DESIGN AND FABRICATION OF A WASTE SEGREGATION SYSTEM

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CERTIFICATION

We undersigned that this work was carried out by the above named students of the Department of Mechanical Engineering, and Mechatronics Engineering, Faculty of Engineering, University of Benin, Benin City under the supervision of **Engr. Martin Oshikhueme,** in partial fulfillment of the requirement for the award of Bachelor of Engineering.

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DEDICATION

We dedicate this project to God Almighty, whose grace has granted us the strength to accomplish all that was necessary for the success of this project. To our families, whose unwavering support and encouragement have been the foundation of our academic journey. To the Department of Mechanical Engineering, whose guidance and commitment to equipping us through extensive training and lectures have been pivotal in shaping us into who we are today. This work is also dedicated to all who have inspired and supported us along the way. Your faith in our potential has ignited our passion for learning and striving for excellence.

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CHAPTER ONE

INTRODUCTION

1.1 Background study

With an increase in the world's population, and a rapid quest for urban living, management of solid waste has proven to be a serious challenge of modern times. Activities like change in consumption patterns, rapid industrialization and many more contributes to an increase in the complexity of waste generated. This is more experienced in domestic settings, such as schools, homes, offices, where different types of waste, ranging from leftover food to plastic and paper are found in large amounts; Hence the need for proper waste handling and management.

Often times, a large amount of wastes gotten from these environments are collected without proper segregation, especially at the source. These wastes usually contain combinations of organic, recyclable and sometimes harmful substances. In many developing countries, i.e. Nigeria, Ghana etc. the wastes are transported to dumpsites where the sorting is later carried out. This method of manual sorting is very ineffective, and could also lead to many health risks for workers sorting the wastes, due to unhygienic practices and poor working conditions. This limits recycling and proper waste management, which could be important for the country.

A Long-lasting solution to these problems lies in proper waste segregation, especially at the source. This way, the waste is less hazardous since it is not fully decomposed, and its easier to segregate in small quantities as opposed to large quantities. Doing this early, waste is properly and efficiently more processed downstream, leading to proper waste handling. This reduces the amount of wastes sent to landfills, even reducing the need for them. It also cut downs emissions from decomposition, increasing hygienic conditions.

In a modern times, due to technological advancement, waste segregation is no longer dependent on manual labor alone. Technological advancements in areas like electronics, embedded systems, sensors, and automation have opened up new possibilities for creating systems that can detect and separate different types of waste with minimal human efforts. Sensors capable of detecting characteristics such as material type, weight, shape, and moisture levels can now be integrated with microcontrollers or embedded processors to create intelligent waste sorting systems. These systems can be designed to automatically sort waste into appropriate bins using mechanical arms, actuators, and conveyor belts, based on the real-time analysis of the waste's properties.

This project centers on the design and the building of an automated waste segregation system, which uses the methods mentioned above to segregate waste. It is specifically made for domestic environments like school, houses etc. where moderate amount of waste are generated on a daily basis. The system is designed to identify and classify basic kinds of wastes: paper, plastic, glass etc. and sort them into separate bins, which then can be easily handled, or processed. However, this study also aims to research and document the decision-making processes involved in the selection of materials, sensors, control logic and the design of mechanical components.

By combining theoretical understanding with practical technologies, this project contributes to the growing field of proper waste management technologies and also demonstrates how segregation of waste at source can have a positive long lasting effect on the environment.

1.2 Statement of the problem

Nigeria is currently facing a serious waste management challenge that keeps getting worse with time. As cities grow and more people move into urban areas, the amount of waste being generated is increasing at an alarming rate. Unfortunately, the processes and systems that have been developed to put this increasing waste in checks isn’t efficient enough, thereby leading to poor waste management, especially in the rural areas. The United Nations Environment Programme **(UNEP)** says in a report from **2018** that Nigeria makes more than 32 million tons of solid waste every year, but less than **20%** of it is collected or managed correctly. This statistics shows how badly waste is managed in Nigeria. The other **80%** of waste unaccounted for is badly disposed, and is often dumped in open spaces, drainages, roadsides, or burnt, causing serious environmental, health, safety issues or even flooding.

A major contributor to this problem is the lack of waste segregation at the point of disposal. In most households and public areas, waste is dumped without separating organic materials, plastics, metals, glass, and hazardous substances. This practice makes the recycling process more complicated, expensive, and often ineffective. The **World Bank (2020)** notes that mixed or unsorted waste greatly reduces recycling efficiency and contaminates otherwise recyclable materials. As a result, a large proportion of waste that could have been reused ends up in landfills, contributing to environmental degradation.

The health risks linked to poor waste segregation are significant. In many Nigerian cities, informal waste workers manually sort through open dumpsites in search of materials they can sell or recycle. These workers, who often lack basic protective equipment, are exposed to toxic chemicals, infectious waste, and physical hazards. According to the International Labour Organization **(ILO, 2017)**, informal waste pickers in developing countries face some of the most dangerous working conditions globally, with frequent exposure to hazardous substances that threaten their long-term health and safety. The poor quality of unsorted waste also affects recycling businesses, which spend excessive time and resources trying to separate usable materials from contaminated ones. This inefficiency reduces profit margins and discourages private sector investment in the recycling industry. The **African Development Bank (2019)** has pointed out that the success of recycling enterprises in Africa largely depends on the availability of clean, pre-sorted waste. Without this, businesses are forced to discard large volumes of potentially recyclable materials, which further burdens the environment.

Although environmental laws and sanitation policies exist in Nigeria, they are often not implemented effectively at the community level. Many local governments lack the infrastructure and capacity to enforce regulations or provide support for waste segregation. Households are not provided with proper bins for different waste categories, and public collection systems rarely account for waste separation. The National Environmental Standards and Regulations Enforcement Agency **(NESREA, 2021)** identifies policy enforcement and operational capacity as two of the biggest challenges facing waste management in Nigeria today. Public awareness also remains low. Many Nigerians are not informed about the importance of waste segregation or its impact on health and the environment. Waste is commonly viewed as something to be discarded quickly and forgotten, rather than as a resource that can be managed responsibly. The United Nations Human Settlements Programme (**UN-Habitat, 2019**) emphasizes that successful waste segregation initiatives rely heavily on community participation, education, and long-term behavior change.

On the global stage, countries with similar socioeconomic and environmental conditions have started adopting smart technologies to address waste segregation. For instance, nations like India, Brazil, and Indonesia have implemented automated systems using sensors, image recognition, and AI-based tools to sort waste at the point of disposal or during collection. These technologies have proven to reduce contamination, improve recycling rates, and increase workers safety, **(**United Nations Economic and Social Commission for Asia and the Pacific **[UNESCAP], 2020**). In contrast, Nigeria continues to rely on manual, outdated methods due to limited investment in innovation, technical expertise, and infrastructure.

Introducing an automated waste segregation system in Nigeria could address many of these issues. By using smart components like motion sensors, image-based sorting, or mechanical separators, the system could detect and classify different types of waste before they are collected. This would not only increase the amount of waste that can be recycled but also reduce human exposure to hazardous materials. The United Nations Industrial Development Organization **(UNIDO, 2022)** has reported that automated waste sorting technologies can increase recycling efficiency by over **50%** in low- and middle-income countries. Such a system would also help reduce the burden on local governments, improve the working conditions of waste handlers, and contribute to a cleaner urban environment. Additionally, it could open up new opportunities in green job sectors such as recycling, environmental monitoring, equipment maintenance, and public education. The World Health Organization **(WHO, 2020**) notes that clean environments directly contribute to lower disease rates and improved overall well-being in urban communities. Nigeria's ongoing waste problem is made worse by the lack of waste segregation at the source. The current system marked by poor public awareness, weak enforcement, and outdated technology is not sustainable. An automated waste segregation system, supported by public education and policy reform, offers a practical and effective solution. If properly implemented, it can improve recycling outcomes, protect public health, and help Nigeria move toward a cleaner and more sustainable future.

1.3 Aims and Objectives

AIM

This project aims to design and build an automated system that can segregate waste more effectively and with little to no human effort. The goal is to make waste management easier and more organized, especially at the point where waste is first disposed. By separating materials like plastic, paper, metal, and organic waste automatically and at source, the project hopes to reduce the health risks faced by waste handlers and support better recycling practices that benefit both people and the environment.

OBJECTIVES

This project sets out to achieve a few key goals that come together to form a practical and working solution to the problem of poor waste segregating. These include:

1. Designing a system that can recognize and segregate different types of waste like plastic, paper, metal by combining simple mechanical parts with sensors that can detect what kind of material is being disposed of.
1. Creating an interface that's easy to use and responds in real time, so the system doesn't just work behind the scenes but gives clear, immediate feedback while operating.
2. Developing the internal logic needed for the system to work on its own, which involves writing and uploading code to a microcontroller (such as an ESP32 board) that tells the machine what to do when it sees different waste materials.
3. Physically building the machine and testing it with real waste samples, so the final product is not just theoretical, but something that can be demonstrated to work under everyday conditions.

1.4 Scope of Study

The scope of this project covers different areas, and cuts across many intertwined fields such as; electronics, mechanical design, embedded programming, and environmental safety. Creating a functional and reliable sorting system requires a strong understanding of the different types of waste materials commonly generated in households and small institutions, as well as the challenges that come with handling and disposing of waste.

The fabrication of the system involves different stages , ranging from conceptual design, to the integration of sensors capable of detecting different materials. It also includes the design and mechanical setup of the sorting mechanism, that direct each waste type to its bin.

The programming stage makes use of an ESP32 board, which is a micro-controller whose function would be interpretation of signals from the sensors, and activating the correct sorting mechanism. This requires a knowledge in embedded programming, with use of programming languages such as C or C++ , and how to manage input and output operations. In relation to software, the system would also feature a simple user interface to allow for basic monitoring processes such as; notifying workers when a said bin is full , during its operation.

