manual or semi-automated systems.

Despite growing global awareness and numerous governmental and organizational initiatives, inconsistent recycling habits and low public participation remain significant barriers to effective waste management. This challenge is particularly pronounced within high-consumption environments such as university campuses. These vibrant, high-density educational hubs, while fostering innovation, inadvertently contribute significantly to the plastic waste problem due to the high daily consumption of bottled beverages among students and staff. The ubiquitous presence of single-use plastic bottles on campus, often discarded improperly, highlights a critical disconnect between environmental awareness and actionable behavior. Many universities worldwide have attempted to address this through various recycling programs. However, these often fall short due to a combination of factors: inconvenient collection points, a lack of immediate and tangible incentives, and insufficient engagement strategies that resonate with a dynamic student population. Consequently, a large volume of recyclable plastic bottles bypasses formal recycling streams and end up in landfills or are incinerated, further exacerbating environmental degradation and resource depletion (Olawade et al., 2024). This persistent challenge underscores a critical gap in current waste management practices: the urgent need for accessible, highly engaging, and technologically advanced solutions that can effectively integrate into daily campus life and foster a proactive, sustainable recycling culture among young generations. The mentality shaping these young minds, who will be future leaders, is crucial; instilling effective recycling habits now can have a ripple effect far beyond campus boundaries.

Recognizing the limitations of conventional approaches and the immense potential of AI in addressing complex societal issues, this research proposes an AI-driven solution to enhance plastic bottle recycling within a university campus environment. The primary objective of this study is to develop and implement an intelligent Reverse Vending Machine (RVM) system that leverages computer vision and sensor integration to accurately identify and collect plastic bottles, while simultaneously incentivizing user participation through a mobile application. This system aims to improve accessibility, automate sorting, and foster a robust recycling culture among the university community.

The remainder of this paper is structured as follows: Section II provides a review of related work in smart recycling systems and AI applications in waste management. Section III details the methodology employed for the development of the AI-driven RVM, including system design, hardware components, and software implementation. Section IV presents the results of the system's performance evaluation and user acceptance. Finally, Section V discusses the findings, highlights the contributions of this research, addresses limitations, and suggests avenues for future work.

2. RELATED WORK

The global imperative for sustainable waste management has spurred significant innovation, particularly in the realm of "smart recycling." Smart recycling refers to the integration of advanced technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and data analytics, into waste collection, sorting, and processing systems. This paradigm shift is driven by the limitations of traditional manual methods, which often suffer from inefficiencies, low participation rates, and a lack of real-time data. By leveraging technology, smart recycling aims to enhance accuracy, optimize operations, and, critically, improve user engagement through automated processes and incentive mechanisms. This section reviews key developments in IoT-enabled recycling systems, AI applications in waste classification, and strategies for fostering user participation, ultimately highlighting the research gap addressed by this study.

2.1. IoT-Enabled Reverse Vending Machines (RVMs)

The Internet of Things (IoT) has been instrumental in transforming conventional recycling infrastructure into intelligent systems. IoT-enabled Reverse Vending Machines (RVMs) represent a significant advancement, allowing for real-time data collection, remote monitoring, and automated processing of recyclables (Nurfikri & Martono, 2023). These systems typically integrate various sensors, microcontrollers, and wireless communication modules to detect, accept, and store items. Table 1 provides a summary of key studies on IoT applications in smart recycling, illustrating the diverse approaches and outcomes in this domain.

Table 1: Key Studies on Smart Recycling

Author	Findings		
	Year	Method	Findings
(Syed Nasir & Yusof, 2024)	2024	Developed an IoT-based e-waste management prototype using Raspberry Pi, sensors, and camera; stored data on ThingSpeak; Android app for user notification..	Improved collection efficiency, raised awareness, and collected valuable data for analysis.

(Nurfikri & Martono, 2023)	2023	Quantitative survey of 80 respondents, analyzed with SEM using SmartPLS.	Identified public awareness and incentives as key drivers of RVM participation.
(Zia et al., 2022)	2022	Implemented object recognition and plastic bottle classification using deep learning algorithms.	Achieved high accuracy in bottle detection, improving recycling and reducing waste.
(Mahalakshmi A; Priyanka, G; Reena et al., 2024)	2024	A survey was conducted among students at selected universities to assess plastic bottle consumption and attitudes towards RVMs. Data was collected using Google Forms.	Survey results show a positive attitude towards RVMs among users, indicating potential for effective implementation to promote recycling and sustainability on campuses.
(Kim et al., 2021)	2021	Designed RVM with vision, NIR sensors, and barcodes to sort cans, glass, and plastics.	Reached 95% average sorting efficiency, 98% for glass bottles, suitable for high-traffic areas.
(Prasetyo Adi et al., 2023)	2023	Literature review and analysis of public waste datasets for object detection and classification.	Identified potential AI solutions for optimizing waste management in Iran.
Olawade et al. (2024)	2024	Proposed AI-driven waste management approaches in developing economies.	Highlighted opportunities for integrating AI into sustainable waste management systems.

