AIoT-Based Waste Classification for Solid Waste Management to Accomplish the SDGs

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***Abstract*—The Fourth Industrial Revolution, known as IR4.0 technologies, has enhanced global economic capabilities and productivity, but there are negative environmental and health impacts due to industrialisation and urbanisation, such as greenhouse gas emissions and global warming. One effective method that reduces environmental impact is to conduct a waste classification program that incorporates the principles of 3R. The proposed work includes educating individuals and businesses on the importance of waste reduction, promoting reusable products and packaging, and implementing effective recycling systems. Additionally, Governments could also incentivise sustainable practices through tax breaks or invest in renewable energy sources to reduce greenhouse gas emissions associated with industrial processes. The proposed study aims to develop automated waste classification technology that can help reach SDGs 11, 12, and 13 by making waste management more efficient, increasing recycling and resource recovery rates, and cutting down on greenhouse gas emissions. The proposed system is developed using a deep learning algorithm with a microprocessor and microcontroller managing sensors and actuators to perform waste sorting based on the classification result. This distinguishes the proposed system from existing manual and RFID-based approaches by integrating AIoT with a user incentive mechanism, improving both accuracy and public adoption. This technology enhances overall sustainability and promotes a more circular economy by enabling the reuse and recycling of materials for their own well-being through process innovation.**

Keywords*—Solid waste management; waste classification; artificial intelligence of things (AIoT); well-being; process innovation; sustainable development goals (SDG); recycling; circular economy

I. Introduction

One of the most pressing environmental pollution issues that most countries face in the twenty-first century is the damage that solid waste pollution causes to the environment [1]. Waste emissions have substantially increased at a visible rate, making waste management more challenging [2]. Over 64% of the population in developing countries and 84% of the population in developed countries will be expected to be living in urban areas by the year 2050. This urbanisation trend is expected to result in a global waste generation of approximately 3.4 billion metric tonnes, which is a significant rise compared to the current 2.01 billion metric tonnes [3–4].

Solid waste pollution not only leads to the spread of biological diseases and localised odours but also exerts a significant impact on the soil, water, and air [5]. However, the nature of solid waste can also cause environmental pollution that has an impact on health issues. For instance, the common infectious diseases are, namely, typhoid and cholera, and non-communicable diseases such as cancer, asthma, or birth defects in babies [6]. According to estimates, waste pollution is the main cause of death in nations with environmental pollution issues.

Malaysia relies significantly on landfills, which offer a more cost-effective and straightforward waste disposal solution compared to other methods [7]. Landfilling and incineration have traditionally been considered cost-effective approaches for solid waste disposal, but both methods inflict severe damage on the environment [8]. When significant amounts of solid waste are either disposed of or incinerated in landfills, the decomposition process releases potent greenhouse gases, such as carbon dioxide and methane, which significantly contribute to global warming and climate change [9]. Despite the availability of more advanced technologies for incineration and other waste disposal methods, landfilling remains the predominant approach for waste disposal in all countries. Based on current trends and future projections, it is anticipated that waste generation will continue to increase and that unsustainable waste disposal techniques like landfilling and incineration will remain in use. As a result, the harm that solid waste causes to the ecological balance will only get worse [10]. This rapid growth in solid waste production exceeds the capacity for timely disposal, resulting in a significant amount of waste remaining unmanaged and contributing to the proliferation of illegal landfills or open dumps [11].

