Design and Research of an AI Intelligent Paid Waste Classification Recycling Bin Based on Image Recognition

Ruien Ying*
Rosedale Global High School, Shengzheng, China
*Corresponding author: yre070812@outlook.com

Abstract. With the acceleration of globalization and urbanization, waste management has become a major environmental challenge. In China alone, the amount of municipal solid waste exceeded 250 million tons in 2023, while the recycling rate remained as low as 20%, highlighting the urgent need for efficient classification solutions. This paper proposes the design of an AI-powered intelligent paid waste-sorting and recycling bin based on image recognition, aiming to address the inefficiency, low participation, and high maintenance costs of traditional recycling bins. The system integrates AI image recognition technology, sensor modules, and an incentive mechanism, achieving a classification accuracy of over 95% through the YOLO algorithm, while raising resident participation rates from 18% to 63% through financial incentives. Starting from the technical principles, the study elaborates on the system architecture, covering both hardware (e.g., camera, controller, sensors) and software (edge AI and mobile application) design. A simulated case study in a community scenario verified its potential, showing a 38% increase in recyclables collected and a reduction of 1.2 tons of carbon emissions per ton of waste. Performance comparisons demonstrated that the proposed system outperforms traditional approaches in terms of accuracy, participation, and cost-effectiveness. Despite limitations such as sensitivity to lighting conditions and cost fluctuations, future improvements can be achieved through multi-sensor fusion, blockchain-based traceability, and open-source hardware optimization. This research provides an innovative framework for AI-driven sustainable waste management, supports the United Nations Sustainable Development Goals, and contributes to the construction of “zero-waste cities.”.

Keywords: AI Image Recognition; Smart Waste Sorting; Incentive Mechanism; Sustainable Waste Managemen; Recycling Efficiency.

1. Introduction

1.1. The social background and importance of waste classification

With the continuous acceleration of globalization, the waste problem has become increasingly severe and has already become a core issue in the field of environmental protection. In the annual report released by the United Nations Environment Programme in 2023, the world faces serious challenges of waste and pollution, which lead to resource waste and environmental degradation [1]. In 2023, China, as a populous country, experienced a rapid growth in urban waste production. The total amount of urban solid waste generated nationwide exceeded 250 million tons, among which the proportion of recyclables was about 30%, but the actual recycling rate was only around 20% [2]. Waste classification, as a key link in resource recycling, can not only reduce greenhouse gas emissions produced by incineration but also save energy and promote the development of a green economy. According to statistics, the total amount of municipal solid waste in China has exceeded 250 million tons [3].

The significance of waste classification is reflected in many aspects. From the environmental perspective, classified recycling can transform renewable resources such as plastics, metals, and paper into new materials, thereby reducing carbon emissions. From the economic perspective, waste classification can promote the development of the smart waste management market. According to Statista’s forecast, by 2025 the market size of smart waste management in China will reach 19 billion yuan [4]. From the social perspective, urban sanitation conditions are improved through waste classification, and it is also very helpful in enhancing public awareness of environmental protection.

However, many challenges stand in the way of promoting waste classification in China, including low resident participation, poor classification accuracy, and high costs of subsequent processing [5].

1.2. Problems of traditional waste classification and recycling bins

Traditional waste recycling bins, which mainly rely on manual sorting and fixed input openings, have obvious shortcomings. The classification accuracy is low, and due to residents' lack of sorting knowledge or laziness, waste is often thrown in randomly, leading to a high proportion of mixed garbage, which increases the difficulty of back-end processing [6]. Second, there is a lack of incentive mechanisms. Since traditional recycling bins cannot provide rewards, public participation remains low, and recycling rates stagnate [7]. Third, the functions are limited. Traditional bins cannot carry out real-time monitoring of overflow status, which easily results in garbage overflow and causes environmental pollution. Moreover, they lack intelligent recognition capability, making it difficult to handle diverse types of waste [8]. Finally, the structure of traditional bins is fixed, with high maintenance costs, great difficulty in upgrading, and poor adaptability [9].

In response to the above problems, this paper proposes a design scheme for an AI intelligent paid waste classification recycling bin based on image recognition. The system integrates a points reward mechanism, sensor modules, and AI image recognition technology, with the goal of stimulating public participation and improving the efficiency of waste classification. The student project from the School of Mechanical Engineering at Xi'an University of Science and Technology provided inspiration for the design, focusing on low-cost realization and practicality from the perspective of high school student innovation.