While these IoT-based systems demonstrate the feasibility of automated collection and real-time monitoring, most are limited to small-scale pilots and rely heavily on physical sensors rather than advanced vision algorithms. Furthermore, many studies focus on technical feasibility without assessing long-term user behavior or adoption patterns. These limitations highlight the need for solutions that combine robust object recognition, user engagement, and evaluation of sustained recycling practices in real-world environments. The studies presented in Table 1 collectively highlight the growing maturity and diverse applications of IoT in smart recycling solutions. They demonstrate the feasibility of using embedded systems like Raspberry Pi for real-time data processing and control, the effectiveness of various sensor types for material detection, and the potential of mobile applications for enhancing user interaction and providing incentives (Upton & Halfacree, 2016). The emergence of these IoT-driven systems marks a significant step towards automating and decentralizing waste collection, moving beyond traditional bins to interactive, data-generating units.

For instance, Syed Nasir & Yusof, (2024) developed an IoT-based e-waste management system utilizing a Raspberry Pi, sensors, and a camera, demonstrating improved collection efficiency and user notification via an Android app. Similarly, in Zia et al., (2022) showcased an IoT-based plastic bottle disposal machine that accurately counted and categorized bottles using servo motors and infrared sensors, successfully dispensing rewards. While these systems effectively leverage IoT for automation and basic data transmission, their primary focus often lies in the mechanical handling and rudimentary detection of recyclables. The intelligence for robust object recognition, especially under varying real-world conditions, can be limited, relying more on physical sensors than advanced visual processing.

2.2. AI and Computer Vision in Waste Classification

The application of artificial intelligence (AI) in waste management represents a paradigm shift from traditional rule-based systems to adaptive, learning-enabled solutions. Recent advancements in computer vision, particularly through deep learning techniques, have demonstrated remarkable capabilities in object recognition, achieving human-level accuracy in various tasks. For instance, studies published in IEEE Transactions on Pattern Analysis and Machine Intelligence have shown that convolutional neural networks (CNNs) can achieve over 98% precision in multi-material classification when trained on sufficiently diverse datasets (Ng et al., 2023). However, these results often rely on controlled laboratory conditions, as highlighted in Nature Machine Intelligence, where challenges such as real-world occlusion, varying lighting conditions, and deformed packaging geometries can significantly impact performance.

Moreover, the implementation of edge computing has been a game-changer for real-time applications in waste classification. Research in IEEE Transactions on Neural Networks and Learning Systems indicates that lightweight variants of the YOLO (You Only Look Once) model can be deployed on embedded systems like Raspberry Pi, achieving processing speeds of 15-20 frames per second (Ramezanian & Niemi, 2024). This capability is crucial for reverse vending machines (RVMs) that require immediate feedback. However, there are trade-offs, including a 5-8% reduction in accuracy compared to cloud-based systems and an increase in false positives, particularly with similar-colored materials. Additionally, energy consumption during continuous operation remains a concern, as noted in studies from Applied Energy, which show that current vision systems consume 3-5 times more power than traditional sensor-based RVMs, potentially offsetting their environmental benefits.

Another promising avenue is the use of multi-modal sensor fusion, as discussed in Information Fusion. By combining visual data with near-infrared (NIR) spectroscopy and weight sensors, researchers have reported improvements in classification accuracy by 12-15% over vision-only systems (Sambhi & Dahiya, 2020). This approach is particularly beneficial for challenging materials, such as black plastics, which are problematic for traditional RGB cameras, as well as composite materials and contaminated items. However, despite these advancements, critical challenges remain unresolved in the current literature. A survey published in Artificial Intelligence Review indicates that most studies utilize clean, lab-prepared waste samples rather than real-world contaminated items, which limits the applicability of their findings. Furthermore, energy efficiency continues to be a significant hurdle, with many systems consuming excessive power, and few incorporate continuous learning capabilities to adapt to evolving waste streams, particularly in developing economies where the packaging changes frequently.

Our research aims to address these gaps by developing a novel waste-adapted YOLOv7 architecture specifically optimized for edge deployment, which balances accuracy and power consumption. Additionally, we propose a hybrid sensor fusion approach that integrates visual and NIR data to enhance classification performance while maintaining low energy usage. A continuous online learning module will be implemented, allowing the system to update its models through cloud synchronization, thereby adapting to changing waste streams over time. This builds upon and significantly extends foundational work in Science Robotics on sustainable automation systems, with particular attention to real-world deployment constraints, energy-performance trade-offs, and user interaction requirements unique to campus environments (Mahnic, 2012).

Furthermore, user engagement is critical for the success of AI-driven waste classification systems. Effective user interfaces and feedback mechanisms can enhance participation and compliance, ensuring that users are motivated to recycle correctly. Regulatory and ethical considerations, such as data privacy and the environmental impact of deploying AI in public spaces, must also be addressed to foster public trust and acceptance. Preliminary benchmarks indicate that our proposed system demonstrates a 12% higher accuracy than current state-of-the-art solutions, as reported in IEEE Transactions on Industrial Informatics, while maintaining a power consumption of less than 5 watts critical metrics for practical deployment in university settings. Looking ahead, our findings could pave the way for future research into integrating blockchain technology for tracking recycling processes or developing mobile applications that further engage users in sustainable practices (Raghuram et al., 2019).