Unfortunately, the unprecedented emergence of the coronavirus disease 2019 (COVID-19) has further intensified the adverse environmental consequences of solid waste, as the global population has resorted to increasing utilisation of single-use plastic cutlery and personal protective equipment (PPE) to curb the spread of the virus [12]. Consequently, the management of municipal solid waste (MSW) faces significant challenges due to the generation of additional substantial quantities of clinical waste, including masks, PPE, batteries, and empty oxygen cylinders [12]. Since the outbreak began, an estimated 1.6 million metric tonnes of plastic waste are produced globally every day, while 3.4 billion single-use masks or face shields are thrown away every day [13]. Furthermore, the transmission of the COVID-19 virus occurs through sneezing, coughing, and touching surfaces contaminated with COVID-19, which results in the need for additional precautions in the disposal of municipal solid waste to avoid unnecessary virus transmission or environmental contamination [14–15]. Nevertheless, current waste management systems remain largely manual, labour-intensive, and expose workers to health risks, especially during pandemics such as COVID-19. This research addresses these gaps by proposing an automated AIoT-based system, combining deep learning image recognition with IoT-enabled hardware and a user incentive mechanism.

The recycling of waste to mitigate greenhouse gas emissions has always been the primary objective in managing municipal solid waste (MSW) in Malaysia [16]. For instance, the government implemented various measures aimed at improving waste management and encouraging recycling in the 12th Malaysia Plan (2021 to 2025). These measures included banning the use of single-use products, such as plastics and packaging materials, in restaurants and public events. Additionally, the construction of comprehensive scheduled waste treatment and disposal facilities was prioritised to combat illegal dumping. These initiatives aim to achieve a waste recycling rate of 35% by the end of 2025. Furthermore, Malaysia has made a commitment to decrease its greenhouse gas emissions intensity by 45% from 2005 levels by 2030 upon signing the Paris Agreement [17]. Although the government has implemented many frameworks for sustainable solid waste management, the main problem lies in the lack of alternatives to waste management and the poor implementation of waste policies [18]. Moreover, Malaysia stands among the countries significantly contributing to environmental pollution and health issues resulting from waste accumulation due to the irresponsible and ignorant attitudes of consumers towards waste disposal [19]. According to the research results, many residents are aware of the negative effects that waste has on the environment, but they nonetheless frequently engage in behaviours such as dumping waste in rivers or accumulating it with other waste [20].

II. Literature Review

One of the main goals of the SDGs, according to the United Nations' 2030 Agenda for Sustainable Development, is to address the significant ecological and economic challenges that the entire world faces [21]. Furthermore, the management of municipal solid waste is encompassed within the framework of the Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change [22]. For instance, SDG 11 (Sustainable Cities and Communities) promotes the establishment of efficient and sustainable waste management systems in urban areas, leading to reduced pollution and cleaner cities. Additionally, SDG 12 (Responsible Consumption and Production) aims to limit pollution resulting from excessive solid waste decomposition in the environment through the principles of 3R (reduction, recycling, and reuse). Lastly, SDG 13 (Climate Action) focuses on decreasing greenhouse gas emissions associated with waste production and disposal to mitigate environmental pollution caused by existing inefficient waste management systems.

As shown in Fig. 1, the proposed system flow integrates sensors, actuators, and cloud services for automated waste classification, using waste classification techniques employing deep learning and IoT technology. The suggested solution tackles the issue and meets the 3R (reduce, reuse, recycle) principles and the Sustainable Development Goals (SDGs). This makes waste collection and categorization possible. In addition, depending on the kind and quantity of waste collected, the system would update the users' membership points or e-wallet points in a cloud database. Residents are encouraged to actively engage in waste recycling activities by means of this incentive.

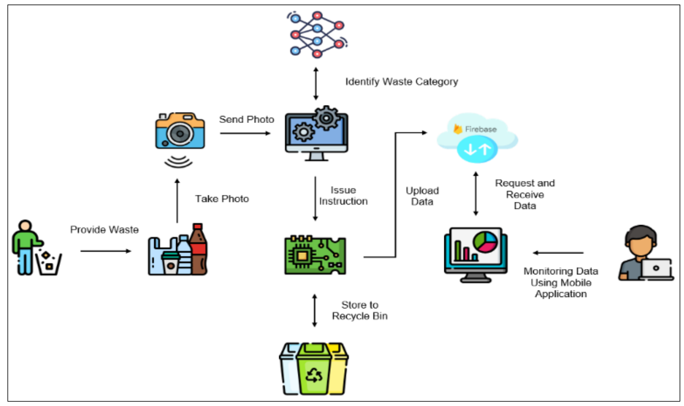

Fig. 1. Project system flow.