These areas, ranging from sensor logic to mechanical assembly and micro-controller integration are of great importance to the design and implementation of the automated waste segregation system. While the project will not extend to industrial-scale deployment, waste transportation logistics, or policy enforcement, it provides a practical and scalable approach to tackling waste mismanagement at the source.

1.5 Relevance of the Study

The relevance of this project lies in its potential to significantly improve how waste is managed in school environments where large volumes of mixed waste are generated daily.

Schools often face challenges in handling and sorting waste properly, which can lead to unhygienic surroundings, health risks, and environmental degradation. The introduction of the automated segregation system to those institution can push students and staff alike to adopt good waste disposal practices.

Furthermore, the prototype encourages innovation and investment in low-cost, locally engineered technologies. Rather than relying on expensive imported systems, this project showcases how available materials and basic electronics can be used to build functional machines that solve real problems. It highlights the possibilities of applying knowledge particularly in electronics, programming, and mechanical design to benefit the immediate environment.

In terms of public health and sanitation, the automated segregating process reduces direct human contact with waste, minimizing the risk of disease transmission. This is especially important in schools where young people may be more vulnerable to unhygienic conditions. The contactless design of the system also helps promote a cleaner, more organized disposal routine.

Overall, this project supports environmental awareness, local innovation, and healthier school environments, making it relevant and timely contribution to both technological learning and sustainable practices.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction to Waste Segregation Technologies

Waste segregation is an important process in modern waste management system. It is the separation of different types of wastes; organic, plastic, metal, glass, which could either be at source, or during processing. Segregation of waste can be carried out based on different categories such as; dry or wet waste, organic or inorganic waste etc.

Waste segregation technologies involve methods or techniques for separating different categories or types of waste materials to facilitate and improve recycling, resource recovery, and proper disposal. These technologies range from manual sorting processes to advanced automated systems mainly known as smart bins, which uses sensors and learning models. Effective waste segregation practices enhance recycling potential and ease, while reducing the risks of environmental pollution. With the right and effective processes, resource recovery and usage are greatly improved and promoted, hence rendering reuse of recyclable materials almost effortless.

In order to segregate waste effectively, it is important that the type of waste is to be correctly identified at source. For the purposes of segregation at source, waste is identified and then classified into different categories depending on their chemical, physical and biological properties. The classification is as follows;

- **Dry Waste:** This refers to all waste that are not wet or soiled. They also include recyclable and non-recyclable materials. Dry waste includes materials such as can, bottle, wood, glass etc.

- **Wet Waste:** These are wastes that are mostly organic, and may include soiled food wrappers, hygiene products, tissues etc.

- **Sanitary Waste:** These are all liquid or solid wastes solely emancipating from human activities.
- **Inert Waste:** These wastes are not chemically and biologically reactive, and does not decompose easily.

- **Hazardous Waste:** These refers to all wastes that are or contain corrosive, toxic or reactive ingredients.

By properly identifying waste type, waste could be effectively segregated at source, making it easy to be recycled for re-use, or properly disposed, thereby reducing environmental pollution.

2.1.1 Types of Waste Segregation Technologies

In a bid to manage waste effectively, various methods have been developed to make sorting less time consuming and more efficient. These methods help separate different types of waste based on different factors. These factors could include; size, weight, material type, chemical composition. Ranging from simple manual sorting, to advanced automated systems that makes use of AI, each method plays a vital role in improving recycling, and reducing pollution.

The first type of segregation method is called Manual sorting. It is the simplest, and traditional form of segregation. It is the physical separation of wastes, usually by hand. In this method, individuals usually sorts wastes into categories like plastics, wood, glass, and organic waste etc. based on visual inspection. An advantage of manual sorting is that it allows for careful identification of some waste that might confuse or be looked over by automated systems. The perks of manual sorting is that it is labor intensive, and might be inconsistent due to human error or negligence. The most important disadvantage of manual sorting is that it is time consuming and less effective, but despite its limitations, it is crucial in aspects where precision and human judgement are needed to compliment machine-based processes.

Another type of waste segregation technology is mechanical sorting. It involves the use of machines to separate waste materials based on their physical properties such as size, shape, weight, and magnetic characteristics. This method is used mainly in large scale waste management and recycling facilities because it can process high volumes of waste more quickly and effectively than manual methods. A typical equipment used in mechanical sorting includes conveyor belts to move materials, trommels to separate waste by size, shredders to break down large items, and air classifiers that uses blasts of air to sort lighter materials like plastics from heavier ones. it is often used to optimized performance when combined with other forms of sorting such as manual and optical sorting.

Optical sorting is also a method used in waste segregation. It is a high tech method and makes use of sensors, and imaging systems to identify waste. It is particularly useful when sorting materials which have different optical properties under light. Such materials include; paper, wood, plastic. Etc. This type of sorting uses sensors to detect specific wavelength of light, and its interaction with a material. This allows the system to properly identify different materials, after which an automated mechanism directs it into the correct bin.

Magnetic Density Separation is an advanced type of sorting technology that combines both magnetism and fluid dynamics to separate materials based on density and magnetic properties. In this method, waste materials are passed through a special liquid that behaves like a dense fluid under the influence of a magnetic field. Due to the flexibility of the magnetic field, the liquid's effective density can be manipulated. As a result, different materials float or sink at different levels based on how dense they are. This sorting method is effective for sorting types of plastic or recovering non-ferrous metals from electronics or automative wastes.

The downside to this method is that it is expensive and technically demanding.

The last waste segregation technology to be discussed is the **Automated Waste Segregation Systems**. These systems makes of robotics, AI, and machine learning to learn, recognize and sort different types of waste materials. They make use of imaging cameras, sensors, and AI models that are used to identify materials based on color, shape, texture etc. Once a material is detected, the robotic arms or jets of air are triggered to sort them out into the correct category. Over time, the system learns from the previous data, adapting to the variables, and becoming more efficient and precise.

Automated waste types are widely used in facilities handling large volumes of waste, where speed, precision, and consistency are crucial. They also help reduce labor costs and risks of injuries associated with manual sorting.

2.1.2 Benefits of Waste Segregation Technologies

Waste segregation is an important aspect of effective waste management. By separating waste at source, materials can be directed into appropriate channels for recycling, composting, treatment, or safe disposal. This improves the efficiency of waste handling systems and also contributes to broader environmental, economic, and social goals.

Below are key benefits of implementing proper waste segregation technologies:

1. **Improved Recycling Efficiency**: Wastes which are properly sorted are less prone to be contaminated. This increases the suitability of recyclables such as plastic. It also reduces the time and cost needed to clean those plastics. As a result, recycling plants can operate more efficiently, with fewer rejected loads, ultimately leading to higher recycling rates.

2. **Reduced Landfill Burden**: Segregated wastes at source greatly lowers the need for landfills. This is possible because recyclable wastes are easily directed to where they are being used. In the long term, it helps cities and countries avoid the environmental and health hazards often associated with overflowing or poorly managed landfills.

3. **Enhanced Resource Recovery:** When waste is well-sorted, valuable materials can be recovered and reused more effectively. Items like aluminum, steel, and certain plastics can be melted down or reprocessed into new products. This reduces the demand for new raw materials.

4. **Cost Savings in Waste Management**: A proper waste segregation reduces cost of waste processing. For example, separating organic waste at the source makes it easier to compost, while sorting recyclables decreases the need for labor-intensive sorting later. This leads to cost savings on transportation, landfill fees, and processing expenses.

5. **Lower Environmental Impact**: Waste segregation plays a vital role in minimizing environmental harm. By keeping recyclables and organics out of landfills, it reduces methane emissions which is a potent greenhouse gas produced by decomposing waste. It also prevents toxic substances from entering the soil and water, helping to protect ecosystems.

6. **Higher Quality Recyclables:** When materials are contaminated or mixed, it lowers the quality of recyclables , often making then less valuable or even completely useless. Source segregation ensures that recyclables remain clean and sorted by type, which increases their market value and makes recycling processes more effective.

7. **Safer Waste Handling:** Separating hazardous waste such as batteries, chemicals, and medical materials from general waste reduces the risk of accidents, fires, and exposure to dangerous substances. It ensures the safety of sanitation workers, waste pickers, and the public, especially in regions where informal waste collection is common. Clear labeling and designated bins for specific waste types further enhance safety during collection and disposal.

8. **Support for Composting and Organic Waste Use:** When biodegradable waste is separated from other materials, it can be directed toward composting. This produces compost that can be used for farmers, and bio-gas that can be used for energy production.

9. **Encouragement of Responsible Consumer Behavior:** Implementing waste segregation systems in communities, schools, and workplaces encourages individuals to have a habit of waste handling. It raises awareness of environmental issues and promotes sustainable habits such as recycling, reusing, and reducing waste at the source.

2.2 Smart Waste Bins

A smart waste bin combines traditional waste collection with modern technology to make waste handling more efficient. They are usually equipped with sensors and supported with IOT (internet of things), which lets them identify a material and effectively sort waste.

According to **Singh et al. (2018)** from the international Journal of Scientific and Engineering research, a smart waste bin is defined as, “a waste container integrated with sensors and communication technology that allows it to detect waste levels and communicate with waste management authorities for timely disposal”

Similarly, the **University of Cambridge’s Institute for Manufacturing (IFM)** describes smarts bins as “sensor-equipped containers that support automated waste monitoring and data collection, enabling predictive analytics and smart city infrastructure”

A smart waste bin is usually equipped with different functionalities and capabilities to ensure automation of recycling processes. Some may have Ultrasonic or Infrared sensors that detects how full the bin is, and this information can be sent to a User via GSM, Wi-fi, or some networks. They also have a user interaction interface, where by Users could modify some settings, or for notifications. These may include display screens or indicator lights to guide users to dispose waste correctly, promoting source segregation.

In a study by **Rathore et al. (2016),** smart bins are mentioned to be an important component of a smart city. Integrating IOT into smart bins, the system can log data over time and help collection team efficiently collect waste.

2.2.1 Evolution of the Smart Waste Bin

The development of smart bins arose for the demand for cleaner cities with effective waste management. This ranges from sensors that could only detect fill level in the early 2010s to AI-powered sorting now in the 2020s.