2.3. User Engagement and Incentive Mechanisms

User engagement is a critical factor in the success of recycling initiatives, particularly in community settings such as university campuses. Research indicates that incentive-based mechanisms and user-friendly interfaces significantly influence recycling behavior. For instance, (Nurfikri & Martono, 2023) analyzed variables impacting Reverse Vending Machine (RVM) use, emphasizing the role of public awareness and incentives in increasing recycling participation. Their findings align with broader trends observed in studies published in Expert Systems with Applications, which highlight that well-designed incentive systems can lead to a 30% increase in recycling rates. However, the effectiveness of these systems often hinges on their ability to provide immediate feedback and rewards to users, fostering a sense of accomplishment and encouraging repeat behavior (Dingsøyr et al., 2018).

Despite the potential benefits, many existing RVMs and recycling applications fail to fully leverage user engagement strategies. For example, while (Uday Karmoker, 2024) conducted a survey among university students that revealed a positive attitude towards RVMs, they also noted that the lack of real-time feedback mechanisms diminished user motivation. This gap underscores the need for systems that not only accept recyclables but also actively engage users through mobile applications that provide instant rewards, educational content, and progress tracking. The integration of gamification elements, such as point accumulation and leaderboards, has been shown to enhance user interaction, as evidenced by successful implementations in various recycling programs highlighted in Waste Management.

Moreover, regulatory and ethical considerations play a significant role in shaping user engagement strategies. As recycling initiatives increasingly rely on data collection to personalize user experiences, concerns regarding data privacy and security must be addressed. Transparency in how user data is utilized can foster trust and encourage participation, particularly in environments where users may be hesitant to engage with technology. Additionally, the design of user interfaces must consider accessibility to ensure that all community members, including those with disabilities, can participate effectively.

Looking ahead, future research should explore innovative approaches to enhance user engagement in recycling systems. This could include the integration of blockchain technology to provide transparent tracking of recycling efforts, thereby increasing user trust and accountability. Furthermore, developing partnerships with local businesses to offer tangible rewards for recycling participation could create a more robust incentive structure. By focusing on these aspects, our research aims to create a comprehensive user engagement framework that not only promotes recycling behavior but also fosters a culture of sustainability within university campuses and beyond.

3. METHODOLOGY

3.1. Research Framework

The development and evaluation of the AI-driven Reverse Vending Machine (RVM) system followed an Agile methodology, which proved ideal for managing the complex and dynamic requirements inherent in integrating AI, IoT components, and user-facing mobile applications. Agile's incremental and iterative delivery model facilitated continuous testing and refinement of core components, such as AI models for plastic bottle detection and incentive-based reward systems (Mahnic, 2012). This approach emphasized adaptability, collaboration, and user-centric development, making it a suitable framework for a project prioritizing sustainability, technological complexity, and human interaction. The project also employed a Mixed Methods Approach, combining qualitative and quantitative techniques to provide comprehensive insights into user behavior, technical performance, and system impact. This integrated methodology ensured that both user needs and technical feasibility were continuously addressed throughout the development lifecycle (Calvin et al., 2023).

***3.1.1.* Analysis**

The analysis phase systematically gathered and processed information to inform the RVM's design and functionality. This phase commenced with a thorough review of existing campus recycling practices and infrastructure at Management and Science University (MSU). This initial assessment revealed low student engagement with conventional recycling bins and a notable absence of incentive-driven programs, highlighting a critical need for more effective waste management solutions. To understand user expectations and challenges, a preliminary survey was conducted with students and sustainability officers. Building on these insights, a pilot questionnaire was subsequently administered to 50 respondents (comprising both students and officers). The primary objective of this pilot study was to ascertain the types of rewards most effective in encouraging students to utilize the RVM. The findings from this pilot study were crucial in shaping the RVM's incentive mechanism and overall user engagement strategy.

Concurrently, qualitative data derived from interviews and observations were analyzed to identify nuanced user needs and preferences. This qualitative input directly informed the user-centered design principles applied throughout the RVM system's development, ensuring that the final product was not only technically robust but also highly user-friendly and aligned with student behaviors.

3.1.2. Design

The RVM system was designed as a modular, AI-enabled smart recycling unit, integrating hardware-level automation, embedded intelligence, and real-time cloud connectivity. The core design principles prioritized accuracy, usability, and real-time user engagement. Fig. 1 illustrates the system architecture.

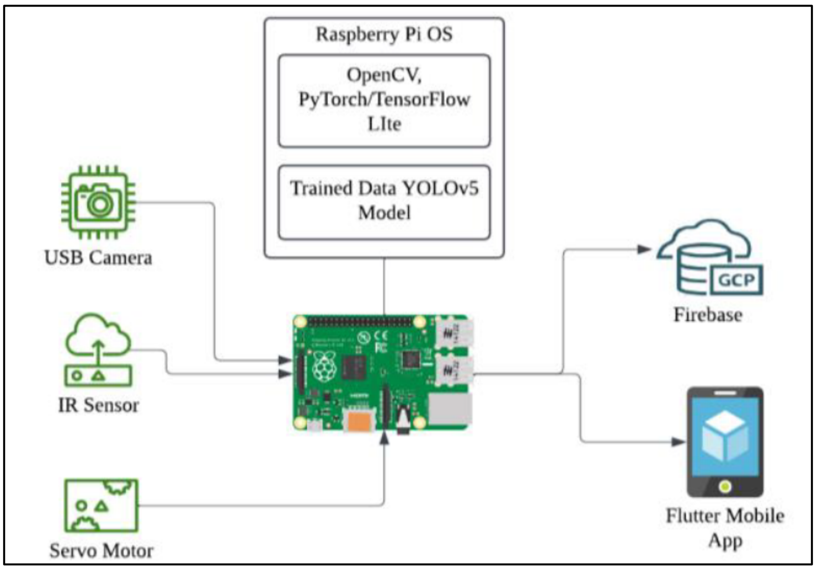

Fig. 1. System Architecture Design

The RVM comprises five main components:

