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Revolutionizing waste management system through the development of an i-smart trash bin solid waste sorter

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ABSTRACT

This study presents a structured approach to creating an efficient waste management solution capable of segregating papers, plastic bottles, and metal cans. Following a developmental research design, the study progresses through three main phases: design and construction, development and programming, and performance evaluation. In the design phase, this study integrates electronic components such as inductive proximity sensors, ultrasonic sensors, servo motors, LEDs, LCD, a buck converter with an Arduino ATMEGA 2560 microcontroller, and a backup power source from solar energy to operate each bin with an 11-gallon capacity. The development and programming phase implements a sophisticated waste management system using Arduino IDE, incorporating sensor inputs to classify and sort waste items accurately. Results showed an overall accuracy rate of 97% in waste segregation with a minimal error of 6%, where paper waste achieved 100% accuracy, while a 97% accuracy rate was seen in both plastic bottle and metal waste. These findings underscore the prototype's potential as a reliable waste management solution, contributing to more effective and sustainable waste segregation practices. Further enhancements can be explored to optimize functionality and usability, ensuring continued innovation in waste management technology.

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INTRODUCTION

Solid waste management (SWM) is a crucial worldwide concern, aggravated by growing urbanization, population increase, and insufficient infrastructure (Ashraf et al., 2025). Moreover, SWM is a major environmental problem, especially in developing nations that continue to rely on antiquated practices with little regard for environmental hazards (Tayyeh and Fadhullah, 2025). Improper dumping, landfilling, incineration, and vermi-composting are the most prevalent waste processing and management methods. Burning biomass pollutes the environment, contaminates soil and groundwater, and affects environmental hygiene and human health, which are the disadvantages of the first three approaches (Hajam et al., 2023). For underdeveloped nations, SWM systems have considerable obstacles, such as insufficient service coverage, operational inefficiencies, and restricted recycling operations (Abubakar et al., 2022). These inefficiencies result in uncontrolled dumping, open-air incineration, and incorrect disposal methods, all of which harm the environment, pose health hazards, and create social inequality. Inadequate waste management techniques not only harm public health but also increase the rate of global warming by emitting methane gas and leachate contamination. Traditional waste management methods have proven ineffective, causing environmental degradation, resource waste, and the underutilization of valuable materials (Raab et al., 2021).

In the Philippines, waste management is still hindered by ongoing difficulties with garbage segregation, even though the Republic Act 9003 legislation, termed as the "Ecological Solid Waste Management Act of 2000," which lays the groundwork for pioneering research in the field of sustainable waste management, requires segregation at the barangay level. The law also requires the establishment of Materials Recovery Facilities (MRFs) in each barangay or group of barangays to efficiently sort and process recyclable materials (Coracero et al., 2021). The rule has not yet been effectively enforced by many local government units (LGUs), which has led to rampant mismanagement at the local level. Little lifestyle adjustments and poor compliance result from this lack of enforcement, which is exacerbated by limited money, technical support, and a general lack of awareness among households about the significance of appropriate segregation. Because of this, hazardous, recyclable, and compostable wastes are frequently combined, overflowing landfills and contaminating streams rather than being handled by the proper recovery or treatment facilities. Previous research indicates that although segregation is recognized in many communities, actual implementation varies due to a lack of infrastructure, technical assistance, and education initiatives to maintain behavior change (Bueta et al., 2023; Sayson et al., 2022).

To align with the mandate of Sustainable Development Goals focusing on Sustainable Cities and Communities (SDG #11) and Responsible Consumption and Production (SDG # 12), researchers from other countries came up with so-called smart trash bins to provide a viable answer to some of these issues by incorporating technology into garbage management. These are considered cutting-edge waste management tools that use technology to improve user experience and efficiency. To monitor garbage levels and optimize collection schedules, these bins frequently use sensors, including load, humidity, and level sensors, which lower labor costs and have a positive environmental impact (Bano et al. 2020). With this development, several researchers have come up with interesting ideas, such as Keerthana et al. (2017) from India, who consider system alerts collection vans, set threshold limits for bins, and ensure efficient garbage disposal. Another is from Wahab et al. (2017), who presented a unique model with online monitoring, auto-open/close features, and waste-type-specific incentives, and this approach not only provides efficient waste separation but also provides data for planning and analysis while Sohail et al. (2019) came up with Intelligent Trash Bin (ITB) using an Android application, where the ITB features included live mapping, flame alerts, trash level monitoring, and collection efficiency tracking. To address issues with waste collection scheduling and odor, Wilson et al. (2019) used the Internet of Things (IoT) in the design of their smart trash can. Another innovation is from Lin et al. (2024), who created an intelligent MSW sorter robot by combining it with a YOLO-based model.