The sensor revolution started the earliest smart waste bins which began appearing around 2010-2012, during smart city initiatives in Europe and North America. They were equipped with sensors that can detect fill levels, and could also send alerts via GSM or Wi-Fi to collection operators. This helped reduce the number of unnecessary trips by collection trucks and minimized the chances of overflowing bins, thereby reducing costs. According to **Rathore et al. (2016),** this stage marked the integration of **IOT** into urban waste systems, especially in cities looking to improve waste management through automation.

Through **2013 – 2016**, collection of data became widely integrated with smart bins. Starting with cities like Amsterdam, Helsinki, and New York. **Enevo,** for instance, reported in **2015** that their system helped reduce collection costs by up to **50%**, while improving route efficiency and cutting down on fuel use and emissions. These years also saw the use of solar-powered compacting bins, like Bigbelly Solar, which compacted waste internally and reported capacity levels to waste authorities.

In 2017, Smart Waste and Traceability Research, the Massachusetts Institute of Technology (MIT)'s Senseable City Lab launched the Trash Track project. Although it was not technically a smart bin product itself, it attached GPS trackers to pieces of waste to follow their journey through city infrastructure.

IN 2018, AI-Powered Sorting Began, thereby taking smart waste bins a major leap forward with the introduction of artificial intelligence and computer vision. Companies like Bin-e (Poland) developed bins capable of identifying different types of waste such as plastic, metal, and paper, and automatically sorting them into the appropriate compartments or bins. The systems used built-in cameras and AI algorithms trained to recognize objects and materials**.**

Presently, there has been a growing movement to adapt smart bin technologies for use in developing countries. In Nigeria, students and researchers at institutions like the University of Lagos and Covenant University have developed low-cost smart bin prototypes using Arduino micro-controllers, GSM modules, and ultrasonic sensors. For example, in **2021**, a student team at the University of Lagos created a solar-powered smart bin that sends SMS alerts to waste authorities when full.

Looking into the future, smart bins are becoming key parts of smart city infrastructure, offering benefits that go beyond waste collection.

2.2.2 Core Technologies Used in a Smart Waste Bin

Micro-controllers and Embedded Systems: Micro-controllers are commonly used in smart waste systems. An example is Arduino, which is ideal for simple tasks like opening a bin lid, while raspberry pi is more powerful and can run full programs. These devices help make smart bins responsive and autonomous.

Sensors for Waste Identification: Sensors play a vital role in detecting and classifying waste. For example, Infrared (IR) and Ultrasonic Sensors are often used to detect objects or measure how full a bin is. Load Cells can determine the weight of the waste, which may help in classifying it. Moisture Sensors are useful for separating wet waste from dry (recyclable) waste **(IARJSET, 2025).** Gas Sensors help detect harmful emissions from decomposing materials, especially useful in compost or hazardous waste bins.

Artificial Intelligence and Vision Systems: Some systems uses camera and AI-based models such as CNNs to identify waste visually. These models are trained on thousands of images so they can recognize objects like plastic bottles, paper, or food waste. For example; **White et al. (2020)** developed **WasteNet,** a **CNN** model that reached 97% accuracy on six types of waste.

Mobility and Robotics: In some designs, mobility is added to allow the bin to move around or follow users. This is made possible using Motorized wheels controlled by DC motors. It also uses sensors for obstacle avoidance, GPS and optical tracking systems for movement control.

User Interfaces: User interfaces make it easier to operate and monitor smart bins. These interfaces could be as simple as LED lights that change color when the bin is full, or as advanced as a touchscreen that lets the user view bin status or activate different features.

2.2.3 Components of a Smart Waste Bin

A smart waste bin combines traditional waste storage with embedded hardware and software. It enables sensing, and automated sorting for proper waste handling. These components work together to collect data, and transmit information to central waste management systems.

Below are the key components typically found in a smart waste bin:

1. **Micro-controller Unit (MCU) / Processor:** The micro-controller is the brain of the system. It processes data received from sensors and controls other components such as GSM modules, indicator LEDs, and compactors. Common micro-controllers include Arduino UNO, ESP32, or Raspberry Pi for more advanced applications.

2. **Ultrasonic Sensor:** This sensor is used to detect the fill level of the bin by measuring the distance between the sensor and the waste surface. It is often mounted at the top of the bin lid and faces downward.

3. **Weight Sensor (Load Cell):** A weight sensor is used to estimate the mass of waste deposited. This can be useful for tracking waste volume and user activity.

4. **Camera Module:** The camera modules is incorporated with AI or computer vision software to identify waste types. i.e. distinguishing between plastic, paper, and metal. The Raspberry Pi Camera Module or ESP32-CAM are the most common options.

5. **GSM/Wi-Fi Module:** These makes use of communication modules like SIM800L (GSM) or ESP8266/ESP32 (Wi-Fi/Bluetooth) which are used to transmit data from the smart bin to a remote dashboard or cloud service.

6. **Power Supply:** These provides continuous power to sensors and control units. This can be in form of solar power, batteries etc.

7. **Indicator Lights / Display Unit LED:** These are lights or small displays that give real-time feedback to users. A good example, green for “space available,” red for “bin full,” or screen instructions like “Insert Plastic Waste Here.”

8. **Waste Container / Casing:** This is the outer structure that houses all electronic components and holds the waste. It is typically made from durable plastic or stainless steel to withstand the environment and user handling.

9. **Compacting Mechanism**: Some advanced smart bins include a compactor that reduces the volume of waste using a motor-driven press. This is commonly found in airport bins or solar-powered street bins like Bigbelly Solar.

2.3 Review of Related Works

This section reviews cutting-edge smart waste management systems that showcase the current state of the art in technology, deployment scale, and functionality.

1. **Bin-e**: This is an AI powered waste bin for indoor environment. Bin-e is one of the most advanced smart waste bin systems designed for indoor use. It was developed in Europe around 2018, and was created to address the ongoing problem of improper waste sorting in public spaces like offices, schools, shopping malls, and hospitals. The idea behind Bin-e is to make recycling easier, smarter, and more accurate by combining modern technology with a user-friendly experience.

Bin-e uses **Artificial Intelligence**, especially image recognition, which makes it able to identify the type of waste. For example, when someone drops an Item like a plastic bottle, Bin-e uses a built-in camera and sensors to scan the item and classify it into categories such as plastic, paper, metal, or general waste. Once the item is identified, it is moved into the correct compartment using a mechanical system. Each compartment inside the bin is also equipped with a compactor, which reduces the volume of the waste to make space for more items. This means the bin doesn't need to be emptied as often, saving time and cost for maintenance teams.

Bin-e is also connected to the internet, so it can send data to a cloud-based dashboard. Facility managers or cleaning staff can check how full the bin is, how much of each type of waste is being collected, and even get alerts when it’s time to empty it. Reports from early deployments in Europe show that Bin-e can achieve over 90% sorting accuracy, which is a big improvement over traditional bins that rely on users to separate waste properly. However, like many high-tech solutions, Bin-e has its limitations. It is designed mainly for indoor environments, and the cost of purchasing and maintaining the system is relatively high. It also works best when trained on specific waste types, which means it might struggle with unusual items or local waste variations if not properly updated. However, Bin-e shows how AI and automation can significantly improve how we handle everyday waste.

1. **TrashBot by CleanRobotics**: Unlike traditional smart bins that simply monitor fill levels or rely on user input for sorting, TrashBot takes a more active role by automatically sorting waste using artificial intelligence, cameras, sensors, and robotic mechanisms. When a user

disposes of an item into the bin, the system immediately scans the object using cameras and sensors. These inputs are processed using a convolutional neural network (CNN) that has been trained on thousands of waste images. The AI analyzes the shape, texture, and material of the object in real-time and classifies it as recyclable, compostable, or landfill waste. Once classified, a robotic arm or air jet mechanism physically moves the item into the correct internal compartment. TrashBot doesn't only sorts, It also records detailed data about each disposal, which can be accessed by building managers through a connected dashboard. This data helps track recycling rates, waste contamination levels, and usage patterns, which are valuable for sustainability reporting and behavior analysis.

Despite its benefits, TrashBot does have limitations. It's primarily designed for indoor environments due to the sensitivity of its electronics and sensors. It is also relatively expensive, both to purchase and maintain, which can limit its accessibility to only large facilities or institutions with sustainability budgets.

3. **Enevo**: This uses the internet based on Waste Collection Optimization System. Enevo, a Finnish Company has performed crucial roles in transforming conventional waste practices

through smart monitoring and data analyses. Launched in 2015, this system focuses not only on waste sorting rather on other practices such as monitoring waste levels, predicting collection needs, optimizing collection routes using Internet Of Things [IOT] , and cloud based software. At the center of the Enevo system is a small, battery-powered ultrasonic sensor that can be installed in standard waste bins or containers. This sensor measures the fill level of the bin in real-time and transmits the data wirelessly via GSM, 3G, or LPWAN networks (such as LoRa or NB-IoT) to Enevo's cloud platform.

The platform then processes the data using predictive algorithms to identify when each bin is likely to become full. These predictions are used to automatically generate optimized collection routes, reducing unnecessary trips, fuel usage, and operational costs for waste collection companies or facilities. One of Enevo's most successful large-scale deployments occurred in Amsterdam, where the system was used to monitor hundreds of underground bins across the city. Reports from the project indicated a 40–50% reduction in collection trips, leading to lower carbon emissions and improved operational efficiency. Similar results were observed in trials across the United States, United Kingdom, and parts of Asia **(Enevo, 2019)**. Though **Enevo** does not sort or classify waste types, it solves a different but equally important problem which is inefficient and schedule-based collection systems. By making collection data-driven, Enevo helps cities and private operators reduce costs, minimize overflow and littering, and extend the life of waste containers. The system is especially useful in urban settings with high traffic, where bin overflow can cause hygiene issues. Its reliability and scalability have made it popular among smart city initiatives worldwide. However, its scope is limited to monitoring and logistics; it does not perform any physical or AI-based waste segregation.

