Reverse Vending: A Comprehensive Review of Innovative Approach in Embedded System, Sensing Accuracy, and Sustainability Implications

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Abstract
Reverse vending machines (RVMs) offer a promising technological intervention to improve recycling rates and reduce plastic pollution by automating material collection and providing user incentives. This review synthesizes literature (2015–2025) retrieved via Google Scholar and selected through a PRISMA-guided screening to examine RVM design, embedded-system architectures, sensor accuracy, and sustainability impacts. Findings show that contemporary RVMs commonly employ infrared, load-cell, LDR, ultrasonic and similar sensors—often managed by microcontrollers such as Arduino and higher-level processors like Raspberry Pi—to validate and sort plastic bottles with reported detection accuracies frequently exceeding 95%. Despite high baseline performance, studies identify persistent challenges: environmental interference, limited material discrimination, vulnerability to fraudulent inputs, and long-term durability concerns. Advances in sensor fusion, computer-vision classification, depth sensing, and high-precision weight measurement are highlighted as effective strategies to reduce false accepts/rejects and increase robustness. Sustainability and social-impact evidence indicates that RVMs integrated with deposit-return schemes and incentive mechanisms markedly raise return rates and community participation, while hybrid designs (e.g., dual-mode token/coin operation), renewable energy integration, and user-identification controls can enhance accessibility and prevent misuse. The review concludes that combining advanced sensing, layered embedded architectures, and well-designed incentive and governance measures is essential for scaling RVMs as reliable, equitable components of sustainable waste-management systems.

Keywords: Embedded systems, Recycling technology, Reverse vending machines, Sensing accuracy, Sustainability.

INTRODUCTION

The rising trend of plastic waste disposal has thus become a major environmental concern across the world. Improper disposal of plastic materials has been found to cause pollution, leading to adverse effects on the environment and human health. Recycling strategies are therefore essential to minimize waste and adopt environmentally safe practices.

Reverse vending machines (RVMs) are found to be an innovative method of promoting recycling activities, enabling the recycling of recyclable materials such as plastic bottles and aluminum cans.

Users of RVMs are often rewarded for their recyclable materials, such as cash, coupons, or points, for the deposited materials.

Reverse vending machines use embedded systems to perform critical functions. Embedded systems are composed of microcontrollers, sensors, and actuators, which are used to automatically detect and verify recyclable items. In reverse vending machines, different types of sensors such as infrared sensors, weight sensors, and image recognition are used for item identification and verification.

This review paper aims to review different studies about reverse vending machines and their sustainability.

Review of Related Literature

A. Reverse Vending Machine

Waste has become one of the most serious global environmental issues today, with improper disposal contributing to pollution and resource depletion. Recycling remains one of the most effective strategies for sustainable waste management. Reverse Vending Machines (RVMs) are automated systems designed to collect recyclable materials, particularly plastic bottles, in exchange for incentives. This technology promotes responsible waste disposal behavior and encourages community participation in recycling initiatives (Baribad et al., 2024).

As these systems evolve, dual-mode vending machines capable of accepting both coins and plastic bottles have emerged as innovative responses to environmental and socio-economic needs. These systems combine traditional vending functionality with recycling incentives, making sustainability practices more accessible and practical in public and institutional settings.

Smart reverse vending machines integrated with IoT technologies have further enhanced operational efficiency. Research on IoT-enabled waste management systems indicates that real-time tracking of fill levels and machine status improves reliability and reduces maintenance costs. Cloud-based monitoring systems also enable data-driven planning and decision-making for waste management authorities (Longhi et al., 2012). These advancements demonstrate the expanding role of embedded and connected technologies in optimizing recycling infrastructure

B. Sensing Accuracy

Reverse vending machines utilize discarded plastic bottles as physical tokens that trigger rewards or services when inserted into the system. To ensure proper validation, recent designs employ embedded systems integrated with various sensors such as load cells, light-dependent resistors (LDR), and ultrasonic sensors connected to microcontrollers. These components identify plastic bottles based on parameters including weight, transparency, and volume. Studies report detection accuracies exceeding 95% across bottles of varying sizes, demonstrating the effectiveness of sensor-based recognition methods (Juansah et al., 2024).