Despite of the smart solutions aforementioned, there is a gap in optimizing trash collection efficiency, where the majority of the previous researchers have primarily concentrated on automated trash bins featuring a range of features, including live mapping, flame alerts, and trash level monitoring; without sufficiently exploring the design elements and sensor integration necessary for effective waste segregation. For instance, the study of Zaharin and Fuad (2024) utilized light-dependent resistor (LDR) sensors, which as a 50% accuracy rate in identifying plastic and paper due to sensor constraints, but inductive proximity sensors have an 80% accuracy rate in detecting metals. In contrast, AI-powered systems that use deep learning models like VGG16 and convolutional neural networks (CNNs) offer substantially higher accuracy, with classification rates up to 98.9% for sorting plastic bottles, metals, and paper by assessing visual cues (Gunaseelan et al., 2023). To facilitate more dependable segregation at the source, a CNN-based model reports 97% accuracy in identifying trash into categories such as paper, metal, and plastic (White et al., 2020). That's why the authors came up with the idea of developing an i-smart trash bin solid waste sorter to address the issue of trash collection efficiency, which has not yet been fully explored in this aspect.

OBJECTIVES OF THE STUDY

The objective of this study centered on the development of an automated solid waste sorter, an advanced waste management system designed to automatically classify and segregate recyclable materials, specifically paper, plastic bottles, and metal cans, from mixed wastes. The primary aim is to address the shortcomings of traditional waste disposal methods, encouraging responsible waste management practices among users while promoting environmental sustainability.

Specifically, it aims to attain the following research objectives:

1. To design and construct an i-smart trash bin solid waste sorter prototype that segregates papers, plastic bottles, and metal cans.
2. To evaluate the functionality of the i-smart trash bin solid waste sorter prototype in segregating paper, plastic bottles, and metal cans with not more than 10% error.

MATERIALS AND METHODS

In the development of an i-smart trash bin solid waste sorter for papers, plastic bottles, and metal cans, just as shown in Fig. 1, developmental and applied research is utilized in the design and understanding of how the technology evolves. The term developmental research is a methodical approach to designing, creating, and assessing educational programs, procedures, and outputs that satisfy internal consistency and effective standards (Richey et al. 2004). This design is critical for tracking changes and optimizing the sorter's performance. An iterative testing and refinement of the sorter's design based on field experimentation and observation is implemented in this study. The approach focuses on technical analysis and practical experimentation when it comes to sorting papers, plastic bottles, and metal cans. This ensures a rigorous evaluation of the sorter's performance that excludes subjective user experiences. On the other hand, applied research is conducted to solve a "real-world problem" (Brondolo, 2012), such as finding solutions on how to resolve waste management issues.

The proposed i-smart trash bin solid waste sorter prototype is an octagon-shaped container equipped with several sensors, including proximity and ultrasonic ones. By using this sensor array, the waste collection process will be run more efficiently, and waste segregation accuracy will be increased. The suggested i-smart trash bin solid waste sorter also has an LED to show the full level of the bin and an LCD to show the kind of waste that is thrown in. To ensure operational dependability even in the event of power outages, these smart trash bins also feature a solar-powered backup power source.