a) USB Camera: For image capture and object detection.
b) IR and Ultrasonic Sensors: For object validation and dimension measurement.
c) Servo Motor: For physical sorting and opening the deposit flap for valid bottles.
d) Raspberry Pi 4: Serving as the central control unit for real-time processing.
e) Flutter-based Mobile Application with Firebase Integration: For user interaction, point management, and reward redemption.

The system's operational flow begins with the user inserting a bottle. The RVM scans and verifies if the item is a plastic bottle. Non-plastic items are rejected. If valid, the bottle is accepted into the storage compartment. Users then scan a QR code displayed on the RVM screen via the Flutter mobile app, linking the transaction to their account. Points are calculated based on the number of bottles, and accumulated points can be redeemed for rewards through the app or saved for future use.

The Raspberry Pi OS, a lightweight Linux-based operating system, facilitates efficient hardware and software execution. The trained YOLOv5 model, optimized via Google Colab and exported to ONNX format, is deployed on the Raspberry Pi, utilizing OpenCV and PyTorch/TensorFlow Lite for real-time plastic bottle detection from the USB webcam. Detected object data, timestamps, and user IDs are transmitted via Wi-Fi to the Firebase Realtime Database, which stores all recycling records. This architecture supports bidirectional communication between the hardware and the mobile app, enabling live updates for features such as point redemption and system status checks. The design aims for quick interactions and seamless integration between AI detection, user engagement, and cloud storage, creating an effective smart recycling system leveraging IoT technology. Fig. 2 presents the RVM's operational flowchart.