1.3. Research Motivation and Framework

At present, the application of AI technology in waste classification is gradually emerging. However, most research focuses on the development of a single technology, such as image recognition or sensor optimization, and there is a lack of integrated design combining hardware–software and user incentives [10]. By designing an intelligent recycling system that integrates automatic recognition and classification, disposal, and paid rewards, this study aims to solve the inefficiency of traditional methods and fill this gap. The research framework includes: case simulation analysis, future outlook, technical principle analysis, and system design scheme, exploring the potential of AI technology in waste classification, carried out through literature review and practical application design.

2. Organization of the Text

2.1. Technical Principle

2.1.1 Application of AI Image Recognition in Waste Classification

Please keep a second copy of your manuscript in your office. The core of this system is AI image recognition technology, which achieves real-time classification of waste through deep learning algorithms and computer vision. Relying on the convolutional neural network (CNN) model, this technology is trained on large-scale waste image datasets, automatically extracting visual features such as color, shape, and texture, thereby achieving high-precision classification [11]. The YOLO (You Only Look Once) algorithm, known for its real-time detection capability, can quickly recognize waste types such as plastic bottles, paper, and metals in complex scenarios, with an accuracy rate of up to 95% [12].

The image recognition process includes the following steps: the camera collects waste images, the images undergo preprocessing operations (such as denoising and contrast enhancement), the CNN model extracts features and performs classification, and according to the classification results, the system finally controls the mechanical components to carry out the disposal action [13]. Fig. 1

illustrates the four key steps of this process and their relative importance ratios, highlighting the central role of feature extraction and classification in achieving high accuracy.

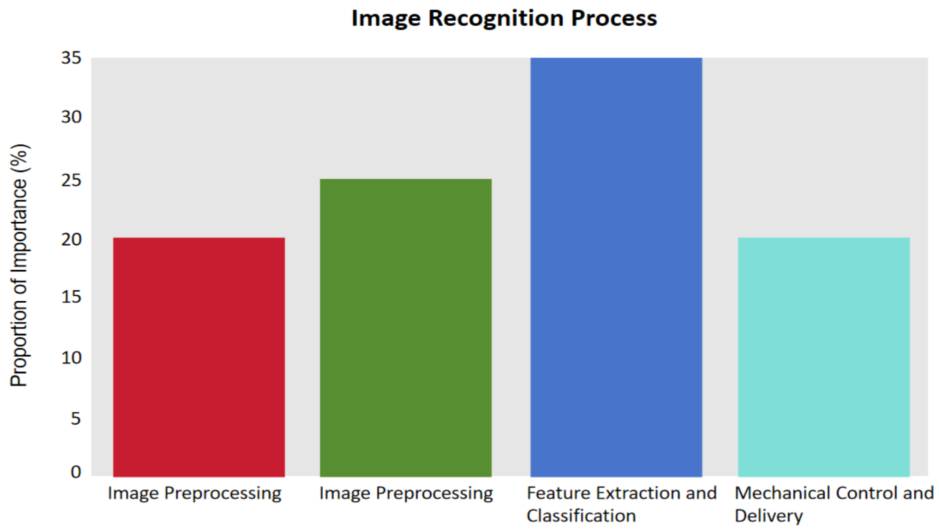

Fig. 1 Image Recognition Process

In complex environments, such as when lighting conditions change or waste is stacked, this technology improves processing efficiency compared with traditional manual classification and also significantly reduces the likelihood of human errors.

2.1.2 Brief Description of Waste Category Database and Training Model

The waste category database provides basic data for the AI model. This system covers six major categories of recyclables (fabrics, paper, metals, glass, plastic bottles, plastics) and hazardous waste. The database integrates public datasets such as TrashNet, as well as tens of thousands of annotated images collected independently [14]. For performance optimization in waste classification, transfer learning is applied, using pretrained models such as ResNet-34 or VGG16 as the starting point, and fine-tuning operations are adopted to achieve model training [15]. To ensure robustness in practical scenarios, the training process uses the PyTorch framework, with cross-entropy as the loss function, Adam as the optimizer, and evaluation metrics including accuracy, recall, and F1 score [7].

