

"Design and Development of a Smart Mechatronic System for Waste Sorting, Shredding, and Compaction Based on Sensor Integration and Microcontroller Control"

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Abstract

This study presents the development of an automated Smart Waste Sorting, Shredding, and Compressing System to improve waste management efficiency. The system integrates capacitive and proximity sensors to classify waste into organic (leaves) and plastic categories with 100% accuracy in testing (20 plastic samples and 9 liters of organic waste accurately sorted). The shredded waste is reduced to 3 cm fragments, and subsequent compression achieves a 60% volume reduction, significantly optimizing storage and transport.

The system utilizes an ESP32 microcontroller for real-time control, supported by ultrasonic sensors and servo motors for precision. Experimental results demonstrate the effectiveness of the integrated design, highlighting its potential for sustainable waste management in communities and institutions. This innovation offers a practical solution to enhance recycling processes and reduce environmental impact through automation.

Keyword: Smart Waste System, Capacitive Sensor, Proximity Sensor, ESP32 Microcontroller, Automated Sorting, Waste Shredder

INTRODUCTION

The waste problem has become an increasingly complex and urgent global challenge over the past few decades. Population growth, rapid urbanization, and changing consumption



patterns have led to a significant increase in the volume of waste generated worldwide. According to the World Bank (2020)(World Bank Group, 2018) , global waste generation reached 2.01 billion tons per year in 2020. Without significant intervention, this figure is projected to soar to 3.40 billion tons per year by 2050(Jambeck et al., 2015) .

In Indonesia, the waste issue is equally alarming. Data from the Ministry of Environment and Forestry (KLHK) indicated that in 2022, total waste generation in Indonesia reached 68.5 million tons per year, with plastic waste accounting for 15–20% of the total. Meanwhile, organic waste such as leaves and food scraps contributes approximately 60% of the total waste. The impact of waste on the environment, public health, and the economy has become increasingly evident in the past five years. Improperly managed plastic waste has polluted marine ecosystems, with Indonesia ranking as the second-largest contributor of plastic waste to the ocean—amounting to 0.48 to 1.29 million tons per year (Adjie Suwignyo et al., 2022)(Li et al., 2022). Organic waste, like leaves that accumulate in landfills, generates methane (CH₄), a potent greenhouse gas that significantly contributes to global warming. From a public health perspective, waste accumulation provides a breeding ground for disease, with 30% of infection cases in urban areas linked to poor waste management. Open burning of waste also releases toxic substances such as dioxins, which are harmful to respiratory health. Economically, the cost of waste management continues to rise, with the government allocating up to IDR 10 trillion in 2021.

One of the primary causes of high landfill accumulation is the low rate of waste sorting and processing. Most household and commercial waste is discarded as mixed waste, without separating organic from inorganic materials. As a result, waste that could be composted or recycled becomes more difficult to process efficiently(Meyrena and Amelia, 2020). Waste shredding and compacting technologies offer a potential solution to this problem. Shredding is the process of cutting or breaking down waste into smaller pieces, making it easier to process or recycle. Compacting, on the other hand, reduces the volume of waste by pressing it into smaller units. These processes significantly reduce the space required for storage and transportation, thereby lowering operational costs and greenhouse gas emissions from waste transport (Rizal and Karyana, 2019). In Indonesia, automated shredding and compacting technologies are still limited, despite extensive research and technological development in the field of waste management. Existing machines often face several shortcomings, such as high energy consumption, costly production, and limited flexibility in handling different types of waste. Most of these technologies are only used at an industrial scale or in large recycling facilities (Dwinanda Soewono et al., 2021)(Lianawati et al., 2023)(Lianawati et al., 2024). In response to these



challenges, this research proposes the design and development of an innovative device capable of automatically shredding and compacting both organic and plastic waste. With proper shredding, organic waste can be transformed into valuable compost, while recyclable materials such as plastic, paper, and metal can be processed into new products. Moreover, compacting waste will improve storage and transportation efficiency, ultimately reducing operational costs.

METHOD

This study adopts a Research and Development (R&D) methodology consisting of six key stages. It begins with a comprehensive literature review and field data collection to identify challenges in waste management and assess current smart waste technologies. Based on these insights, the system is planned and designed to include automatic waste sorting using sensors, along with integrated shredding and compacting units and a real-time monitoring system. The third phase involves developing a functional prototype embedded with sensors and automation components (Xiong et al., 2021). This prototype undergoes rigorous testing to evaluate sorting accuracy, shredding efficiency, pressing effectiveness, and data transmission stability. The results are analyzed against predefined performance benchmarks to determine the system's success. Finally, improvements are made to the hardware, sensor configuration, and control algorithms to enhance the system's reliability and operational performance in addressing mixed waste management issues (Siregar, 2023).