4 **Sensoneo**: Invented in Slovakia and deployed globally since 2017 , senseneo is a smart waste management solution. Unlike systems that focus on sorting or user interaction, Sensoneo is designed to handle waste collection logistics at large scale. It uses ultrasonic sensors, cloud software, and data analytics to monitor waste container fill levels and optimize collection routes, thereby helping cities and waste management companies become more efficient, and cost-effective, also reducing pollution.

Each Sensoneo unit includes an ultrasonic fill-level sensor that can be installed in bins, dumpsters, or underground containers. These sensors measure the height of waste inside the bin and transmit data via LPWAN technologies like LoRaWAN, NB-IoT, or Sigfox. The sensors are rugged, waterproof, and powered by long-life batteries, making them suitable for both indoor and outdoor environments. The data is sent to a centralized dashboard where real-time monitoring, historical data analysis, and predictive modeling are used to generate efficient collection plans. Although Sensoneo does not perform AI-based waste classification or sorting like systems such as Bin-e or TrashBot, it addresses the collection problem of waste management, which is a critical aspect of smart city design. The platform also includes a citizen app that helps residents report illegal dumping, check bin locations, and even participate in waste tracking initiatives.

4 **Ecube Labs**: This is a Solar-Powered Smart Waste system. Ecube Labs is a South Korean clean-tech company that has been developing smart waste management solutions since 2011.

The CleanCUBE smart bin is a solar-powered, waste compactor. It uses a solar panel to power an internal compaction mechanism that compresses waste as it accumulates. This compaction increases the bin's capacity to about 800% compared to its traditional counterpart. This significantly reduces the frequency of waste collection, which in turn cuts down on labor, fuel consumption, and operational costs. The bin comes with ultrasonic sensors that measure fill levels, and the data is transmitted wirelessly to collection teams

6. **Bigbelly**: Bigbelly is a public smart bin designed for outdoor public spaces. It is most efficiently used where waste bins usually have a high overflow. The core of its technology lies in its solar-powered compactor. It uses the energy from the solar panel to power the compactor, which can increase the bins capacity up to 5 times.

This compaction helps to reduce the frequency of waste collection. It also uses ultrasonic or pressure sensors to monitor the fill-level of the bin. This data is sent to the waste collection team, which help them with efficient planning of waste collection.

7. **GULP**: GULP, short for Give Up Littering Plastic, is a smart bin system introduced in the United Kingdom in 2021. It was developed due to the growing problem of plastic waste in the Uk. GULP makes use of image recognition for automatic plastic validation, which checks if the waste being put in the bin is plastic. When a user inserts a bottle, the camera validates whether it matches the expected recycling type. Once verified, the system provides real-time feedback via a display screen, often including statistics, fun facts, or a reward system. Unlike smart bins like TrashBot or Bin-e which can sort out different types of wastes, GULP is focused on a single waste type, plastic bottles.

2.4 Limitations of Reviewed Works

Although the reviewed smart bin systems offer a wide range of benefits, there are several limitations that cut across each system, affecting them in their own way.

These limitation includes:

1. **Narrow Specialization**: Some systems are limited to certain materials. An example is GULP which is limited to PET bottles. This makes them less effective for mixed waste environments.

2. **Lack of End-to-End Integration:** some systems like RTS, Enevo focus solely on logistics or monitoring and do not physically sort or manage waste at the disposal point.

3. **High Deployment Costs**: Systems like Bin-e, TrashBot, and Bigbelly are expensive which limit their use to only institutions with high income.

4. **Limited Sorting Capabilities**: Sorting of waste often times is prone to errors. This is due to confinement of just a small number of waste categories. This errors usually occurs in mixed and contaminated wastes.

5. **Infrastructure Dependence**: Some system which uses Cloud-based platforms require strong internet connectivity and power supply. This may not be available in rural or underdeveloped areas.

6. **Indoor vs Outdoor Suitability**: Some systems are only designed for indoor use like Bin-e, limitinug their application in outdoor public spaces, and for commercial uses.

2.5 Identified Gaps in Literature

Though the reviewed works and commercial systems offer effective solutions, there are some areas in which there are gaps, and that future works can address.

Firstly, only a few smart bins makes use of real-time sorting, waste monitoring, data analytics, and user interaction. Many of the existing models prioritize some aspects over others. Also, most of the smart bins are expensive, which would not be affordable for rural communities, or low-income areas leading to why they aren't yet deployed in rural areas. Additionally, user interface are basic which lead many smart bins to operate without guiding users, or educating them about the processes.

Finally, the topic of autonomous mobility whereby the bin would be able to move and self empty itself. This would be a very good area to look into for future improvements.

2.6 Safety and Reliability of a Smart Bin System

Smart waste systems are highly safe. Most systems use non-contact sensors, which reduces contact with the bin, thereby promoting hygiene. Advanced models like TrashBot and Ecube Labs' CleanCUBE are enclosed, preventing exposure to harmful materials.

Also, they are also highly reliable. These systems often include redundant sensors, long-lasting batteries, and wireless connectivity to report faults or maintenance needs. However, despite the high reliability, mechanical failures could happen. This includes problems such as compactor jams, sensor errors from dirt buildup etc. In other to maintain reliability, these bins often require periodic maintenance, software updates, and calibration.

2.7 Current Challenges Facing Smart Bin Systems

Despite the many benefits smart waste bins may have to offer, they also do come with challenges. A lot of them do rely on expensive components which many require frequent servicing, make it cost-ineffective. A persistent issue that contributes to the challenges includes waste contamination. The system might have a hard time or even be inconsistent while trying to recognize wastes that have been contaminated. This could lead to inaccurate results.

Furthermore, misuse of bins by users; forcing of incorrect waste into the bins could damage internal mechanisms.

Finally, scalability is a factor that hinders use of smart waste systems. Though smart waste systems might show success at domestic institutions, trying to scale it up to cities or large environmental scales might show failure due to financial constraints and management.

2.8 Benefits of a Smart Bin System

Smart waste bin systems offers a range of benefits as they promote segregation at source. This improves the handling of waste, and improve its efficiency. Also, they promote cleaner environments by reducing the overflow of bins. Sensors which can help monitor the fill-level of bins allow authorities to optimize routes, which cuts down money by saving fuel and optimizing labor hours. Compaction technology increases bin capacity, further reducing the frequency of pickups.

With proper classification and real-time monitoring of the bins, recyclable materials are less likely to be contaminated by other types of wastes, improving recycling outcomes.

CHAPTER THREE

METHODOLOGY

Our approach to the design and fabrication of the waste segregation system followed the design flow chart shown in **figure 3.1** below ;

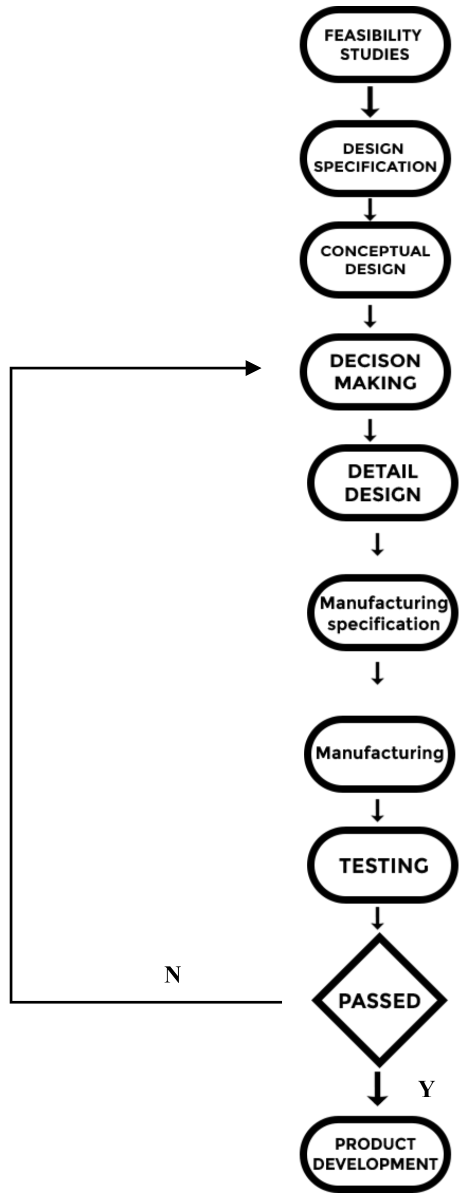


Figure 3.1 ; design flow chart of the waste segregation system

3.1 FEASIBILITY STUDIES

The feasibility studies of this project seeks to examine the possibility of designing and fabricating the waste segregation system and it also evaluates the technical, financial and economic feasibility studies. The possibility of developing this project for use at departmental level and domestic purpose was also carried out.

Prior to the commencement of the design and fabrication of this project, a background studies was carried out within the confines of the mechanical engineering department in order to ascertain the most frequently consumed waste within the department. This study spanned for a period of two weeks and upon completion of this study, it was concluded that paper, plastic and nylon are the most frequently disposed waste within the department. This system which is developed for use in the mechanical engineering department, has its designs and specifications hinged on the background studies that was carried out. Owing to this, the developed system has three compartments for segregation which include a compartment for paper, another compartment for plastic and a last compartment which is to accommodate for other kind of waste.

Cost estimates include expenses for materials, labor, equipment, and overhead costs, while revenue projections are based on projected sales volumes and pricing strategies. The financial analysis assesses profitability, Return on Investment (ROI), and payback period, while the economic viability considers job creation, income generation, and local economic development.

Technical as well as financial problems where the major challenges faced while carrying out this project, however, strategies were used to minimize these challenges.

3.2 DESIGN SPECIFICATION

Designing a waste segregation system requires careful planning of the specifications in order to minimize technical challenges that may arise upon manufacturing.

1. Capacity; The various waste compartment in the drum can hold waste up to about 5-7kg of waste with the drum itself having a capacity of about 22kg.

2. Material; coated mild steel for the surface while welded iron is being used for the surface.

3.Compartments; The waste segregation system has a drum to hold waste and this drum is segmented into three compartments for different types of wastes.