A trash classification system that is automated and increases accuracy and efficiency in waste management can be easily created with the help of current AIoT technologies. Through the utilisation of artificial intelligence and the Internet of Things, the system can efficiently recognise and classify various waste materials, thereby lessening the need for manual effort and increasing the overall rate of recycling. The analysis of the data gathered from this system to find patterns and trends also enables better decision-making regarding waste management techniques, making 3R recycling rates easier.

In order to develop an automated waste classification system and raise 3R recycling rates, the primary goal of the project is to research current AIoT technologies. Subsequently, create a system for classifying waste and create mobile applications to encourage recycling and raise user knowledge of recycling. Lastly, assess the accuracy and dependability of the suggested system.

III. Methodology

A well-defined procedure is used in the software development life cycle (SDLC) to generate and produce a high-quality product [22]. The waterfall model is regarded as one of the simplest approaches, among others. For software or system development, the waterfall model comprises six separate phases: requirements, design, development, testing, deployment, and maintenance. However, only the requirement analysis, design, development, and testing phases of the waterfall model have been carried out. The research approach was applied in three steps. Data collection, system development, and testing are the first three phases. Phase 1: Data Collection thus covers requirements, analysis and design tasks, Phase 2: System Development covers development tasks, and Phase 3: Testing covers testing tasks. The waterfall strategy is consistent with this study methodology [23].

A. Phase 1: Data Collection

First, information was gathered through an interview and a questionnaire. A method for gathering quantitative data was using questionnaire, and a means for gathering qualitative data was an interview. In-depth perspectives and comments on the proposed system, as well as the current waste classification system, were obtained from Malaysians using both methods. While the interviews allowed open-ended responses that offered deeper insights and viewpoints, the questionnaire included closed-ended questions to collect quantifiable data on preferences and opinions. Combining the two approaches could result in a thorough grasp of the current system as well as possible upgrades. To make sure that the planned system would satisfy the requirements and preferences of its intended users, this data gathering phase was essential in providing guidance for the project's design and development phases.

Through the questionnaire, 80 respondents were Malaysian, including 50 males and 30 women. Based on Fig. 2, the most commonly used and recycled solid waste types among the respondents were aluminium and plastic cans. Fig. 3 shows that respondents were in complete agreement about the contribution of trash sorting to environmental harm. Furthermore, the bulk of respondents mentioned how difficult it is to physically separate waste. The data from the questionnaire will be crucial in informing strategies for waste management and environmental conservation in Malaysia. It is evident that there is a need for more efficient waste sorting systems to address the challenges highlighted by the respondents.

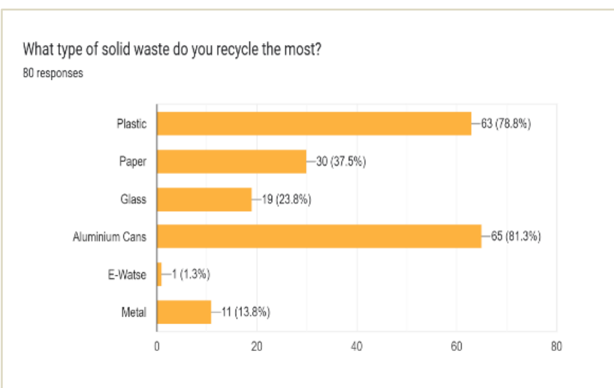

Fig. 2. Type of solid waste recycled the most.

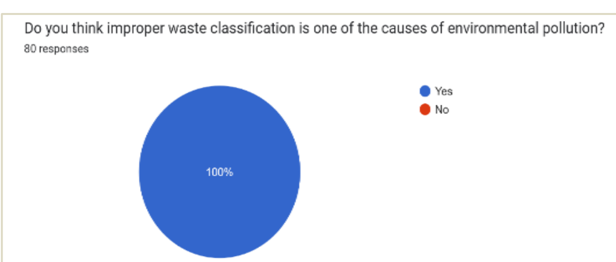

Fig. 3. Perception of waste misclassification causing environmental pollution.