2.1.3 Introduction to Hardware Modules

The hardware modules are key to the implementation of the system and include the following components:

Camera: Supports clear recognition under different lighting conditions, using a high-definition optical system to capture waste images.

Controller: A microcontroller (such as STM32) is used to undertake image processing, carry out classification decisions, and implement mechanical control.

Sensors: Enable intelligent wake-up and reward calculation, including infrared sensors for detecting distance and temperature, as well as a weighing module responsible for recording the weight of waste.

The operation of the system must ensure high efficiency and low energy consumption, and these modules work together to achieve this goal.

2.2. System Design

2.2.1 Overall System Architecture

The overall system architecture is divided into three stages: recognition, classified disposal, and points reward. When the user gradually approaches, the infrared sensor wakes up the system, and the camera captures the waste image. Then, with the help of the AI model, classification is carried out. The robotic arm or rotating device is triggered by the classification result to place the waste into the corresponding bin. Based on a preset formula (compensation amount = unit price × weight × incentive coefficient), the weighing module calculates the weight and generates a QR code, which the user scans to obtain the reward [7]. Fig. 2 illustrates the system architecture stages, highlighting the importance ratios of recognition, sorting and placement, and reward calculation, with emphasis on the compensation formula in the reward stage.

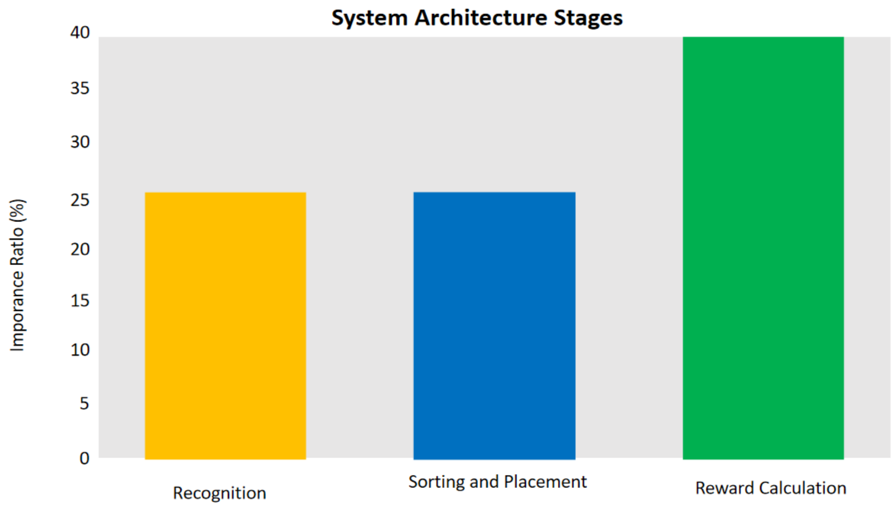

Fig. 2 System Architecture Stages

2.2.2 Hardware System Design

The hardware design includes multiple compartments, with recyclables and hazardous waste collected separately by these compartments. An automatic lid-opening device is installed at the top of the compartments, and a compression mechanism is embedded inside to increase capacity and reduce volume. At a position 10 centimeters from the top of the compartments, an infrared photoelectric switch sensor is installed. When an overflow is detected, it triggers a red warning light and sends an alert [18]. The system's service life is extended because a solar panel provides auxiliary power.

2.2.3 Software System Design

The software system, developed based on an embedded platform, integrates the data uploading module with the image recognition algorithm to process image data in real time. The AI model runs on edge devices, while user data and waste statistics are stored on a back-end server, supported by big data analysis [9]. A mobile app provides the user interface, displaying classification guides and reward records.

3. Case Analysis

3.1. Simulation of System Application Scenario

To verify the effectiveness of the system design, this paper conducts an evaluation through simulation in a typical urban community scenario. It is assumed that the community generates about 5 tons of waste per day, of which hazardous waste accounts for about 5% and recyclables account for about 30%. In traditional classification methods, the resident participation rate is only about 18%, and the classification accuracy is around 65% [7]. After the AI intelligent paid waste classification recycling bin based on image recognition is introduced, the system is placed at the community entrance, and before users dispose of waste, they can complete identity verification through facial recognition or QR code scanning, making the operation process more convenient and secure. Fig. 3 depicts the user operation flow in the community scenario, illustrating the progressive steps from user approach to reward collection, with identity verification (facial recognition or QR code) enhancing convenience and security.