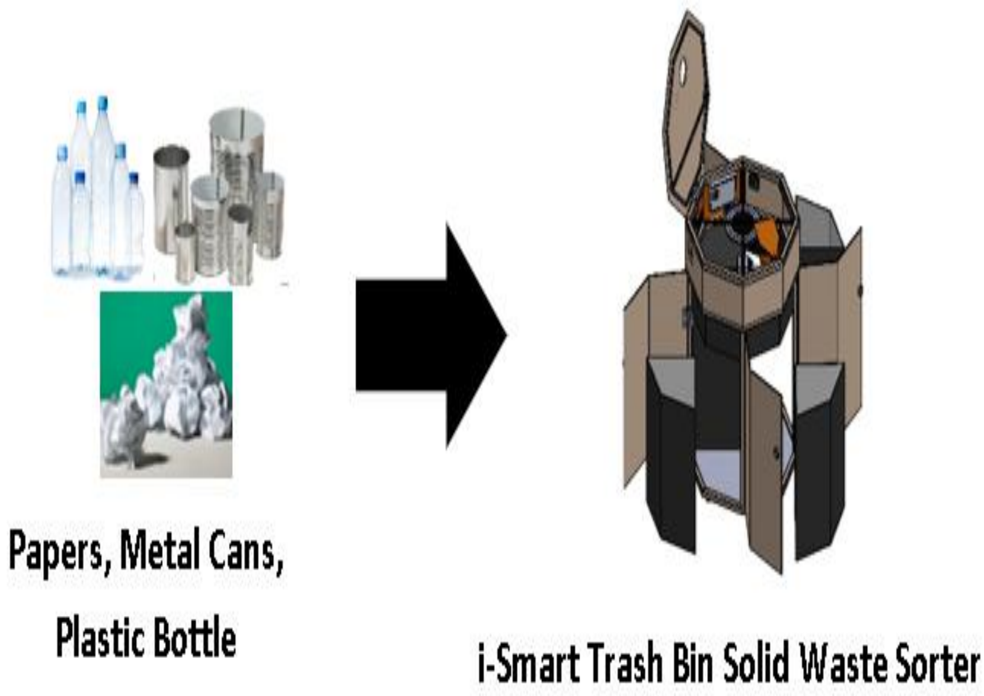


Figure 1. Concept design of the i-smart trash bin solid waste sorter prototype

In line with the objectives mentioned earlier, the procedure for data-gathering is as follows:

1. Several important factors were considered in designing the i-smart trash bin solid waste sorter. It prioritizes the use of local resources for cost-effectiveness and sustainability, ensuring that it can handle waste such as paper, plastic bottles, and metal cans while also reducing the amount of time required for trash segregation. To design the i-smart trash bin solid waste sorter, the first consideration is the determination of the capacity of the trash bins, which is given by ranges from related studies as shown in Table 1, which serves as the reference values.

Table 1. Reference values for the determination of the capacity of the trash bin

Variables	Values
Volume of the bin	2 – 12 gallons
Height of the bin	61 – 71 cm
Side a of the bin	0.3 m
Side b of the bin	0.3 m
Side c of the bin	0.25 m
Load (middle servo motor)	1.680 kg
Distance from pivot to center of mass (middle servo motor)	0.0508 m
Load (top servo motor)	0.09375 kg
Distance from pivot to center of mass (top servo motor)	0.1016 m

To compute the capacity of each trash bin in gallons per bin, which consists of papers, plastic bottles, and metal cans, the volume required is given by the equation (1)

$$\text{Volume} = \text{base area x height} \quad (1)$$

where:

$$\text{Base area} = \sqrt{s(s-a)(s-b)(s-c)} \quad \text{(a, b, c are the sides of the triangle)} \quad (2)$$

Aside from the capacity of the trash bin, the torque in N-m is required for the servo motor to rotate and as well to open the bottom of the bin, allowing the item to drop into the appropriate compartment. This is given in equation (3) as:

$$\text{Torque of the servo motor} = \text{force x perpendicular distance} \quad (3)$$

where:

$$\text{Force} = \text{mass x gravity} \quad (4)$$

Table 2. Parameters of interest and corresponding units

Parameters of interest	Units
Base area	square meter (m^2)
Distance, sides of the triangle	meters (m)
Force	Newton (N)
Gravity	meter per square second (m/s^2)
Mass	kilograms (kg_m)
Torque	Newton-meter (N-m)
Volume	cubic meter (m^3), gallons (gal)