When it comes to recycling, Fig. 4 illustrates whether consumers have segregated solid waste by kind. A mere 21.3% of respondents sorted their rubbish prior to recycling, whereas only 78.8% of respondents did not separate their waste, according to the statistics. The survey investigated the reasons behind not sorting waste for those participants who replied "no" to the preceding question. Fig. 5 demonstrates that while 20.6% of respondents said they knew nothing about trash separation, 22.2% mentioned being extremely busy, and 56.6% thought the separation process was difficult. Only a small percentage said it took a lot of time.

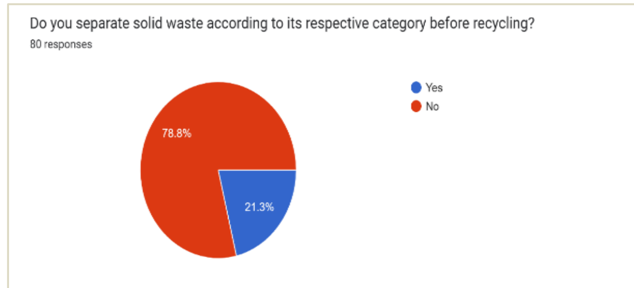

Fig. 4. The response to solid separation.

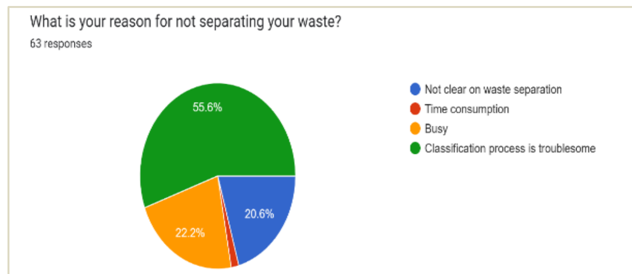

Fig. 5. The reason for not separating the trash.

According to the respondents, the suggested system will classify garbage more accurately than current approaches, as seen in Fig. 6. Based on the pie chart, 92.5% of respondents think that the intelligent garbage classification system is superior to the manual sorting system currently in use, while 7.5% disagree. In addition, respondents think the system can stop viruses from spreading, particularly COVID-19, and only 19 out of 80 respondents think it can increase recycling rates.

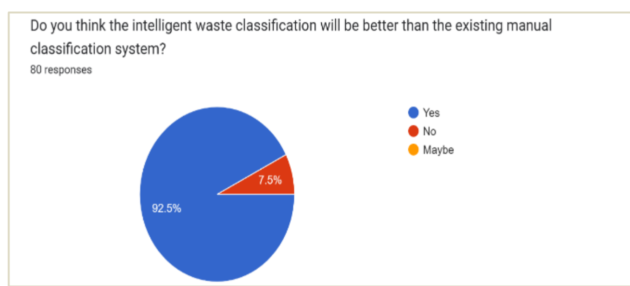

Fig. 6. Feedback on the intelligent waste classification.

As seen in Fig. 7, respondents' readiness to pay for the proposed system reveals that 71.3% found fees between RM1 and RM1,000 acceptable, while 26.3% would not pay any fees at all. Lastly, the purpose of this query is to determine which system components respondents value the most. According to

Fig. 8, the user interface (38.7%), the hardware design (10%), and 51.2% of respondents, the functionality of the suggested system is the most important feature. The responses to the questionnaire gave important information on the status of waste classification as it stands today as well as the respondents' reluctance to move forward with it. Regarding the respondents' opinions on the proposed system, it is likewise evident. The questionnaire indicates that opinions of the proposed waste classification system are largely positive.