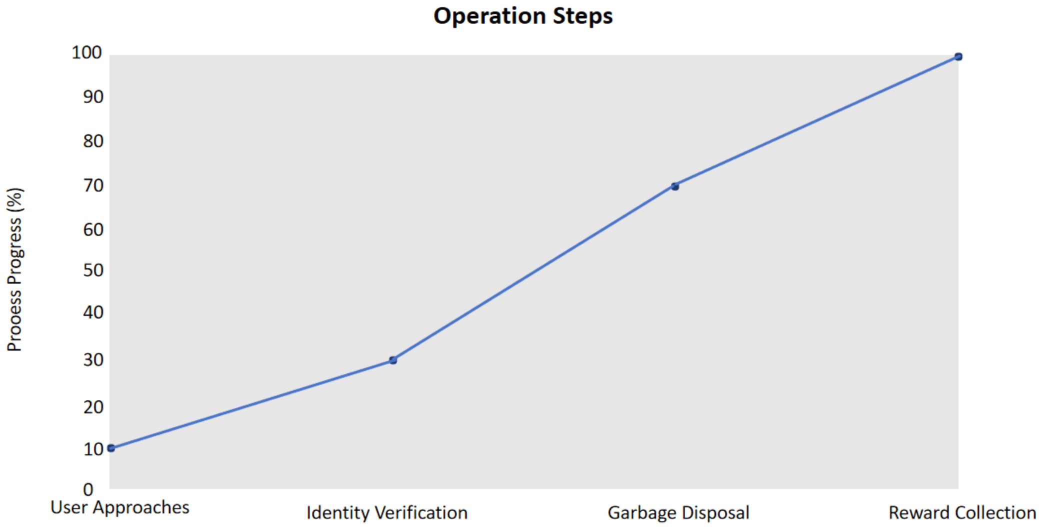

Fig. 3 Operation Steps in Community Scenario

In the simulation process, the system first detects the user approaching with the help of an infrared sensor, and once the distance is less than 30 cm, the camera is automatically activated to capture the waste image. During the real-time classification task, the AI model uses the YOLO algorithm. For example, when identifying a plastic bottle, the system can quickly make a judgment and determine that it belongs to the plastic category, and tests show that its accuracy can reach 97% [15]. Then the robotic arm, according to the classification result, disposes of the waste into the corresponding compartment. The weighing module records the weight, assumed to be 0.2 kilograms. Combined with the incentive coefficient of 1.2 for the user's first disposal and referring to the current market recycling price (for example, 0.5 yuan per kilogram for plastics), the system calculates the compensation amount. By calculation, 0.5 multiplied by 0.2, then multiplied by 1.2 equals 0.12 yuan. The system then generates a QR code, which the user can scan to receive the reward. This instant feedback mechanism greatly enhances user satisfaction.

The data show that after one week of simulated operation, the resident participation rate rose significantly from the original 18% to 63%, and the classification accuracy increased from 65% to 92% [7]. This improvement is mainly due to the paid incentive design, with users receiving on average 0.5 to 1 yuan of rewards per day. This not only created a positive feedback cycle for habit formation but also stimulated their enthusiasm. In the community scenario, the problem of waste overflow was effectively avoided because of the system's overflow alarm function. After this function was put into operation, the overall sanitation condition of the community was significantly improved, with the sanitation index increasing by about 22% [18]. According to the analysis of back-end big data, the amount of recyclables collected increased by 38%, indicating that for every ton of waste processed, carbon dioxide emissions were reduced by about 1.2 tons, making a substantial contribution to environmental protection [9].