4.Display; The system has an LCD screen that displays the waste that has just been segregated at the source.

5.Inlet design system; The system has an inlet system that helps to hold waste while the system is trying to figure out which drum to direct the waste to.

6. Sorting Accuracy; the system has a sorting accuracy that is greater than 70%, thanks to the use of raspberry pi.

7.Power consumption; The system has a power consumption of $<100W$.

8. Response Time ; the system has a response time of less than 5seconds per item

9. Operating temperature; The system operates optimally at normal atmospheric temperature.

10. Frame; Compact modular design (100.5cm x 60cm x 60cm).

3.3 CONCEPTUAL DESIGN CONSIDERATION

The diagrams shown below are some of the conceptual designs which were initially developed, but due to factors stated above only one of the designs would fit best as would be seen.

3.3.1 concept 1: waste segregation system with conveyor belt mechanism

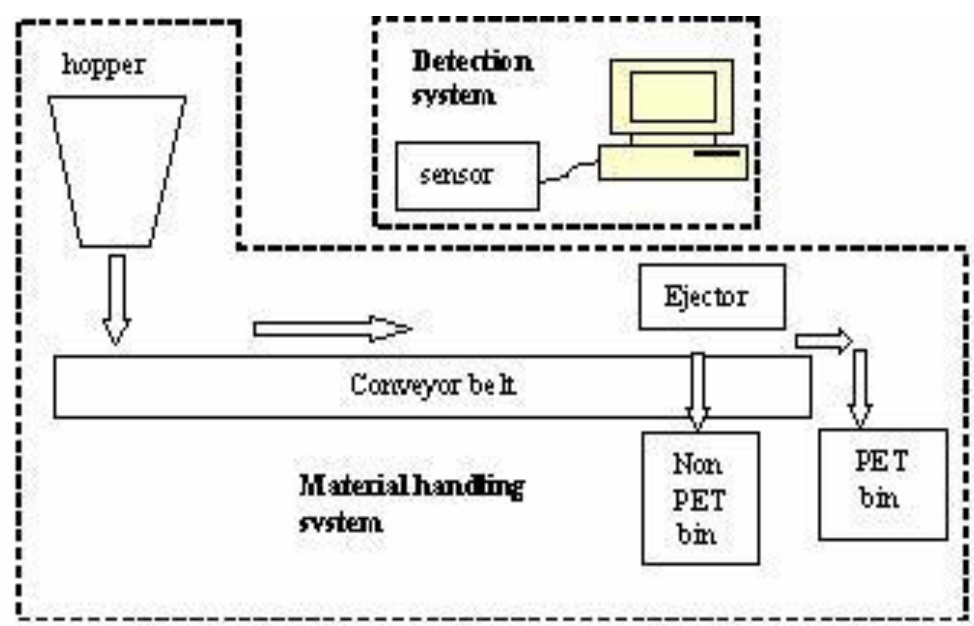


Figure 3.2 :waste segregation system using a conveyor belt

Description of the Design

1. Capturing of Image;

- The web-cam is used to take pictures of waste items as they move along the conveyor belt
- These images are then sent to the connected Raspberry pi for further analysis.

2. Analysis and classification of image;

- The Raspberry pi processes the received image using its attached cameras.
- A trained model analyzes the visuals and categorizes the waste into three main groups: paper, plastic, and miscellaneous materials (others).
- To enhance the model's performance, data augmentation methods such as image rotation and scaling are applied during training. This increases the model's capacity in identifying waste materials under different environmental conditions.
- The final classification is determined by selecting the category with the highest probability score from the model's output, ensuring accurate and reliable sorting results.

3. Transmission of data;

- After classification, the waste category is sent back to the Raspberry Pi development board.
- The received data is used to control the mechanical system for accurate waste segregation

4. Mechanical Actuation;

- The conveyor belt operates to transport waste materials through the system to the appropriate bin.
- According to the classification results, servo motors direct each waste item to its designated bin.
- The system dynamically calibrates servo motor angles to maintain accurate bin alignment and reduce segregation errors.

5. User Feedback;

- An LED indicator displays real-time visual feedback corresponding to the detected waste category.
- This feature enhances system transparency and allows users to intervene manually when required.

3.3.2 Concept 2: waste segregating system using a rotating shaft

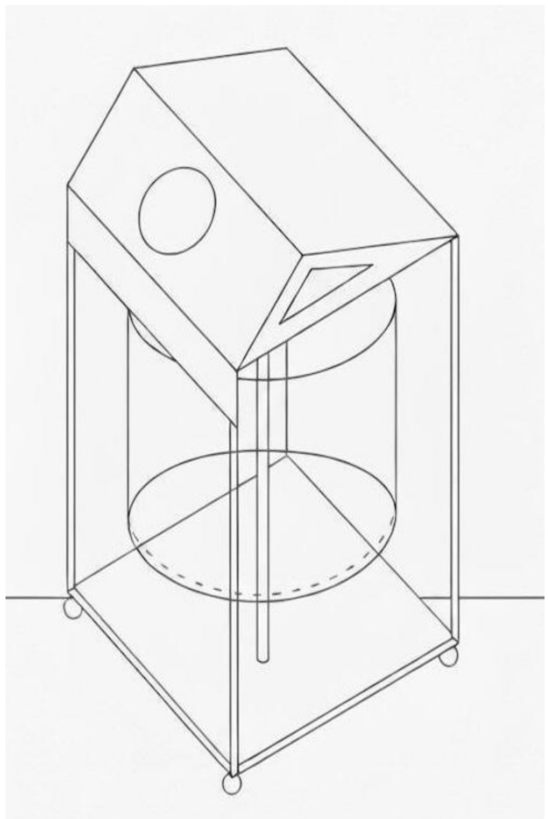


Figure 3.3 :waste segregation system using a rotating shaft

Description of concept

1. Capturing of Image;

- The web-cam is used to take pictures of waste items as they are placed on top of the drum(waste compartment) through the hopper.
- The ultrasonic sensors detect these waste items as they are placed inside the system.
- These images are sent to the connected Raspberry pi for further analysis.

2. Analysis and classification of image;

- The Raspberry pi processes the received image using its attached cameras.
- A trained model analyzes the visuals and categorizes the waste into three main groups: paper, plastic, and miscellaneous materials (others).
- To enhance the model's performance, data augmentation methods such as image rotation and scaling are applied during training. This increases the model's capacity in identifying waste materials under different environmental conditions.
- The final classification is determined by selecting the category with the highest probability score from the model's output, ensuring accurate and reliable sorting results.

3. Transmission of data;

- After classification, the waste category is sent back to the Raspberry Pi development board.
- The received data is used to control the mechanical system for accurate waste segregation

4. Mechanical Actuation;

- After data about the waste has been transmitted to the raspberry pi and the waste has been classified, the shaft rotates to the position of the appropriate bin to receive the waste.
- The drum opens up for the waste item to be received into its appropriate bin.

5. User Feedback;

- An LED indicator displays real-time visual feedback corresponding to the detected waste category.
- This feature enhances system transparency and allows users to intervene manually when required.

3.4 DECISION MAKING (SELECTION OF CONCEPT)

The two concepts considered were compared based on the attribute stated earlier . The attribute were allocated some weighting values by order of importance. For each attribute a grade for value multiplied by its weighted value was scored by the concept and the total sum added up to give the suitability level of the concept.

Table 3.1: Evaluation of the various concept for decision making

Attribute	**weighting**	**Concept**			
		one		**two**	
		score	**Weighted score**	**score**	**Weighted score**
capacity	0.1	7	0.7	7	0.7
material	0.05	4	0.2	6	0.3
Response time	0.05	5	0.25	9	0.45
Operating temperature	0.03	4	0.12	8	0.24
Efficiency	0.3	6	1.8	9	2.7
cost	0.1	7	0.7	7	0.7
frame	0.02	3	0.06	7	0.14
Sorting Accuracy	0.2	4	0.8	8	1.6

maintenance	0.15	5	0.75	6	0.9
Total	**1**		**5.38**		**7.73**

From the Evaluation of the various concept for decision making process in table 3.1 using the weight scale of a total of one in order of importance of the considered attribute, the concept 2 with a total weighted attribute average of **7.73** was selected as against the other concept. Hence the concept 2 was selected.

3.5 COMPONENTS OF THE SYSTEM

1. RASPBERRY PI;

The Raspberry Pi 5 is a single-board microcomputer that serves as the main processing unit for the waste segregation system. It coordinates and executes various control and monitoring operations such as data acquisition, sensor management, and communication between modules. Equipped with a 64-bit quad-core ARM Cortex-A76 processor, the Raspberry Pi 5 provides enhanced computational performance and power efficiency.

In this design, it handles the AI-based image recognition tasks for identifying and classifying waste materials into appropriate categories (paper, plastic and others). It interfaces with other microcontrollers, sensors, and actuators through its GPIO pins and communicates wirelessly via Wi-Fi or Bluetooth.

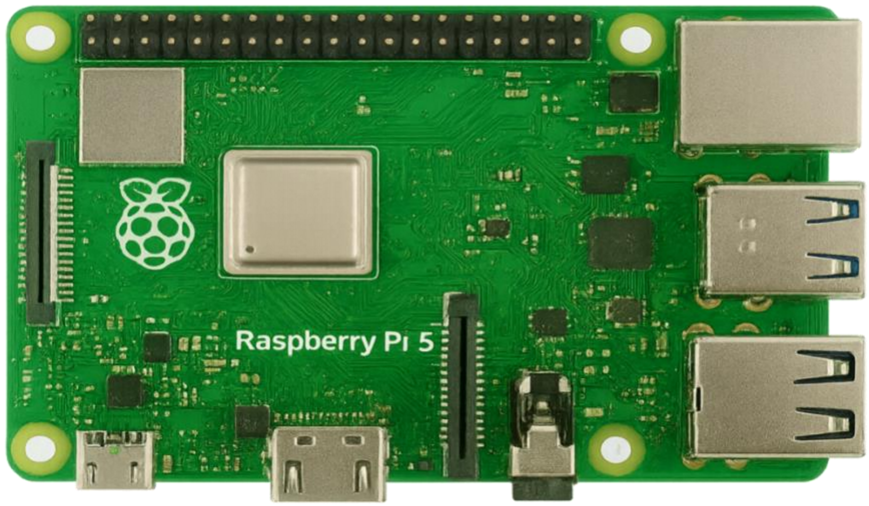


Figure 3.4: Raspberry pi 5

2. RASPBERRY PI 5 LCD SCREEN;

The Raspberry Pi 5 LCD display provides a user interface for the waste segregation system. It visually displays real-time data such as system status, waste classification results, and operational commands.It connects directly to the Raspberry Pi through the DSI (Display Serial Interface) port, ensuring fast data transfer and clear visualization.