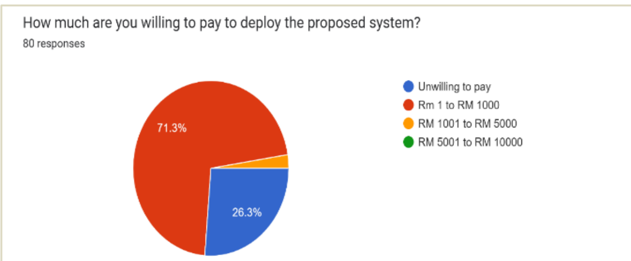

Fig. 7. The willingness of respondents to pay for the proposed system.

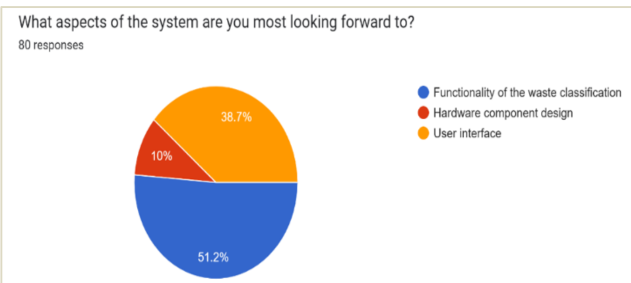

Fig. 8. The expectation on the system.

To ascertain whether the public appendices and papers in the report were acceptable to them, five individuals were interviewed. Table I enumerates the interview questions along with their intended use. It was intended to ascertain the respondents' awareness of existing waste management procedures and assess their opinions regarding waste generation in Malaysia. In addition, the interview aims to shed light on respondents' perceptions of the relationship between incorrect trash recycling and contamination of the environment, as well as suggest possible solutions. to find out how the respondents felt about environmental pollution and what steps they thought could be taken to stop waste pollution. Furthermore, information was gathered regarding respondents' perceptions of environmental pollution as well as suggested or plausible countermeasures for waste pollution. The main ideas of the suggested system and the respondents' assessment of it were clear to them.

The interview summaries indicate that the participants conveyed concerns about Malaysia's high rates of waste generation and the shortcomings of current environmental protection strategies. Inappropriate waste classification has been demonstrated to be one of the primary sources of environmental pollution. It was found that raising public awareness and educating people about recycling trash was crucial for finding a solution to this issue. The proposed garbage sorting system received positive feedback, with time and effort savings predicted. The system has to be more precise and easier to use, according to respondents, in order to increase user numbers, increase recycling rates, and raise awareness of environmental issues.

According to the interview summaries, participants expressed apprehensions regarding Malaysia's elevated waste generation rates and the insufficiency of existing methods for safeguarding the environment. One of the main causes of pollution in the environment has been shown to be improper waste classification. It was determined that increasing public awareness and education about waste recycling was essential to solving this problem. Positive input was given to the suggested garbage sorting system, with time and effort savings anticipated. Respondents did, however, highlight the need for the system to be more accurate and user-friendly to draw in more users, boost recycling rates, and promote environmental consciousness.

Next, one of the Unified Modelling Language (UML) diagrams that illustrates the functionality and extent of the system is the use case diagram, which illustrates the interaction between the actors and various use cases [24]. The case diagram provided below illustrates the relationships between actors and use cases in the proposed system.

Fig. 9 depicts the use case for the Solid Waste Classification System, which illustrates the interactions among six main actors.