In addition to basic sensing mechanisms, reverse vending machines may incorporate ultrasonic, capacitive, inductive, and infrared sensors to verify bottle presence and material composition. RFID systems and coin mechanisms are also utilized for user identification and reward dispensing. Although studies report high functional reliability, challenges remain in maintaining sensor calibration, preventing fraudulent inputs, and ensuring long-term system durability. Scalability and integration of multiple sensing and reward components are identified as critical considerations for broader implementation (Baribad et al., 2024).

These findings highlight the importance of improving sensing precision, minimizing false acceptance or rejection rates, and enhancing system robustness—key aspects directly relevant to evaluating system accuracy in reverse vending technologies.

C. Sustainability & Social Impact

Reverse vending machines are widely implemented in countries with established deposit return systems. A comprehensive evaluation of container deposit systems across Europe found that automated return infrastructures significantly increase recycling rates and reduce littering. Countries utilizing reverse vending technologies consistently achieve return rates above 85%, demonstrating the effectiveness of combining financial incentives with automated validation systems (Hogg et al., 2018).

Beyond environmental benefits, reverse vending systems also contribute to socio-economic development. According to Gabuya (2024), vendo-type services that operate using small coin denominations enhance economic accessibility, particularly within informal or shadow economies. While these services generate income opportunities and provide affordable access to goods, regulatory and consumer protection challenges must be addressed to ensure equitable and sustainable growth.

Furthermore, plastic bottle–based token systems implemented in educational institutions and campus environments have been shown to increase recycling participation and environmental awareness. Incentivized bottle collection programs foster responsible waste management practices among students and staff. The integration of monitoring applications enhances transparency by enabling real-time tracking of collected bottles and system status. Overall, these systems demonstrate strong potential to promote recycling behavior while supporting broader sustainability initiatives such as Green Campus programs and access to essential services (Padios et al., 2021).

METHODOLOGY

A. Databases

The primary database used for this review was Google Scholar, which provides access to a wide range of academic publications including journal articles, conference papers, theses, and technical reports. Google Scholar was selected because it indexes research from various reputable publishers and institutions, making it a useful source for identifying studies related to reverse vending machines, embedded systems, sensing technologies, and recycling systems.

Through Google Scholar, relevant literature was collected by searching for studies that discuss the design and implementation of reverse vending machines as well as technologies used in automated recycling systems. The platform allows researchers to access publications from multiple disciplines, including engineering, environmental science, and sustainability studies, which are all relevant to the topic of this review.

Using Google Scholar enabled the collection of a diverse set of research papers that examine embedded system designs, sensor-based material detection, and the role of reverse vending machines in promoting sustainable waste management practices. These sources formed the basis for analyzing existing technologies and identifying trends and challenges in reverse vending machine development.

B. Search Strategy

For this review, Google Scholar was used to find studies on reverse vending machines, embedded systems, sensors, and sustainability. Searches included keywords like “reverse vending machine,” “embedded system,” “sensor,” “recycling automation,” and “sustainability,” combined with AND/OR to narrow results. Only studies published from 2015 to 2025 were considered, and titles and abstracts were checked to focus on research about machine design, sensor accuracy, or environmental impact. This method helped gather a clear and relevant set of recent research papers.

C. Inclusion Criteria

To ensure the review included only relevant and high-quality studies, the selection focused on peer-reviewed journal articles, conference papers, and theses written in English. Only publications from 2015 to 2025 were considered to capture the most recent developments in technology and sustainability.

The studies had to focus on reverse vending machines or related automated recycling systems, covering aspects such as embedded system designs, sensor performance and accuracy, or the environmental and sustainability impact of these machines. Only papers that provided clear technical details about machine design, sensor integration, or operational outcomes were included, ensuring that the review reflects both the technological and sustainability perspectives of reverse vending machines.

D. PRISMA

To ensure transparency in the literature selection process, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (**PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)**) framework was applied. The PRISMA method provides a structured approach for identifying, screening, and selecting relevant studies for systematic reviews.

The initial search was conducted using **Google Scholar**, which produced a large number of publications related to reverse vending machines, embedded systems, sensing technologies, and sustainability. The search results were then filtered based on the predefined inclusion criteria, publication year, and relevance to the research topic.

During the **identification stage**, all studies obtained from the search query were collected. Duplicate and clearly irrelevant records were removed. In the **screening stage**, titles and abstracts were reviewed to determine whether the study focused on reverse vending machine systems, sensing accuracy, or sustainability aspects.