Table 2 shows the essential factors considered in the design of a smart bin, which are reflected from equations 1 - 4. The bin's footprint is determined by its base area, measured in square meters (m^2). The distance between the sides of the triangle, measured in meters (m), is important for the trash bin's structural geometry and stability. Force is measured in Newtons (N), while gravity, with a constant value of 9.81, measured in meters per square second (m/s^2), indicates its impact on bin operation and load calculations. Mass, measured in kilograms (kg_m), is critical in determining the trash bin's capacity and structural needs. The torque, measured in Newton-meter (N-m), refers to any rotating forces acting on the bin, such as those from automated lids or compaction systems.

2. Assessing the automated solid waste sorter's ability to sort paper, plastic bottles, and metal cans with a 10% error, the following steps include first, setting up the automated solid waste sorter and gathering enough items for testing (papers, plastic bottles, metal cans). Then, at random, place the items (papers, plastic bottles, and metal cans) into the bins and record their location. Next, check the bins regularly, noting how well the prototype sorts the items. After each check, determine the percentage of correctly sorted items for each waste type. Compare this to the 90% target accuracy. If errors occur, record them and assess their frequency and severity. Finally, compile all findings into a report, including any suggestions for improvement.

RESULTS AND DISCUSSION

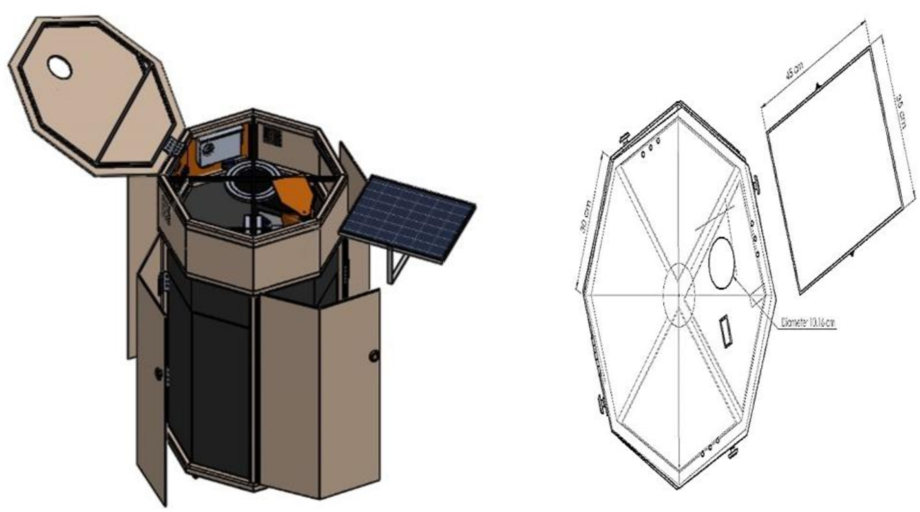
1. Design of an i-smart trash bin solid waste sorter prototype

As shown in Figure 2, with the specified dimensions, the automated solid waste sorter is made up of several key components, including a trash bin unit with four separate compartments for papers, plastic bottles, metal cans, and a storage area for cleaning supplies. An inlet diameter hole of 4 inches on the octagonal structure of the trash bin and 11 gallons per bin as the computed capacity from equation 1 is designed to ensure accuracy and adherence to the intended specifications for shooting the trash into a solid waste sorter system.

As shown in Figure 3a, the hardware components highlight their interconnectivity and interdependence, which serve as the control system. The prototype's major components are the power supply, inductive proximity sensor, ultrasonic sensor, servo motors, LEDS, LCD, battery, solar panel, solar controller, and buck converter, which will serve as the connectivity to the database, and these components and integrated with the Arduino ATMEGA 2560. On the other hand, the component layout found in Figure 3b depicts the overall electronic circuit, which consists of the power supply, which derives the required input voltage from the inductive proximity sensor. The buck converter derives the required input voltage from the Arduino, servo, ultrasonic, LCD, and LED. The LED is used to specify the level of trash present in the bin. The LCD will display the type of object inserted. The inductive proximity sensor is used to detect metal cans. The ultrasonic sensor is used to detect plastic bottles. The servo motor is used to rotate components to designated positions. The Arduino is used as a programmable device for the automated trash bin.