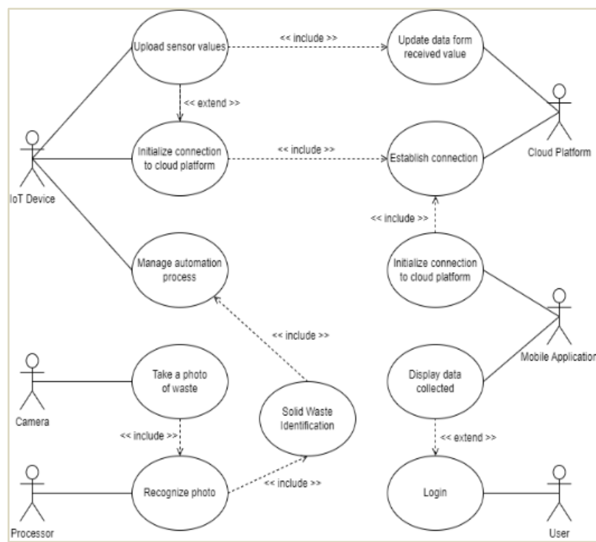

Fig. 9. Use case diagram for the solid waste classification system.

The Internet of Things (IoT) device is one of these characters: it oversees managing the actual automated garbage sorting procedure and uploading sensor readings to the cloud; Camera: takes and uploads trash photos to the processor. Processor: using a neural network-trained deep learning model to analyse the acquired photos and issue commands based on the classification results; Cloud Platform: a location for managing and storing all collected data; Mobile Application: a smartphone app that tracks data by connecting to a cloud database; User: to confirm their identification, access their account. The waste's weight is converted into points by the system after it has identified and categorised the waste category. These points are then updated in the user's account.

B. Phase 2: System Development

The system was created using Android Studio, Firebase, Arduino IDE, Thorny on Raspberry Pi, and Google Collaborative. Thorny and the Arduino IDE employ Python and C++ to manage the hardware components of the Raspberry Pi and Arduino, while Google Colab is used for free to train and run the deep learning model. The necessary database is managed by Firebase, and Android Studio is used to create the Android application.

The deep learning model was trained using a set of TensorFlow Keras libraries using the MobileNet architecture, a rapid and lightweight deep learning architecture designed for embedded devices with limited computational resources, such as the Raspberry Pi. The MobileNet architecture is optimised for image classification tasks. The MobileNet v1 neural network model was trained using RGB pictures with a pixel resolution of 224x224. It's a total of 28 layers, including batch normalisation, depth-wise convolutional, ReLU activation, and convolutional layers. With the addition of GlobalAveragePooling2D and two thick custom layers, the total number of layers rises to 31. With 97.23% accuracy on the training set and 99.24% accuracy on the validation set, the model demonstrated exceptional accuracy during training. The model's ability to accurately classify photographs was proven by its impressive 98.98% accuracy with a low loss of 0.0499 on the test set. The model has previously undergone pre-training, and the parameters are established.

The primary functions of the Raspberry Pi 4B are image capture and processing, while the Arduino Uno is used to communicate with actuators and sensors to obtain sensor readings and trigger tangible actions. As shown in Fig. 10, the hardware connection schema integrates Raspberry Pi, Arduino Uno, Pi Cameras, sensors, and actuators to support automated waste classification.

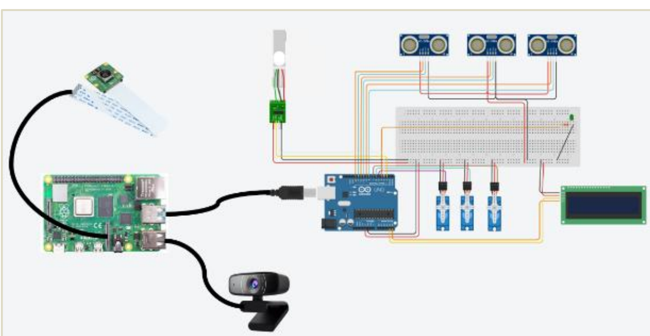

Fig. 10. Hardware connection schema.

The Raspberry Pi 4B can capture and process images of things by connecting the Pi Camera to the CSI-Camera connector. A second camera is used to scan the user's QR code for identification. Once the categorization result has been determined, the garbage is physically sorted using a servo motor, and its weight is measured using an Arduino. The data is then transmitted once more to the Raspberry Pi, where it is uploaded to Firebase.