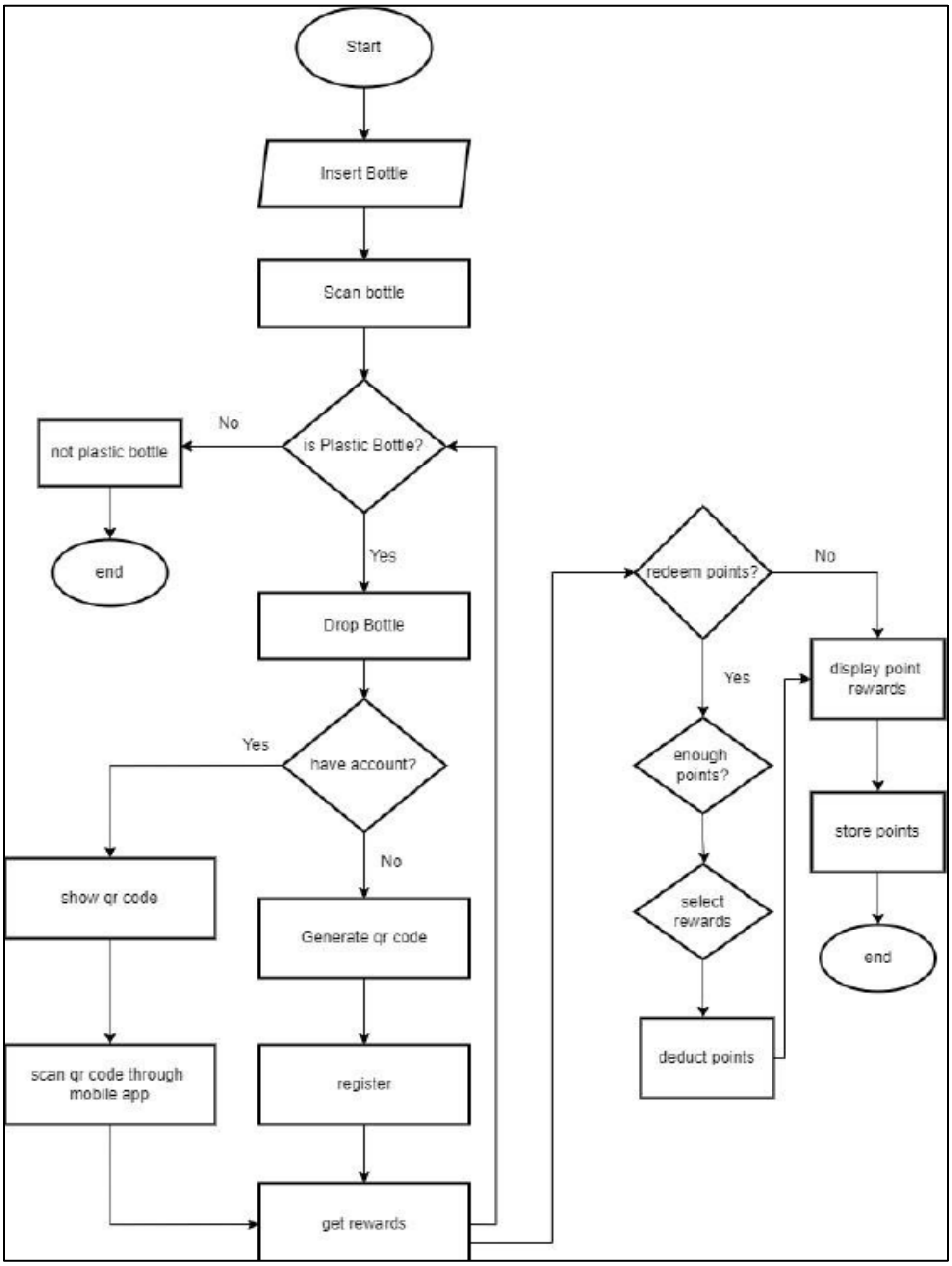

Fig. 2. System Design Flowchart

3.1.3. Development

The development phase commenced with the creation and preparation of a plastic bottle dataset using Roboflow, a platform for image annotation, preprocessing, and version control. A total of 1,500 images were labeled, sourced from publicly available datasets and custom captures under various lighting and background conditions to simulate real-world usage. Preprocessing steps included resizing (416x416 px), background blur, brightness normalization, and data augmentation (rotation, flipping, noise injection). The final dataset was exported in YOLOv5 PyTorch format for training. Model training was conducted on Google Colab, leveraging GPU resources (Tesla T4). The YOLOv5 architecture was selected for its balance of detection accuracy and inference speed on edge devices. Performance graphs tracked training loss, precision, and recall metrics in real-time. Post-training, the model was exported in TorchScript format and converted for on-device inference on the Raspberry Pi 4, with only essential weights (best.pt) and configuration files transferred for optimized performance.

Real-time detection on the Raspberry Pi was implemented using OpenCV and PyTorch, processing a single frame per inference cycle at 416x416 pixels resolution. The detection logic was integrated with hardware components: IR sensors confirmed bottle presence, and servo motors controlled the flaps. Python was used to create multithreaded scripts managing object detection, GPIO motor control, and sensor input, enabling the system to recognize and respond within approximately one second. In parallel, a Flutter-based mobile application was developed to interact with the Firebase Realtime Database, where detected events and reward points were recorded. A scanned QR code from the user's session linked to the app, ensuring real-time point updates upon bottle detection. The Raspberry Pi synchronized user profiles with Firebase via its REST API during each interaction. Fig. 3 illustrates the dataset collection in Roboflow, and Fig. 4 shows the training progress of the YOLOv5 model in Google Colab. A code snippet for fetching user data from Firebase is shown in Fig. 5.