3.JUMPER CABLES

Jumper cables are essential connectors used for linking various electronic components on the breadboard or vero board. They facilitate the transmission of signals and electrical power between the Raspberry Pi,ESP32, Mega, sensors, and other modules. These cables come in male-to-male, male-to-female, and female-to-female types, providing flexibility during circuit prototyping and integration.

Figure 3.5: jumper cables

4. **RESISTORS**

Resistors are passive electronic components that limit or regulate the flow of electric current within the circuit. In the waste segregation system, resistors are used for current control, signal conditioning, and voltage division across sensors and LED. By preventing excessive current flow, they protect delicate components such as the micro controllers and sensors from damage due to high voltage.

Figure 3.6 : set of resistors

6. RASPBERRI PI 5 OFFICIAL CASE

The Raspberry Pi official case provides a protective enclosure for the Raspberry Pi 5, shielding it from dust, moisture, and mechanical damage. The casing also enhances heat dissipation through ventilation openings and ensures the safety of electrical connections. The design allows easy access to ports and GPIO pins for external connectivity.

7. WHITE LEDs

White LEDs are used as visual indicators in the waste segregation system. They provide illumination within the sorting chamber, improving visibility for the vision module (camera) to accurately analyze and classify waste materials. Additionally, the LEDs serve as status indicators, signaling various operational states such as power ON, error alerts, or successful waste identification.

Figure 3.7: white LED

8. 12VOLT LEAD ACID BATTERY

The 24V lead-acid battery serves as the primary power supply for the system’s motors, sensors, and control boards. It provides stable DC power required for continuous operation. Lead-acid batteries are chosen for their durability, high discharge rate, and ability to supply large currents necessary for driving motors. The battery is rechargeable, ensuring long-term use and sustainability.

Figure 3.8: 12V battery

9. ULTRASONIC SENSORS

The ultrasonic sensor stands as the object detection component. It Uses the principle of sound waves to detect if an object is placed through the hopper of the machine. This informs the machine to begin the system’s cycle, and begin segregation.

Figure 3.9 : ultrasonic sensors

10. GEARED DC MOTORS

The geared DC motor converts electrical energy into mechanical motion, providing the necessary torque to rotate the shaft. The inclusion of a gear system allows speed reduction and torque amplification, ensuring precise and powerful mechanical movement for effective waste transportation during segregation.

Figure 3.10: geared DC motors

11.ESP32 S3

The ESP32 S3 is a high-performance microcontroller with integrated Wi-Fi and Bluetooth connectivity. In this project, it provides remote monitoring and control capabilities. It allows data transmission between the waste segregation system and a cloud server or mobile application. The ESP32 S3 enhances the system’s IoT (Internet of Things) functionality by enabling real-time status updates and remote diagnostics.

Figure 3.11: ESP32 S3

12. HIGH TORQUE SERVOS

High torque servos are used to control the movement of the sorting flaps that direct waste into the appropriate bins. They operate on PWM (Pulse Width Modulation) signals generated by the ESP32 Mega, ensuring precise angular positioning. These servos provide high rotational strength, making them suitable for handling varying weights of waste materials.

Figure 3.12: high torque servo

13. VERO BOARDS

Vero boards serve as the platform for assembling and soldering circuit components. They provide a durable and organized base for establishing permanent electrical connections. Each component such as resistors, capacitors, and regulators is carefully placed and soldered to the vero board to ensure stability and reliability of the circuit connections.

Figure 3.13: vero boards

14. CAPACITORS

Vero boards serve as the platform for assembling and soldering circuit components. They provide a durable and organized base for establishing permanent electrical connections. Each component such as resistors, capacitors, and regulators is carefully placed and soldered to the vero board to ensure stability and reliability of the circuit connections.

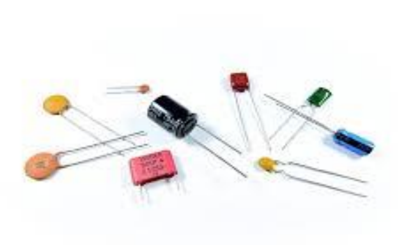


Figure 3.14: capacitors

15. LM2596 VOLTAGE REGULATORS

The LM2596 voltage regulator is a DC-to-DC buck converter used to step down the voltage from the 12V battery to the required 5V level suitable for powering microcontrollers, sensors, and communication modules. It ensures a stable and regulated voltage output, protecting electronic components from voltage fluctuations.

16. SIM800L UNIT

The SIM800L GSM module is a communication unit that enables wireless data transmission through the GSM network. In this project, it allows the system to send notifications or alerts (such as bin full status) to the user's mobile phone via SMS. It communicates with the ESP32 Mega through serial ports, utilizing AT commands for message transmission.

17. RESISTORS(SECOND SET)

A second set of resistors is utilized within the control and power sections to regulate current and maintain balanced voltage levels across sub-circuits. These resistors contribute to power efficiency and ensure consistent operation of both the analog and digital components.

18. DIGNITY BOX

The dignity box houses the major hardware components such as the Raspberry Pi, ESP32 Mega, motor driver, and power modules. It is fabricated from durable, non-conductive material and designed to provide proper ventilation. The box ensures protection against dust, moisture, and accidental contact with high-voltage parts, promoting both safety and aesthetics.

19. BTS 7960 MOTOR DRIVER

The BTS 7960 is a high-current H-Bridge motor driver module used to control the speed and direction of the DC motors. It interfaces directly with the ESP32 Mega and provides current feedback, overload, and thermal protection. The BTS 7960 allows the system to drive motors efficiently using PWM control, ensuring smooth sorting and waste movement operations.

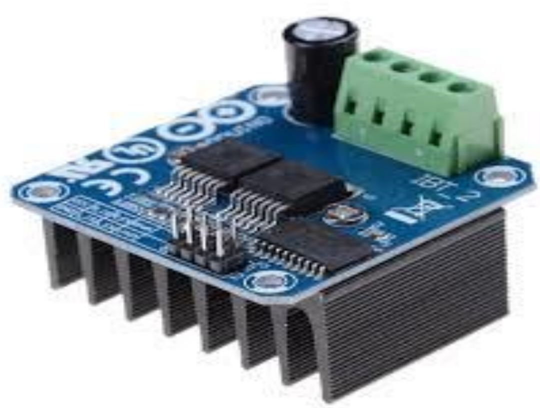


Figure 3.15: bts 7960 motor driver

19. SHAFT

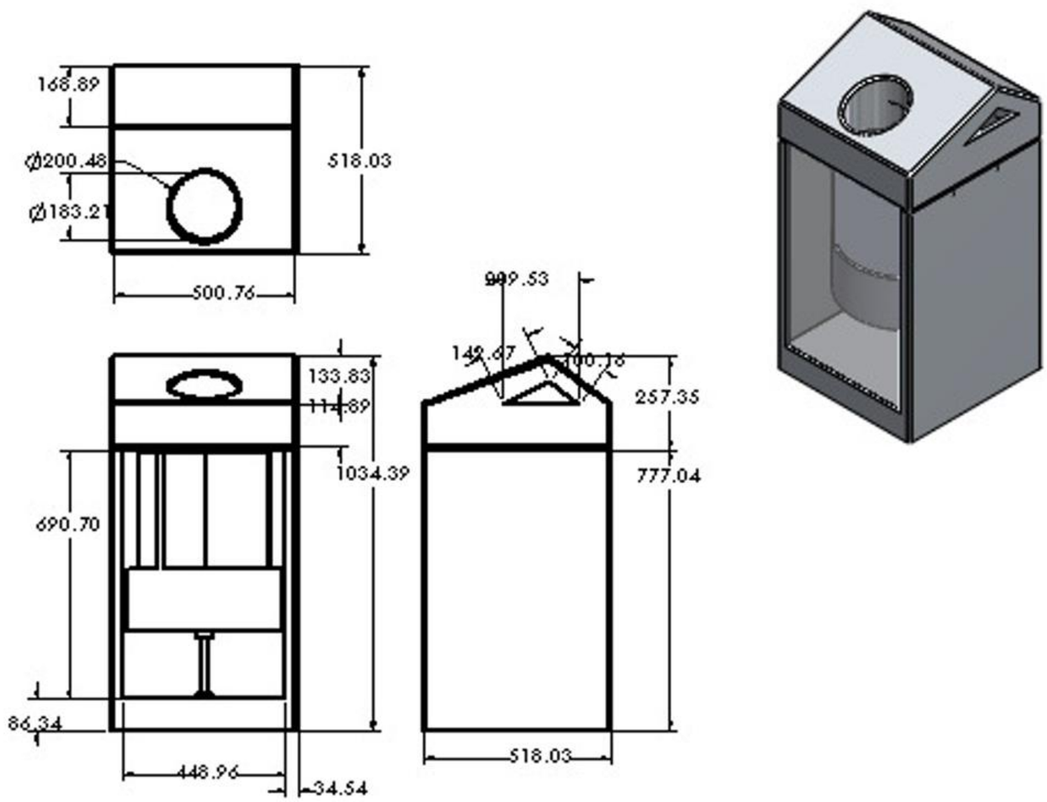
The mechanical helps to rotate the bin to its appropriate position for waste segregation.