The **eligibility stage** involved reviewing the full text of the remaining studies to ensure that they contained sufficient technical or analytical information relevant to the objectives of this review. Studies that did not discuss embedded systems, sensor technologies, or sustainability impacts were excluded.

Finally, the **included stage** consisted of the selected studies that met all the criteria and were used in the synthesis of this review paper.

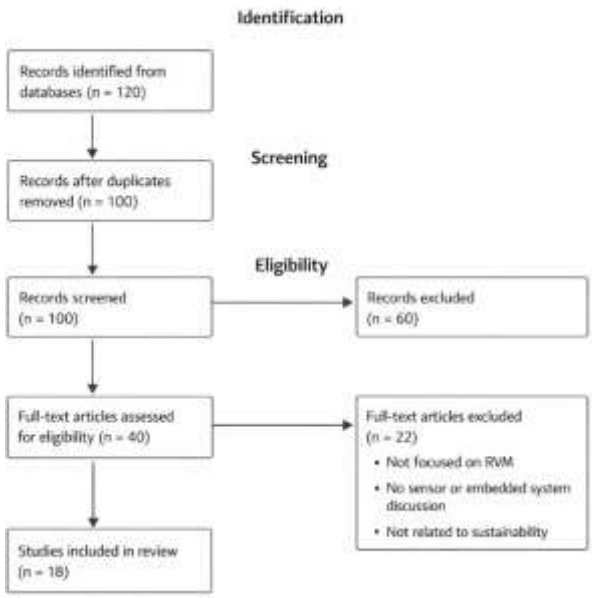

Figure 1. PRISMA Diagram

Discussion

The reviewed studies demonstrate that reverse vending machines (RVMs) have significant potential to improve recycling participation while integrating modern embedded technologies into waste management systems. Most existing systems rely on combinations of basic sensors such as infrared sensors, load cells, and light-dependent resistors to detect the presence and characteristics of plastic bottles. These sensors typically identify objects based on parameters such as weight, transparency, and physical dimensions. Previous studies report detection accuracies exceeding 95%, indicating that sensor-based identification systems can effectively support automated recycling processes (Juansah et al., 2024). However, several technical limitations remain, including susceptibility to environmental interference, limited material recognition capability, and potential detection errors when bottles vary in size, transparency, or physical deformation. These challenges highlight the need for continuous improvement in sensing accuracy and system reliability in reverse vending machine development (Baribad et al., 2024).

To address these limitations, future reverse vending machine systems may incorporate more advanced sensing technologies that enhance identification accuracy and reduce false acceptance or rejection of items. Computer vision–based detection systems combined with embedded processing platforms such as Raspberry Pi 4 Model B or NVIDIA Jetson Nano can perform real-time image recognition of recyclable materials. By applying machine learning algorithms, these systems can analyze bottle shapes, labels, and surface textures to verify whether an object meets recycling criteria. Compared with conventional optical sensors, computer vision approaches provide higher classification accuracy and improved resistance against fraudulent inputs such as non-recyclable materials or damaged containers.

Additional sensing improvements may also be achieved through the integration of depth and dimensional detection technologies. For instance, the Intel RealSense Depth Camera D435 enables three-dimensional object detection, allowing the machine to measure bottle volume and structure more accurately. This capability improves the system's ability to distinguish plastic bottles from other objects with similar weight or transparency. For weight verification, high-precision load cell systems using components such as the HX711 Load Cell Amplifier Module can improve measurement accuracy and minimize errors caused by irregular bottle shapes. Ultrasonic sensors may also be integrated to verify bottle dimensions and confirm whether the inserted object meets the expected size parameters. By combining these sensing technologies through a sensor fusion approach, reverse vending machines can achieve more reliable validation and reduce incorrect transactions.

Beyond sensing improvements, the embedded system architecture plays a crucial role in coordinating machine operations. Embedded processors and microcontrollers manage sensor input, object validation, user interaction, and reward distribution. Platforms such as Arduino Mega 2560 can handle low-level sensor communication and control electromechanical components such as motors, sorting mechanisms, and reward dispensers. Meanwhile, higher-performance processors like Raspberry Pi platforms can support computational tasks including image recognition, data logging, and network communication. This layered embedded architecture enables efficient real-time system operation while supporting more advanced sensing technologies.