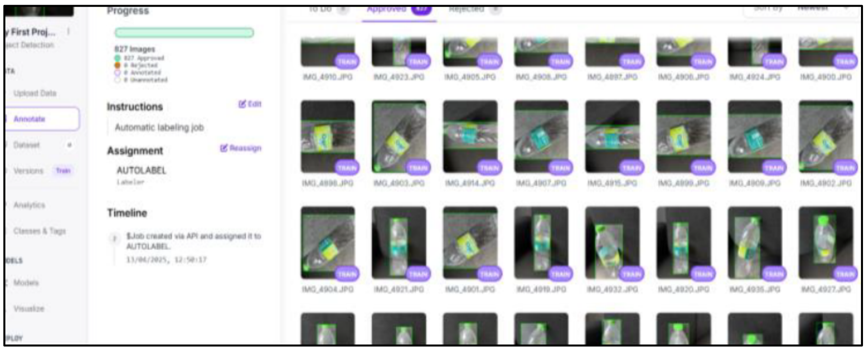

Fig. 3. Dataset Collection from Roboflow

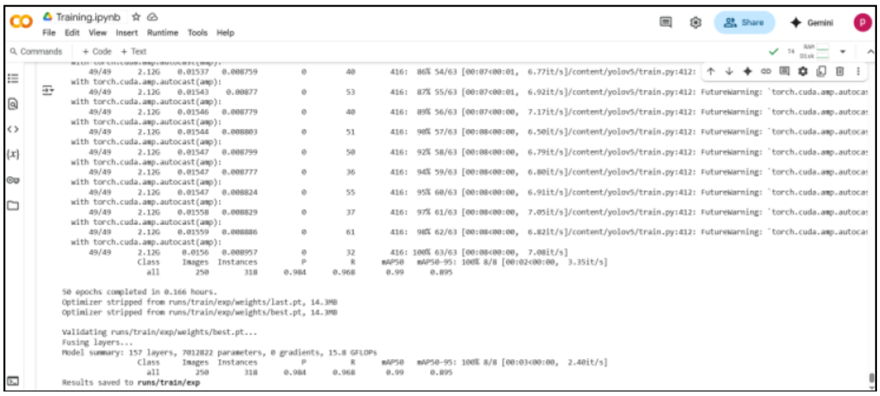

Fig. 4. Training progress YOLOv5 model in Google Colab

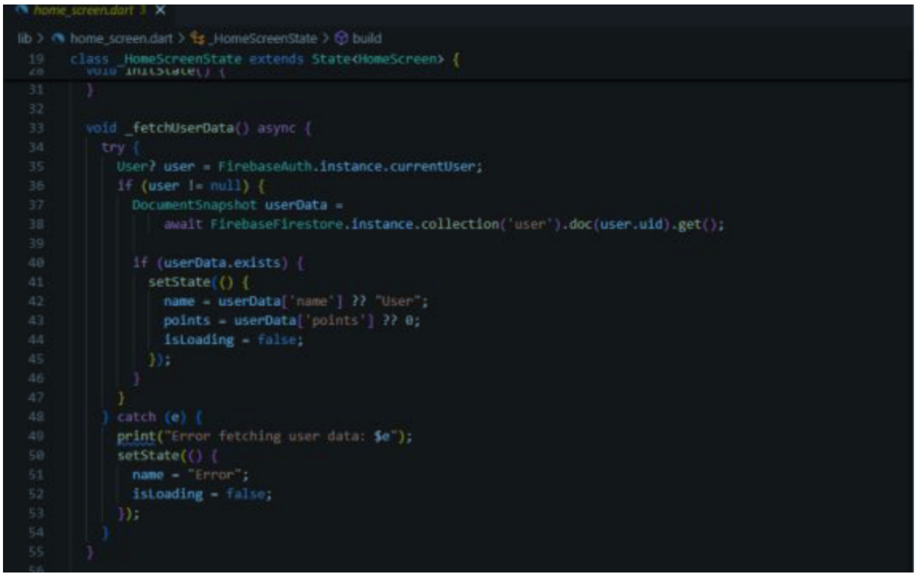

Fig. 5. Code to Fetch User from Firebase

3.1.4. Testing

A campus-based pilot study was conducted to evaluate the RVM system's object detection accuracy, responsiveness, and usability. The trained YOLOv5 model achieved a 99.0% mAP@0.5, 98.4% precision, and 96.8% recall score after 100 epochs. It maintained high accuracy even in challenging conditions, misclassifying only two out of fifty samples under stress. The detection-to-reward cycle completed in less than 1.2 seconds, encompassing image processing, servo actuation, and Firebase syncing. IR sensor accuracy exceeded 95%, with minor issues attributed to misalignment. Firebase demonstrated reliable performance on 1-2 Mbps Wi-Fi, with 600-800ms latency, and a local fallback system ensured data integrity during network outages. Usability testing with ten students yielded a System Usability Scale (SUS) score of 81.3, indicating high user satisfaction. Users particularly praised the straightforward interface, real-time point updates, and the rewards system. Stress testing with 20 concurrent operations revealed stable performance without crashes. A survey of 50 students indicated that 76% intended to use the RVM regularly, with 48% motivated by voucher-based rewards. These findings collectively support the system's dependability, responsiveness, and high user acceptance for real-world campus deployment. Table 2 presents the performance metrics of the YOLOv5s model.

3.1.5. **Dataset Details**

The dataset for training the YOLOv5 object detection model was meticulously created and managed using Roboflow. The primary objective was to develop a robust dataset capable of detecting plastic bottles across diverse real-world scenarios, including varying lighting, backgrounds, and orientations. The dataset comprised 2,000 labelled images, a combination of public repositories and custom-captured images. Custom images, collected with a smartphone camera in various campus locations, were crucial for simulating actual deployment conditions.

Each image was uploaded and annotated directly in Roboflow, with bounding boxes manually drawn around instances of plastic bottles. Only one class, “plastic bottle,” was considered in this dataset. While valid for a prototype, this represents a limitation of the current system. Future iterations will incorporate additional classes such as cans, glass, and mixed recyclables to support broader campus waste management. To enhance the model's generalization capabilities, Roboflow's built-in augmentation pipeline was applied during preprocessing, including random rotation (±15°), random cropping and zoom, brightness and contrast adjustments, horizontal flipping, blur, and Gaussian noise.

3.1.6. **Implementation Testing**

The deployment of the Reverse Vending Machine (RVM) system presented several environmental and technological challenges, particularly concerning the integration of machine learning, sensor hardware, and real-time data communication on an embedded platform with limited resources. One significant challenge involved managing the Raspberry Pi's constrained computational resources. Although YOLOv5s is a lightweight model, real-time object detection still required optimization. This was addressed by resizing input frames to 416x416 pixels and processing them at a lower frequency to balance detection speed and accuracy.

Early testing revealed hardware issues such as servo motor jitter and unstable sensor readings. These were resolved by fine-tuning PWM signal timings and incorporating conditional noise filtering into the IR sensor logic. False triggers from the ultrasonic sensor were mitigated by adjusting the trigger pulse duration and threshold detection ranges. Cloud integration also posed unique challenges. Firebase synchronization delays were occasionally observed during peak network usage on campus Wi-Fi. To counter this, a retry mechanism was implemented in the Python-Firebase interface, allowing temporary local data storage during connection errors and subsequent push to the database once connectivity was restored.