20. THE DRUM (WASTE COMPARTMENTS)

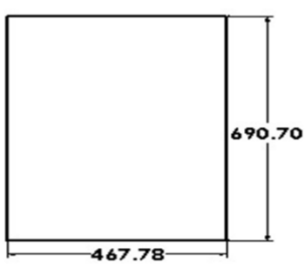
The drum provide space for the already segregated waste for storage.

3.6 MACHINE DESIGN (DETAIL DESIGN)

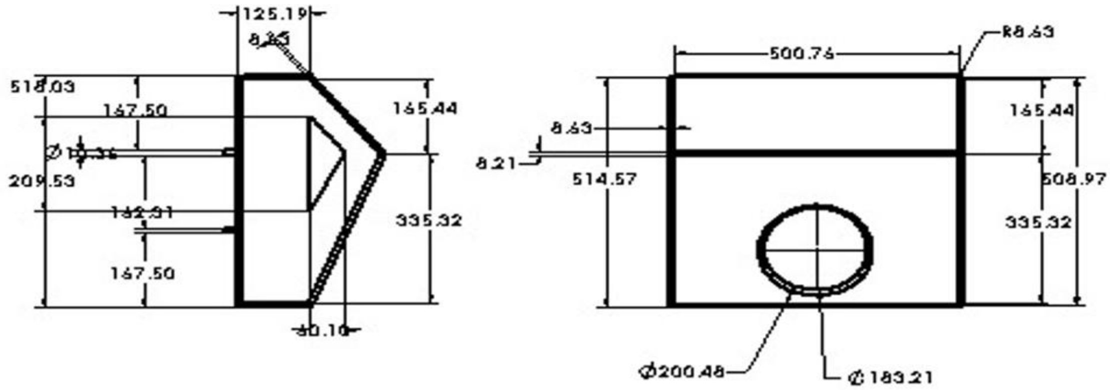
1. The main assembly of the waste segregation system:



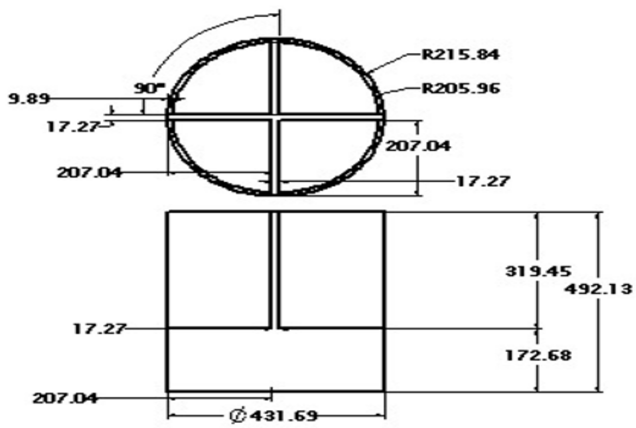
2. The glass screen**:**



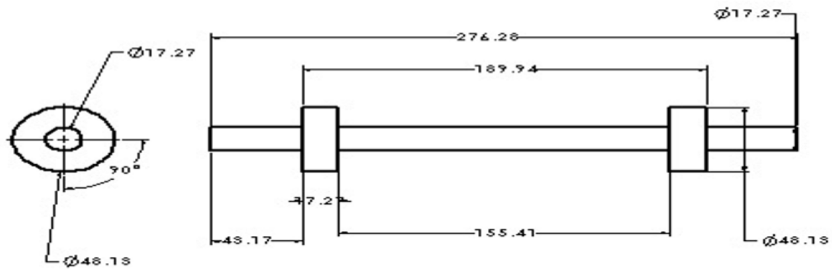
3. The selector cover:



4. The cover:



5. The rotating shaft:



3.7. EQUATIONS/CALCULATIONS

3.7.1 EQUATIONS

- Motor Torque and Rotational Motion

The torque required to rotate the waste segregating shaft is given by ;

$\tau = F \times r$

where ;

τ = Torque (N·m) ,

F = Tangential force at radius r (N),

r = Radius of shaft or pulley (m).

- The power developed by the rotating shaft is given by ;
- $P = \tau \times \omega$

Where:

ω = $\frac{2\pi N}{60}$is the angular velocity (rad/s)

N = shaft speed (RPM)

- The relationship between torque, angular acceleration and moment of inertia is given by;

$\tau = I \times \alpha$

where:

I = Moment of inertia (kg·m²),

α = Angular acceleration (rad/s²).

- Performance index (waste segregation accuracy)

In testing and analysis, the accuracy of the waste segregation system is expressed as

$$Accuracy = \frac{Ncorrect}{Ntotal} \times 100\%$$

Where:

$N_{correct}$ = Number of correctly classified wastes

N_{total} = Total number of tested waste samples

- Efficiency of the overall system

$$\eta system = \frac{Poutput}{Pinput} \times 100\%$$

where

P_{output} = Total useful mechanical/electrical power delivered

P_{input} = Total electrical power delivered by the battery

3.7.2 CALCULATIONS

1. determining the volume of the drum:

From detail design, the diameter of the drum is given by D = 448.96mm

So the radius is $R = \frac{D}{2} = \frac{448.96}{2}$ = 224.48mm

h = 500.78mm

Volume of drum = $\pi r^2 h$

V = $\pi \times 224.48^2 \times 500.78$

V = *0.0793m³*.

2. determining the torque of the rotating shaft:

Shaft diameter

$$\tau allow = 40MPa = 40 \times 106\, N/m\, 2$$

Factor of safety = 2

Effective design shear stress, τd = $\frac{\tau allow}{F.S} = \frac{40\times10^6}{2}$ =20 × 10^6 N/m^2

For a **solid circular shaft**, the relationship between torque and shear stress is:

T = $\frac{\pi}{16}\tau d.d^3$

T = $\frac{\pi}{16}$ × (20 × 10^6) × $(0.04818)^3$

T = 438.2Nm

The rotating shaft can safely transmit approximately ***438.2Nm*** of torque without exceeding the allowable shear stress.

3.8 BILL OF ENGINEERING MATERIALS

ITEM	UNIT	COST PER UNIT	TOTAL(IN NAIRA)
Raspberry pi 5	1	200000	200000
Raspberry pi 5 display	1	60000	60000
Raspberry pi 5 power supply	1	25000	25000
Lead acid battery	1	30000	30000
Ultrasonic sensors	5	3000	15000

Geared DC motor	1	20000	20000
Esp32 S3	1	15000	15000
High torque servo	2	8000	16000
Vero boards	3	1000	3000
capacitors	2	1000	2000
Voltage regulators	2	5000	5000
Fabrication materials and fabrication	1	100000	100000
Sim 800L unit	1	7000	23000
Resistors	2	1000	2000
Raspberry pi 5 64gb A1 SD card	1	140000	14000
Dignity box	1	5000	5000

3.9 FABRICATION PROCESSES INVOLVED IN THE WASTE SEGREGATION SYSTEM

- **Cutting:** Cutting operations refer to the process of removing or separating a portion of a material, such as metal, wood, or plastic, using a cutting tool or machine. The goal of cutting operations is to create a specific shape, size, or design in the material, which can then be used to fabricate a particular product or component.Three primary cutting operations are involved: frame cutting, sheet metal cutting, and component cutting. The frame cutting is to give structure to the system
- **Welding:** Welding operation is carried out to join the structural frame

- **Soldering:** Various component are soldered especially in the vero board.
- **Rolling:** Rolling operation was carried out in the fabrication of the drum of the system.
- **Grinding and Finishing:** Involves smoothening of the welded joints and sharp edges.

- **Surface Treatment:** Applying coatings on the surface of metals to prevent corrosion and for aesthetic purposes.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter delves the results of the tests obtained after the fabrication of the automated waste segregation system. It also discusses the response time, accuracy and how well the system would detect waste in real time(it's reliability) . Furthermore, the outcomes of the test are discussed as relates to the project objectives, which has been stated in other chapters.

4.1 THE FABRICATED SYSTEM

After necessary evaluations and fabrications were completed, the system was fully assembled and tested. It consists of three main compartments which were designed for the three type of waste the system would sort; paper, plastics, and other wastes. The frame of the system was built with coated mild steel. This provides strength to the overall structural element, while also ensuring durability. The three compartments are rotated by a mechanism which is connected to a DC motor. This ensures that the different type of wastes are sorted into the appropriate compartments.

The electrical components and wiring are also housed in a protective covering to prevent damage. This electrical components includes the Raspberry pi, ESP-32,e.t.c Together, the various mechanical and electrical components forms a system that efficiently sorts out waste.

4.2 CONSTRUCTION AND IMPLEMENTATION

4.2.1 MECHANICAL AND STRUCTURAL ASSEMBLY

The structural components of the machine includes;

1. Drum (compartment)
2. Shaft
3. DC Motor
4. Frame

Throughout the fabrication of the system, the structural integrity was a topic of concern. Therefore the frame of the system was made using coated mild steel. Using mild steel as a coat, the strength and durability of the system was improved, ensuring that the system's structural integrity was not compromised. The frame was made with a compact modular design of 100.5cm by 60cm by 60cm. In order to fully ensure the frame was sturdy enough, various operations were carried out, such as; wielding, grinding, and finishing operations.

The Central drum which is the waste compartment was equally segmented to allow for the separation of the types of waste. This segments are divided into three; plastic, paper, and other wastes/nylons, which was determined by the feasibility studies carried out. The drum was mounted on a rotating shaft, which in turn is coupled to the gear DC motor. This motor and shaft arrangement allows for actuation, which positions the correct bin for segregation.

4.2.2 ELECTRONIC AND CONTROL SYSTEM

The electronic components are all house in the dignity box, and are made of different parts as follows;

1) Raspberry PI
2) ESP32 S3
3) BTS 7960
4) Web cam
5) Lead-acid battery

The main unit of the control system is the raspberry pi, which functions as an image processor. It is a high performance unit which processes images , and classifies them based on trained data. During the training of the model, different objects are used, and then the unit learns from the results. Image rotation and gray scale is also used when training to increase the accuracy of the unit. It works in hand and communicates with theESP32 S3 after classification. ESP32 S3 is in charge of motor controls and certain components. Basically, the ESP32 S3 tells the system what to do , and how to move.