Complementing the sensors are servo motors that control the lids of the waste bins. These servos respond dynamically to the detected objects, opening and closing the bins as needed. This interaction ensures efficient waste disposal, with the system adapting in real time to the type of waste being disposed of. Furthermore, the system includes an LCD that gives immediate feedback on the type of object detected by the sensors. This visual feedback improves user interaction by allowing for easy identification and confirmation of waste type. Additionally, LED indicators are used to display the fill level of each waste bin. Green, orange, and red LEDs indicate that the bin is empty, partially filled, or full, respectively. This feature promotes proactive waste management by informing users about the status of each bin and encouraging timely disposal.

(a) (b)



(c)

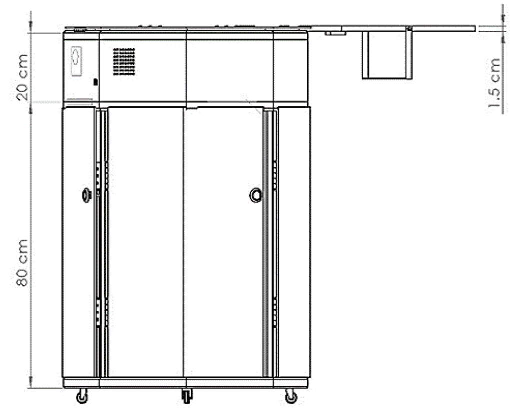


Figure 2. Design layout of i-smart trash bin solid waste sorter prototype (a) isometric or three-dimensional view of the prototype, (b) top view of the prototype, (c) front view of the prototype

(a) (b)