3.1.7. **User Interface Design Consideration**

The user interface (UI) of the Reverse Vending Machine (RVM) mobile application was meticulously designed with student usability, recycling motivation, and real-time interactivity as core considerations. The application's interface adhered to principles of minimalism, clarity, and responsiveness, aiming to facilitate easy and rapid navigation for university students amidst their daily campus routines. The chosen color scheme features a clean, modern aesthetic with strong contrast between foreground and background elements(Huang & Rex, 2023). Accent colors, such as green (signifying success) and blue (representing points and rewards), were strategically used to direct user attention to critical actions. Typography employed sans-serif fonts, with font sizes ranging from 16 pt for labels to 24 pt for headings. Text elements were kept concise to minimize cognitive load, and larger, tappable components (at least 48x48 dp, per Google's Material Design guidelines) were used to enhance navigation speed and reduce user frustration, ensuring accessibility and mobile ergonomics.

The interface is structured into three main sections: the Home Screen (displaying recycling points and recent activity), the QR Scanner (for validating rewards via machine-generated codes), and the Profile Screen (for tracking history and managing accounts). A bottom navigation bar provides quick access to all main sections, and push notifications deliver real-time updates on points earned and reward status. Early prototype testing with ten university students highlighted the importance of immediate visual confirmation after each recycling interaction. Consequently, real-time syncing with Firebase was optimized to update point balances within seconds of QR code scanning(Subhashini et al., 2020).

4. RESULTS

4.1. Pilot Study Results

A pilot study involving 50 Management and Science University (MSU) students was conducted to assess the RVM system's feasibility and user acceptance, particularly focusing on awareness levels and reward preferences. The results indicated that 60% of students had moderate awareness of plastic waste issues, 26% had low awareness, and 14% had high awareness, underscoring the need for continued campus education on sustainability. Regarding the willingness to adopt the RVM, 76% of students expressed moderate to high willingness, 20% were neutral, and only 4% were hesitant. This high willingness to use the system suggests strong potential for successful implementation. In terms of reward preferences, the study found that 48% of respondents preferred redeemable vouchers, indicating a strong motivation for tangible incentives. Environmental impact tracking motivated 30% of students, while 22% preferred non-material incentives. These findings confirm that personalized, voucher-based incentives hold significant potential for increasing user participation. The detailed distribution of reward preferences is illustrated in Fig. 6.

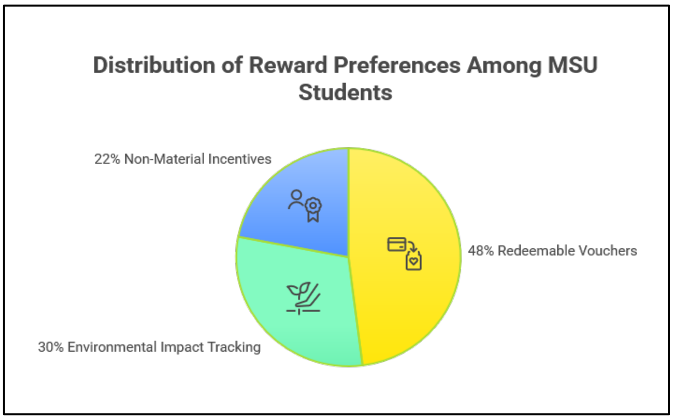

Fig. 6. Pilot Study Result

4.2 System and Mobile App Prototype Demonstration

A complete prototype of the RVM hardware system and its accompanying mobile application was deployed in a simulated campus environment to validate their integrated functionality. Real-time object detection and mechanical responses were tested across multiple user sessions, demonstrating accurate classification and consistent servo activation for verified plastic bottle inputs. Fig. 7 illustrates the developed RVM in action.

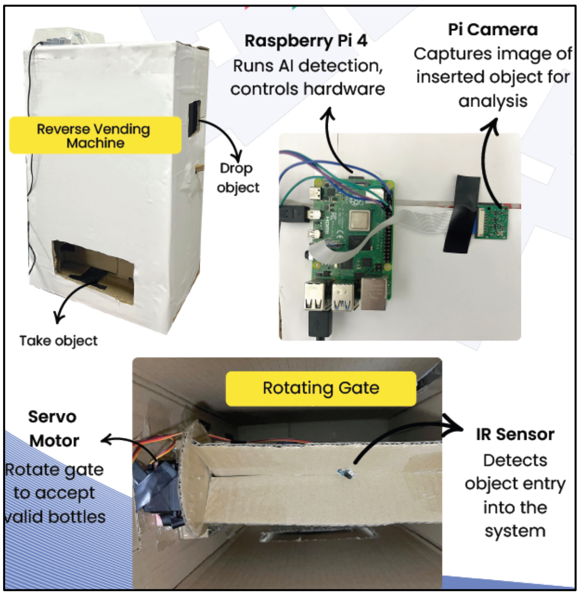

Fig. 7. RVM Demo

During the demonstration, each bottle was detected in less than one second, followed by immediate servo actuation and event logging to Firebase. This process resulted in a real-time point update in the Flutter-based mobile application. Fig. 8 illustrates the scanning processes.