Functioning side to side with the raspberry pi is the web-cam, which acts as the eye of the system. It is placed in such a way to capture waste images, which is then classified by the raspberry pi. Ultrasonic sensors were utilized for object detection , and also to monitor fill-bin levels. This prevents over flowing, and notifies certified personnel of bin level.

The overall power source is maintained by a 12v lead-acid battery, which powers the system. There are also voltage regulators that powers down the voltage for the micro-controllers and sensors.

4.3 PERFORMANCE ANALYSIS

This subsection shows the data from the various tests gotten from the system after fabrication, in other to determine its accuracy and reliability.

4.3.1 Waste Classification Accuracy Test

The system was tested with 100 wastes samples to determine its accuracy.

WASTE CATEGORY	TOTAL SAMPLES TESTED	CORRECTLY CLASSIFIED	ACCURACY
Paper	40	35	87.5%
Plastic	40	31	77.5%
Other/Nylons	20	18	90.0%
Overall	100	84	84.0%

From the table, the Overall system accuracy can be calculated as follows;

Acurracy = $\frac{NCORRECT}{NTOTAL} \times 100\% = \frac{84}{100} \times 100\% = 84\%$

4.3.2 RESPONSE TIME

This test deals with the time taken for the segregation cycle. This includes detection, classification, rotation and drop.

TRIAL NO.	Detection to Classification Time (s)	Rotation and drop Time (s)	Total Response Time (s)
1	0.95	3.98	4.93
2	1.12	3.98	5.10
3	1.05	3.95	5.00
4	0.88	4.14	5.02
5	0.90	4.00	4.90
Average	0.98	4.01	4.99

Average Response Time: The system achieved an average throughput speed of 4.99 seconds per waste, which is approximately 5 seconds.

4.3.3 POWER CONSUMPTION TEST

The power consumption was measured during peak periods, and the results is as follows;

- Measured current Draw during Peak : 5.2A
- Battery Voltage: 12V
- Peak Power consumption : 12V × 5.2A = 62.4W

4.4 DISCUSSION

The experimental results obtained from the tests prove a success against the project's initial design objectives. The system achieved a classification accuracy of 84% , which exceeded the minimum design accuracy. Specifically, high accuracy was recorded for paper(87.5%) and other/nylon(90%). This indicates a reliable performance for these types of materials and also validates the utilization of vision-based classification. However, despite these high accuracy for paper and Nylon, the result shows a challenge in segregation plastic. This is most likely due to the variation in optical properties of plastic wastes. Such variations could be caused by contamination, varying colors, and opacity. These variations could introduce errors in the vision model, and reduce the accuracy when classifying plastic waste.

A critical requirement, the response time was also successfully met. The system recorded an average time of 4.99 seconds, as opposed to the design time of 5 seconds. However, further analysis reveal that a major factor increasing the throughput time is the rotation and drop time, which takes up more than half of the throughput time. This reveals that the delay is not in the image classification, but the mechanical actuation, and segregation. This could be looked upon in future projects, and improved. In a broader contest, the system addresses the problem of poor waste management in developing countries, and helps to bridge that gap. It also proves the feasibility of a cost effective segregation unit at source.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The successful completion of this project marks a significant milestone in the application of engineering principles to solve real-world environmental challenges. The Waste Segregation System developed during this study was designed to automatically identify and sort waste into three categories: metallic, wet, and dry. Using a combination of sensors like inductive proximity sensors for metal detection, moisture sensors for wet waste, and infrared sensors for dry waste the system was able to classify waste items with a high degree of accuracy and efficiency.

Throughout the design and testing phases, the system demonstrated its ability to function reliably in a controlled environment. The sorting mechanism, powered by servo motors, responded promptly to sensor inputs and directed waste into the appropriate bins. This automation reduces the need for manual sorting, which is often labor-intensive, unhygienic, and prone to errors. By minimizing human contact with waste, the system also contributes to improved public health and safety.

One of the key achievements of this project is its demonstration of how low-cost, readily available components can be used to build a functional and effective waste management solution. The use of ESP32 microcontroller, basic sensors, and simple mechanical parts makes the system affordable and accessible, especially for communities with limited resources.

However, the project also revealed certain limitations. The system was designed to handle small household waste items and may not perform as effectively with larger or irregularly shaped objects. Additionally, the classification was limited to three types of waste, which does not fully represent the complexity of real-world waste streams. Materials such as glass, hazardous chemicals, and biodegradable plastics were not included in this version of the system.

Despite these limitations, the project has laid a solid foundation for future improvements and innovations. It has shown that automated waste segregation is not only possible but also practical, especially in settings where manual sorting is inefficient or unsafe. The system can be further developed and scaled to meet the needs of larger communities, institutions, and even industrial facilities.

In conclusion, this project has successfully met its objectives and demonstrated the potential of engineering solutions in promoting environmental sustainability. It serves as a stepping stone toward smarter, cleaner, and more efficient waste management practices.

5.2 RECOMMENDATIONS

Based on the experiences and findings from this project, several recommendations can be made to enhance the performance, usability, and impact of the Waste Segregation System in future versions:

1. **Expand Waste Categories**

The current system is limited to sorting metallic, wet, and dry waste. Future designs should include additional sensors to detect other types of waste such as glass, biodegradable materials, and hazardous substances. This would make the system more versatile and suitable for a wider range of applications.

2. Integrate Artificial Intelligence

Incorporating machine learning algorithms can significantly improve the system's accuracy and adaptability. AI can help the system learn from past sorting decisions, recognize patterns, and make better classifications over time. This would be especially useful in handling complex or mixed waste items.

3. **Develop a User Interface**

Creating a mobile or web-based application would allow users to monitor the system remotely, view sorting statistics, and receive alerts when bins are full or maintenance is needed. This feature would enhance user engagement and make the system more interactive.

4. **Use Renewable Energy Sources**

To make the system more environmentally friendly, solar panels or other renewable energy sources can be used to power the components. This would reduce dependency on grid electricity and make the system suitable for off-grid or rural areas.

5. **Improve Mechanical Design**

The current sorting mechanism is suitable for small-scale use but may not be efficient for larger volumes of waste. Future versions could include conveyor belts, rotating bins, or robotic arms to increase throughput and handle more diverse waste items.

6. Enhance Sensor Protection

Sensors are sensitive to environmental conditions such as dust, moisture, and temperature. Protective casings and environmental shielding should be added to ensure consistent performance, especially in outdoor or industrial settings.

7. Promote Public Awareness

For the system to be effective, users must understand how to use it properly. Educational campaigns, training sessions, and instructional materials should be provided to encourage correct usage and maintenance. This will also help promote responsible waste disposal habits.

By implementing these recommendations, the Waste Segregation System can evolve into a more robust, intelligent, and scalable solution. It has the potential to make a meaningful contribution to environmental conservation, public health, and sustainable development. With continued research and development, this project can serve as a model for future innovations in smart waste management.

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APPENDIX

VIEWS OF THE FINAL FABRICATED WORK

ESP 32 CODES FOR WASTE SEGREATING SYSTEM

```
  - YOLO detection via I2C from Raspberry Pi
  - TCS3200 color sensor for compartment detection
  - Ultrasonic sensor for object presence
  - Relay-controlled drum rotation
  - L298N motor driver for door control
  - Limit switches for door position feedback
*/

#include <Wire.h>

// ====== I2C CONFIGURATION ======
#define I2C_SLAVE_ADDR 0x42
#define SDA_PIN 21
#define SCL_PIN 22
#define I2C_FREQ 100000

// ====== ULTRASONIC SENSOR ======
#define TRIG_PIN 25
#define ECHO_PIN 34
#define DETECTION_DISTANCE 20  // cm - adjust based on your setup

// ====== RELAY (DRUM ROTATION) ======
#define RELAY_PIN 26

// ====== L298N MOTOR DRIVER ======
#define MOTOR_ENABLE 13
#define MOTOR_IN1 4
#define MOTOR_IN2 23

// ====== LIMIT SWITCHES ======
```

Final Dustbin 3.ino

```

// ====== GLOBAL VARIABLES ======
TwoWire I2Cslave = TwoWire(0);

String targetColor = "UNKNOWN";
String currentColor = "UNKNOWN";
uint8_t detectedClassId = 255;
String detectedClassName = "Unknown";
uint8_t detectionConfidence = 0;
bool newDetectionReceived = false;

unsigned long stateTimer = 0;
unsigned long colorCheckTimer = 0;
const unsigned long DROP_WAIT_TIME = 3000;  // 3 seconds for waste to drop
const unsigned long DOOR_TIMEOUT = 10000;   // 10 seconds timeout for door operation
const unsigned long COLOR_CHECK_INTERVAL = 200;  // Check color every 200ms

// COCO dataset class names (80 classes)
const char* cocoClasses[] = {
  "person", "bicycle", "car", "motorcycle", "airplane", "bus", "train", "truck", "boat", "traffic light",
  "fire hydrant", "stop sign", "parking meter", "bench", "bird", "cat", "dog", "horse", "sheep", "cow",
  "elephant", "bear", "zebra", "giraffe", "backpack", "umbrella", "handbag", "tie", "suitcase", "frisbee",
  "skis", "snowboard", "sports ball", "kite", "baseball bat", "baseball glove", "skateboard", "surfboard",
  "tennis racket", "bottle", "wine glass", "cup", "fork", "knife", "spoon", "bowl", "banana", "apple",
  "sandwich", "orange", "broccoli", "carrot", "hot dog", "pizza", "donut", "cake", "chair", "couch",
  "potted plant", "bed", "dining table", "toilet", "tv", "laptop", "mouse", "remote", "keyboard",
  "cell phone", "microwave", "oven", "toaster", "sink", "refrigerator", "book", "clock", "vase",
  "scissors", "teddy bear", "hair drier", "toothbrush"
};
```