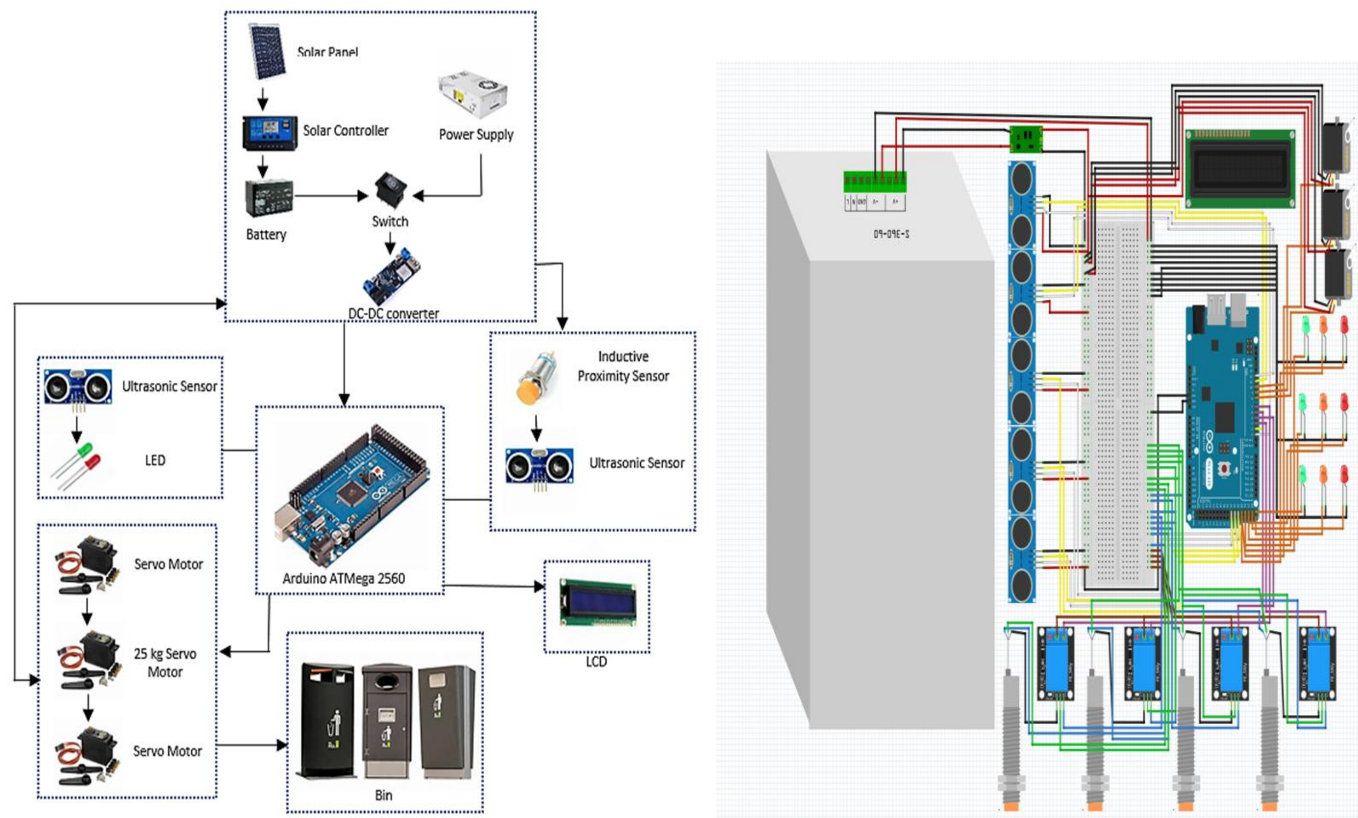


Figure 3. Electronic component integration in the i-smart trash bin solid waste sorter prototype (a) electronic hardware components, (b) overall electronic circuit layout

2. **Classification functionality of the i-smart trash bin solid waste sorter prototype**

In this study, 60 random waste samples were used, including 20 papers as shown in Table 3, 20 plastic bottles as shown in Table 4, and 20 metal cans as shown in Table 5. These samples were tested using a trial-and-error method with the i-smart trash bin solid waste sorter prototype, which was specifically designed to separate paper, plastic bottles, and metal cans. The performance and functionality of the prototype are evaluated by manually recording the samples tested by the solid waste sorter. The results of these tests are presented in the tables below, which provide valuable insights into the prototype's waste segregation efficiency.

Table 3. Confusion matrix for predicting paper waste

Paper waste samples	Positive (✓)	Negative (x)
Graphing Paper	✓	
Colored Paper	✓	
Paper Bag	✓	
News Paper	✓	
Bond Paper	✓	
Paper Plate	✓	
Tissue Paper (rough)	✓	
Glossy Paper	✓	
Brown Envelope	✓	
Cardboard Paper	✓	
Manila Paper	✓	
Cartolina Paper	✓	
Photo Paper	✓	
Vellum Paper	✓	
Carbon Paper	✓	
Illustration Board	✓	
Sticker Paper	✓	
Gift Wrapper	✓	
Writing Paper	✓	
Creep Paper	✓	
Total	20	0

Table 4. Confusion matrix for predicting plastic bottle waste

Plastic bottle waste samples	Positive (✓)	Negative (x)
Coke 1.5L	✓	
Coke 290ml	✓	
Sprite 290ml	✓	
Summit 500ml	✓	
Nature Spring 500ml	✓	
Nature Spring 1L	✓	
Wilkins 500ml	✓	
C2 1L	✓	
Pepsi 290ml	✓	
Sting 290ml	✓	
Sting 290ml	✓	
C2 500 ml	✓	
Blue 500ml	✓	
Lemon 237ml	✓	
Coke 190ml		x
Kopiko 180ml	✓	