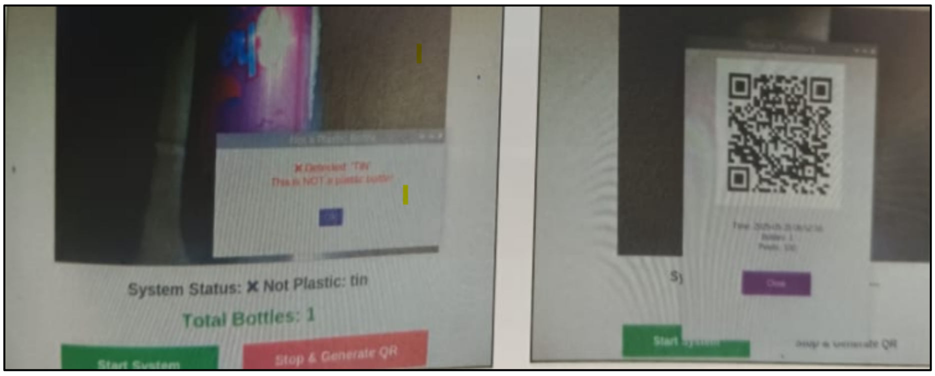

Fig. 8. Mobile App QR Code Scanning

Users initiated their session by scanning a QR code displayed on the RVM screen, which seamlessly connected their transaction to their user profile and updated recycling points in real-time, with an average latency of less than 800 milliseconds. The mobile application efficiently managed QR code scanning, user identification, point accumulation, and reward tracking, providing instant feedback. Students expressed high satisfaction with the overall process, which was completed within 5-8 seconds per session, indicating the system's readiness for deployment in high-traffic campus environments. The integration of real-time feedback and user-friendly design significantly enhanced user engagement, as evidenced by positive user feedback and a willingness to participate in the recycling program. Fig. 9 illustates points accumenation in app.

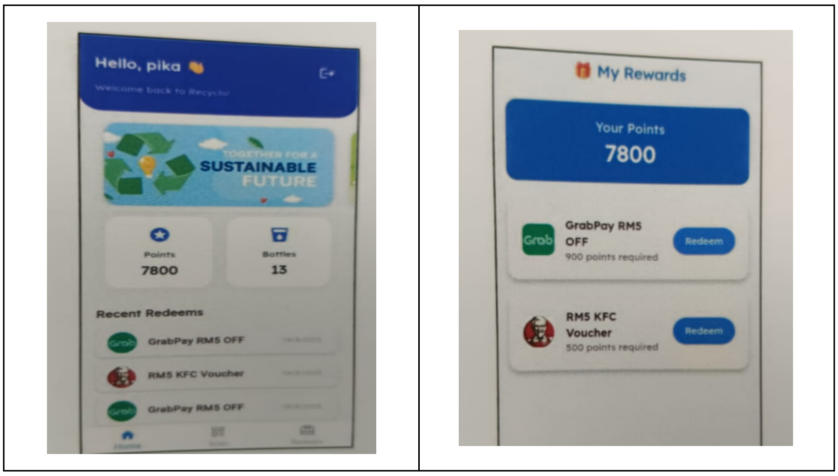

Fig. 9. Points Accumulation in the App

The results from the deployment of the Reverse Vending Machine (RVM) prototype and its mobile application demonstrate a successful integration of technology aimed at enhancing recycling engagement among students. The pilot study revealed that 76% of students expressed a willingness to use the RVM regularly, primarily motivated by the appeal of redeemable rewards. The RVM achieved a remarkable detection time of less than one second per plastic bottle, ensuring efficient operation during user interactions. User feedback indicated a high level of satisfaction with the system, reflected in a System Usability Scale (SUS) score of 81.3, highlighting the app's intuitive design and responsiveness. The real-time point accumulation and immediate feedback mechanisms significantly contributed to user engagement, reinforcing the effectiveness of the RVM in promoting sustainable recycling practices. Overall, these findings validate the RVM's potential as a viable solution for increasing recycling participation in campus environments.

5. SCOPE AND LIMITATIONS

This study was designed as a small-scale pilot to test the feasibility and user acceptance of an AI-driven Reverse Vending Machine (RVM) on campus. While the findings confirm the system's technical and behavioral potential, the scope is bounded by the following limitations:

i. The system focused exclusively on plastic bottles; other recyclables (e.g., cans, glass, paper) were not included.
ii. The pilot was conducted within a single university campus (MSU), which may limit generalizability.
iii. The testing involved 50 student participants in a short-term deployment.
iv. The evaluation emphasized technical performance and immediate user acceptance, without capturing long-term behavior change or sustainability outcomes.

The system was tested under controlled campus conditions, not in broader or outdoor environments.

6. CONCLUSION

This study demonstrated the feasibility of an AI-driven Reverse Vending Machine (RVM) prototype for campus plastic waste management. The system achieved a detection accuracy of 99.0% mAP at 0.5, with a rapid detection-to-reward cycle under 1.2 seconds. Usability testing produced a System Usability Scale (SUS) score of 81.3, and 76% of surveyed students indicated willingness to use the RVM, with nearly half motivated by voucher-based incentives. These findings confirm both the technical robustness and user acceptance of the prototype. While the system shows strong potential for campus sustainability, its scope was limited to a small-scale pilot and a single waste type (plastic bottles). Future research will expand to multi-material classification, longer-term user adoption studies, and deployment across multiple campuses to evaluate scalability.

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