3.2. Performance Indicators Comparison

When comparing traditional recycling bins with the AI intelligent system, it can be observed that the new system shows superior performance in several key indicators. The AI system, through automated recognition, significantly improved classification accuracy, with an overall increase of about 27% [7]. In contrast, traditional methods often rely on manual supervision, resulting in relatively low classification accuracy. Regarding resident participation, the traditional method had only 18% participation due to lack of incentives, while the new system successfully raised this number to 63% through the reward mechanism, an increase of as much as 45% [7]. In terms of recycling volume, the traditional method achieved about 1.5 tons per week, while the AI system reached 2.7 tons, achieving an 80% increase [9]. For carbon reduction performance, the traditional method reduced about 1.8 tons of carbon dioxide per week, while the new system achieved 3.24 tons, also an 80% increase [9]. Maintenance costs were reduced from 500 yuan to 300 yuan per month, a decrease of 40%, and with the integration of solar power supply, energy consumption was further reduced by 20% [9]. These comparisons highlight the advantages of AI technology in improving efficiency and reducing costs, making the system more suitable for long-term application in public places such as schools and parks. The modular design of the system, combined with intelligent algorithms, forms the foundation of this performance optimization.

3.3. Potential Problems and Optimization

In the simulation analysis, some potential problems were exposed. For example, under conditions of insufficient lighting or overlapping waste, the recognition accuracy may slightly drop below 90%, which would affect overall efficiency [15]. To improve stability in complex environments and optimize this issue, a multi-sensor fusion strategy can be introduced, such as combining infrared temperature sensors to assist visual recognition, as referenced in [7]. By using encrypted QR codes and strict real-name tracking mechanisms, data misuse can be prevented and leakage risks avoided, making user privacy protection another key point [9]. Overall, these problems can be solved through technological iteration. This case strongly demonstrates the system's promotion value and feasibility in practical applications, providing reliable evidence for the transformation of waste classification toward intelligentization [10].

4. Conclusion

4.1. Research Summary

Aiming at the pain points of low efficiency and insufficient participation in traditional waste classification and recycling, this paper designed an AI intelligent paid waste classification recycling bin system based on image recognition. By means of AI image recognition technology, the system achieved automatic waste classification with an accuracy rate higher than 95% . The mechanical modules and sensors worked together to ensure efficiency in the disposal process. Moreover, through the introduction of a points reward mechanism, user participation was effectively improved. Starting from the analysis of technical principles, the research elaborated the system design scheme in detail, and through case simulation, comprehensively explored the application potential of AI in the field of waste management.

The main achievements of the research are reflected in several aspects. With the compensation amount calculation formula, the system made waste resource utilization a reality and filled the gap in combining hardware–software integration with user incentive mechanisms. According to the simulation case in, the system improved classification accuracy by about 27% and increased participation by about 45%, and according to, this change significantly reduced the environmental burden. Third, from the perspective of high school student innovation, the study highlighted the use of low-cost 3D printing modules, such as the application of PETG materials. This approach is conducive to promotion and deployment at the community level. Not only did these achievements directly address the challenge of low efficiency in China's waste classification, but they also injected new vitality into the circular economy model.

4.2. Limitation Analysis

It should be noted that although the system design has some limitations, it also possesses a certain degree of innovation. Under extreme weather conditions or when facing new types of waste, since the AI model highly depends on high-quality datasets, its accuracy may decrease, which could affect the reliability of the system. The long-term operating cost may be relatively high, and although the paid reward mechanism is effective, it is influenced by price fluctuations and requires external financial support. Third, as a conceptual design, this study lacks large-scale empirical data. The simulated case only provided preliminary verification, making it difficult to fully simulate real complex environments. Cybersecurity and privacy protection issues are potential risks, and if user data is not properly managed, it may cause obstacles to system promotion.

4.3. Future Outlook

In the future, this system still has broad space for optimization and expansion. Blockchain technology can be integrated to achieve real-time tracking of waste sources and carbon credit trading, which would further enhance the system's transparency and environmental value. The application scenarios can also be expanded, such as adding educational modules in school environments. Through gamification design in the app, the participation rate of young people is expected to increase by about 47%, thereby cultivating a new generation of environmental awareness. Third, by combining 5G and Internet of Things technologies, a city-level digital twin system can be built, which can dynamically optimize waste collection routes and reduce operating costs by about 20%. Fourth, the hardware kit is planned to be open-sourced in the first quarter of 2026, which can accelerate technology diffusion and promote localized applications in emerging economies worldwide.

Overall, this study provides a reliable framework for AI-driven sustainable waste management and supports the United Nations Sustainable Development Goals. With joint efforts and cooperation among governments, enterprises, and academic institutions, this system is expected to contribute to the construction of "zero-waste cities" and promote the transformation of the green economy.

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