Previous research also demonstrates the potential for integrating sustainable energy sources into reverse vending machine systems. A solar-powered reverse trash vending machine prototype utilized a microcontroller-based architecture combined with sensors, servo motors, and a GSM communication module to detect recyclable materials and dispense coin incentives. The system was powered by solar energy, demonstrating that renewable energy integration can reduce operational electricity consumption while supporting environmentally sustainable machine deployment (Rubio & Lazaro, 2016). Incorporating renewable energy sources into reverse vending machines can be particularly beneficial for installations in outdoor public spaces, campuses, or remote locations where access to stable electrical infrastructure may be limited.

From a sustainability perspective, another important improvement to existing reverse vending systems is the integration of a dual-mode token mechanism. In this approach, users can choose between two transaction modes: recycling plastic bottles or using coins as tokens. Allowing both plastic bottles and coins increases system accessibility and ensures that individuals can still utilize the machine even when recyclable bottles are not available. This hybrid design combines the environmental benefits of recycling incentives with the convenience of traditional vending systems.

However, maintaining the environmental objective of reducing plastic waste requires implementing certain sustainability controls. One potential strategy is to limit the number of plastic bottle tokens that a user can redeem within a specific time period, such as a daily submission limit. By enforcing a maximum bottle submission count per user per day, the system encourages responsible recycling behavior while preventing excessive or potentially fraudulent use of the machine. This limitation ensures that the incentive mechanism promotes recycling of existing waste rather than encouraging unnecessary plastic consumption.

Embedded system technologies can facilitate the implementation of such sustainability controls. User identification systems based on QR codes, RFID cards, or mobile applications can track individual transactions and enforce daily submission limits. Data collected through these systems can also provide valuable insights into recycling behavior, allowing operators to analyze usage patterns and optimize machine placement. Furthermore, integrating wireless communication modules enables remote monitoring of machine performance, bottle collection levels, and maintenance requirements. These smart monitoring capabilities contribute to more efficient waste management and operational planning.

Overall, the integration of advanced sensing technologies, intelligent embedded architectures, and sustainability-oriented incentive mechanisms represents a promising direction for future reverse vending machine development. Enhancing detection accuracy through sensor fusion and computer vision can significantly improve system reliability, while hybrid token mechanisms can increase accessibility and encourage broader participation in recycling programs. At the same time, incorporating renewable energy sources and implementing controlled bottle submission limits help ensure that the environmental objectives of waste reduction and sustainable resource management remain central to the system's design. These advancements demonstrate how reverse vending machines can evolve beyond simple recycling devices into intelligent embedded systems that support sustainable waste management practices.

Conclusion

Reverse vending machines have been recognized as an efficient technology for promoting recycling and better waste management practices. A review of existing literature on reverse vending machines, specifically in terms of system design, sensing technology, and sustainability, was conducted. From the study, it is clear that reverse vending machines currently use basic sensing technology such as infrared sensors, load cells, and optical sensors to identify recyclable plastic bottles. While the reverse vending machines have a high level of accuracy in terms of operation, there is still room for improvement in terms of the reliability of the sensors, avoiding misidentification, and ensuring system stability.

The development of better sensing technology is expected to provide better opportunities for improving the efficiency of reverse vending machines. Computer vision, depth cameras, and precise load cells have the ability to improve the accuracy of the identification process. Platforms such as Arduino Mega 2560, Raspberry Pi 4 Model B, and NVIDIA Jetson Nano have the processing capabilities that can support better sensing technology. Reverse vending machines can use better sensing technology to improve the accuracy of the identification process, reducing misidentification and misvalidation.

In addition to this, the factor of sustainability will continue to play an important role in the development of reverse vending machines. The present review has emphasized the benefits that can be obtained from the implementation of a dual token mode in which users can be given the option to use plastic bottles or coins. In addition to this, it can be beneficial to limit the number of plastic bottle tokens that can be used by each user in a single day to promote the sustainability factor.

In summary, reverse vending machines are an interesting area for the integration of embedded systems, sensing, and environmental sustainability. Future work should concentrate on the improvement of the accuracy of the sensors, the integration of intelligent object recognition techniques, and the design of sustainable incentive schemes. With the integration of advanced embedded system technology and sustainable design, reverse vending machines can become an important enabler for an effective recycling infrastructure and sustainable waste management.

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