Tropicana 355 ml	✓	
Calamansi 250 ml	✓	
Wet 330ml	✓	
Royal 250 ml	✓	
Total	19	1

Table 5. Confusion matrix for predicting metal can waste

Metal can waste samples	Positive (✓)	Negative (x)
Fresca Tuna 175g	✓	
Aerosol Insecticide 750ml	✓	
Carburator Cleaner 450ml	✓	
Cleanse Can 450ml	✓	
Refrigeration Lubricant 1L	✓	
Cali 330ml	✓	
Redhorse can 330ml	✓	
Alaska Evaporada 360ml	✓	
Lemon-Dou 330ml	✓	
Tire Sealer 450ml	✓	
Rexco Lubricant 120 ml	✓	
Aircon Cleaner 500ml	✓	
CDO 100g		x
Sizzling Sisig 150g	✓	
Nutrimeats 150g	✓	
King Cup Sardines 155g	✓	
Wow Ulam 150g	✓	
Mega Sardines 155g	✓	
Del Monte Pineapple 220 ml	✓	
Boysen paint 200 ml	✓	
Total	19	1

Table 6. Summary of waste classification effectiveness

Classification of waste	Positive	Negative	Accuracy (%)
Papers	20	0	100%
Plastic bottles	19	1	97%
Metal cans	19	1	97%
Overall	58	2	94%

Summary of results showed from Table 6 that 58 out of the 60 random waste items fed into the machine were correctly (positive) sorted, while two were incorrectly (negative) sorted from three different classifications of wastes, namely paper, plastic bottles, and metal cans. A total of 20 papers, 20 plastic bottles, and 20 metal cans were inserted into the prototype. Out of these, 20 papers, 19 plastic bottles, and 19 metal cans were accurately sorted, while 1 plastic bottle and 1 metal can were sorted incorrectly based on the findings in Tables 3,4,5, respectively. This demonstrates that the accuracy of the prototype for sorting papers is 100%, plastic bottles is 97%, and metal cans is 97%. Notably, the overall accuracy rate of 94% in waste segregation indicates that the prototype successfully met the predetermined goal of achieving segregation with a minimal error of 6%, which satisfies the set error of 10%.

The factors that caused errors in the sorting of metal cans and plastic bottles in Arduino-based smart bins are associated with hardware and sensor restrictions. Misclassification may result from the infrared or metal-detecting sensors' inability to reliably distinguish between similar materials or identify objects with mixed components. While servo motors might not have the fine control necessary for reliable mechanical sorting, the Arduino microcontroller's limited processing capability may hinder the real-time, complicated analysis needed for accurate sorting. Furthermore, environmental elements that affect detection accuracy include contamination on waste objects, sensor positioning, and lighting conditions (Rojat, 2023; Mohankumar et al., 2024; Kavithamani et al., 2023).

CONCLUSION AND RECOMMENDATION

In conclusion, the study has developed a functional i-smart trash bin solid waste sorter prototype that can separate papers, metal cans, and plastic bottles with the integration of a control system such as inductive proximity sensors, ultrasonic sensors, servo motors, LEDs, LCDs, and a buck converter, as well as the Arduino ATMEGA 2560 microcontroller. The prototype's design emphasizes the interconnectedness and interdependence of these components, demonstrating a promising foundation for effective waste management systems. Notably, the i-smart trash bin sorter demonstrated high precision in sorting papers (100%), plastic bottles (97%), and metal cans (97%) with an overall accuracy of 94%, with a 6% error, which is less than the 10% set error value. These findings demonstrate the bin's potential as a reliable waste management solution. By successfully achieving our goal, we demonstrate the feasibility of incorporating the i-smart trash bin sorter into waste segregation systems, thereby supporting waste management techniques that are more sustainable and efficient. Moving forward, additional enhancements can be considered to improve its functionality and usability. Through continued innovation and refinement, the prototype has the potential to make significant contributions to environmental preservation and waste reduction.

Future work includes enhancing smart bins in several important areas, such as classification accuracy and accommodating a greater range of materials by incorporating machine learning-based waste detection. Another is utilizing materials that are waterproof and corrosion-resistant, which will increase durability and guarantee long-lasting performance in a variety of environmental circumstances. A mobile app or dashboard that offers real-time updates, waste analytics, and user interaction elements will be developed as part of the user interface changes. Additionally, this concept might be scaled up for adoption at the barangay or metropolitan levels, promoting more sustainable and effective trash management throughout the community.

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