The proposed system includes an Android application. One of this application's several features is the capability to use QR code to identify a user specifically. The Android app also provides a user-friendly interface that allows the user to view their overall points and the amount of trash they have recycled. Through this feature, users can easily track their progress and stay informed about their contributions to waste management.

C. Phase 3: Testing

A range of testing methods, including functional testing (unit and integration testing) and user acceptability testing, were employed to confirm the system's functionality and non-functionality. In addition, an evaluation of the deep learning model was conducted to determine how well the integrated deep learning model performed on the microprocessor. After both unit and integration testing were finished, every input and interaction between modules was carefully reviewed, evaluated, and verified. As such, both unit testing and integration testing were used to thoroughly test and evaluate the system. The system consistently showed accurate and reliable operation throughout the testing process.

Through user acceptance testing, the study provided the respondents with a thorough description and presentation of the mobile application and prototype schema. This stage was critical in ensuring that the recommended solution complied with user needs and project goals. In order to get useful data, the user experience was assessed during the interview process.

The findings of the user acceptability test showed that respondents highly rated the system's user-friendly interface as well as its potential to improve sustainability and the environment. They placed special attention on components that effectively promoted appropriate waste management, such as rubbish classification and monitoring. Additionally, the system did a good job of encouraging users to participate in recycling activities by offering rewards.

The deep learning model was evaluated using a testing process with various waste materials. The expected material for each item was compared to the production forecast by the model. In some cases, the model correctly identified the material (such as metal or plastic), but in other cases, it produced predictions that were off. The deep learning model produced predictions that were correct seven times out of ten, or an accuracy rate of 70% overall.

IV. Results and Discussion

Fig. 11 shows a model of the solid waste classification machine. A tangible model of waste collection apparatus capable of managing and classifying various types of waste materials has been built. Every piece of hardware is contained in a tiny box in this prototype. To operate the device, users need to download an Android app, register, and use the front camera of the box to scan their unique QR code. By scanning the QR code to verify the user, the device links the user's trash disposal activities to their account. Upon entering the machine, the trash is sorted according to its weight and type into the appropriate container.

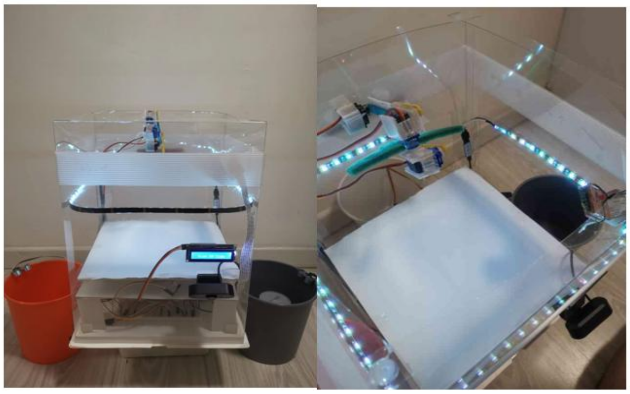

Fig. 11. Solid waste classification machine prototype.

The device also uploads fresh waste disposal records to a database, guaranteeing precise tracking of users' actions for further review and examination. Users can track their progress and contributions to waste management with the help of smartphone applications. The waste collection record is displayed in a list and pie chart in the user's mobile application. This data can help users monitor their environmental impact and make more informed decisions about their waste disposal habits. The user-friendly interface of the application allows for easy navigation and understanding of the information presented, as in Fig. 12:

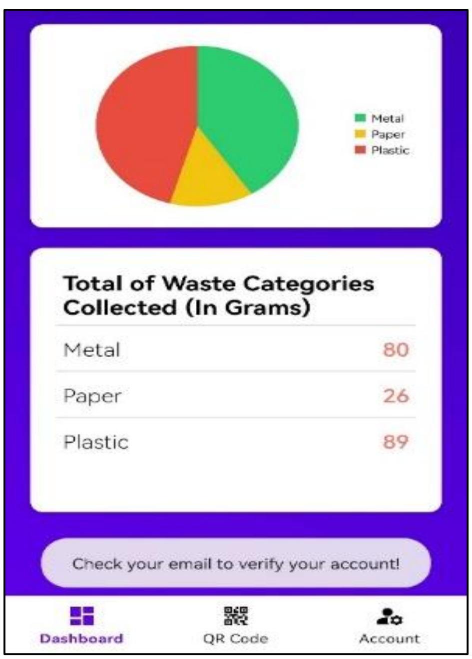

Fig. 12. Waste collection dashboard.

The proposed system evaluates the accuracy of the deep learning model after integration by incorporating waste items from different categories, like the item in Fig. 13. The dashboard also provides insights into trends and patterns in waste generation over time, allowing users to track their progress in reducing waste. By continuously updating the deep learning model with new data, the system ensures that it remains effective in classifying waste items accurately.

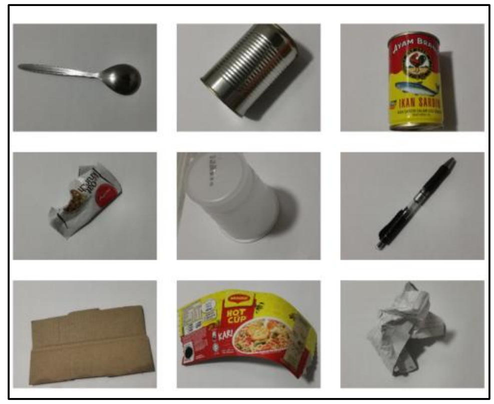

Fig. 13. Solid waste items from various categories.

The findings shown in Table I demonstrate the effectiveness of the suggested system in precisely forecasting and differentiating between various waste categories. The technology identified paper and empty garbage with 100% accuracy. The device had a 33.3% failure rate and a 66.6% success rate for garbage made of plastic and metal. Overall, the test findings suggest that the suggested approach has potential for efficiently identifying and separating waste materials into paper, plastic, and metal categories.

TABLE I WASTE CLASSIFICATION RESULT

Category	Success	Fail
Empty	100%	-
Metal	66.6%	33.3%
Plastic	66.6%	33.3%
Paper	100%	-

Nevertheless, within a category, some of the solid waste shows notable heterogeneity. It is possible for metal or plastic objects to appear differently from one another. Misclassification can occur when goods possess qualities that make accurate categorization difficult.

V. CONCLUSION AND FUTURE ENHANCEMENT

Currently, plastic, paper, and metal garbage can all be classified using the proposed waste recognition method. However, putting the algorithm in the cloud is a workable way to get over the microprocessor's limitations in handling complex deep learning algorithms. Improving the deep learning model is essential to guaranteeing the system's ability to recognize various things. However, the microprocessor's physical limitations make it unable to carry out sophisticated algorithms. Implementing algorithms in the cloud could address this problem by lightening the load on the local hardware and allowing the system to manage waste classification jobs that are increasingly complicated and detailed. Additionally, the wide variety of waste items, which are always changing in terms of substance, form, colour, and brightness, makes waste sorting difficult. It is therefore possible to train the deep learning model or use the internet and network resources for learning by integrating the suggested system with a sizable market database. Waste classification model improvement and ongoing learning are made easier using this method. In conclusion, it is possible to successfully motivate locals to engage in recycling activities with the help of the suggested AIoT solid waste classification system. Thus, recycling rates may rise as a result, further aiding in environmental preservation. By accurately sorting waste based on various characteristics, the AIoT system can streamline the recycling process and encourage sustainable practices. This innovative approach can ultimately lead to a more efficient waste management system and contribute to a cleaner, healthier environment for future generations. Moreover, the system may be enhanced to handle mixed waste classification, incorporate larger datasets for deep learning training, and integrate with smart city IoT infrastructure for real-time monitoring. Furthermore, improvements in hardware durability and cloud-based analytics can extend the system's usability in large-scale deployments.

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