RESULTS AND DISCUSSION

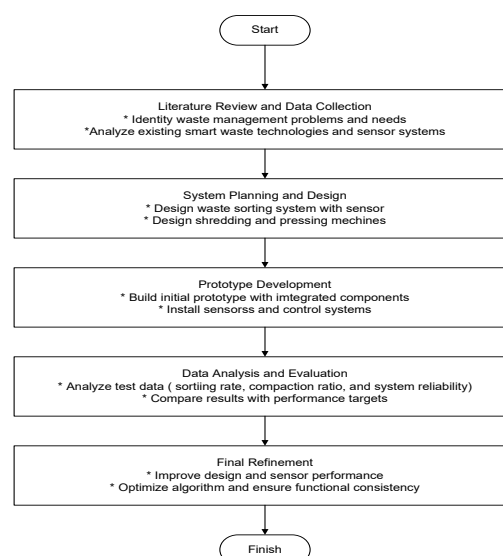


Figure 1 Flowchart of the Research Methodology

Figure 1 illustrates the workflow of the system in this study, beginning with the waste sorting process. Incoming waste is identified using a proximity sensor, after which the sorted waste is directed into designated storage compartments. Once the waste type is confirmed, the system proceeds to the shredding stage. The shredded waste is then transferred to the pressing machine, which operates only if the waste in the compartment meets the predefined criteria.

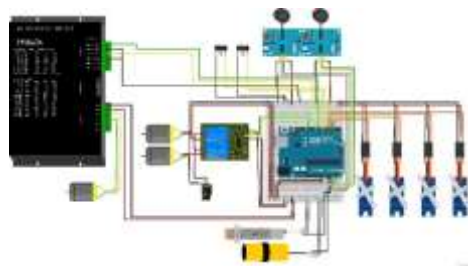


Figure 2 Schematic Design

Figure 2 illustrates the schematic diagram of the control system designed to operate linear actuators and sensors. The system employs an **Arduino Mega ADK** as the central control unit, which receives input from two inductive sensors connected at the top section to detect the material type of waste. Additionally, three linear actuators, controlled via a relay module interfaced with the Arduino, facilitate lifting or pressing actions upon waste material detection. Once the Arduino issues a command, the relay module activates to supply or cut off power to the actuators. For circuit testing, all components are interconnected using a breadboard as a temporary interfacing medium, with cable pathways indicating data and power flow within the system.



Figure 3 Smart Waste Processing Machine Prototype for Sorting, Shredding, and Compaction

Figure 3 The image shows the final prototype of the smart waste processing machine, designed to perform automatic sorting, shredding, and compacting of waste. The device is equipped with sensor-based detection systems to distinguish between organic and inorganic materials. It integrates mechanical components for cutting waste into smaller parts and compressing it to reduce volume. The compact design allows for efficient space usage and is intended for small-scale waste management applications, such as in schools, households, or local communities. This prototype represents the physical realization of the system developed during the research and serves as the basis for performance and functionality testing.

PROTOTYPE TESTING AND PERFORMANCE ANALYSIS

The prototype was tested on various types of household plastic waste, including thin plastic wrappers, regular PET bottles, and thick rigid plastic containers. The system successfully processed thin plastic and PET bottles. However, thick plastic materials could not be shredded due to torque limitations of the motor and insufficient blade strength. The pressing mechanism operated effectively, successfully compacting the shredded output.

EXPERIMENTAL RESULTS

Table 1. Waste Sorting Sensor Testing Result

No	Total Waste Tested	Target Waste Type	Correctly Sorted (units)	Sorting Time (seconds)
1	1 Bottle	Plastic	1 bottle	0.2 seconds
2	8 Bottles	Plastic	8 bottles	1.6 seconds
3	10 Bottles	Plastic	10 bottles	25 seconds
4	5.304 L	Organic (leaves)	5.304 L	12 seconds

Table 1. Waste Sorting Sensor Testing Results Testing on the automatic sorting system revealed a high level of accuracy in identifying both plastic and organic waste. Across four different test scenarios, the system accurately sorted all targeted waste items. One, eight, and ten PET bottles were correctly identified and sorted in 0.2, 1.6, and 25 seconds respectively. Meanwhile, 5.304 liters of dried leaves were sorted within 12 seconds. These results

demonstrate the system's efficiency in handling both types of waste, maintaining reliable performance across varying quantities and waste characteristics.

Table 2. Waste Shredding Performance

No	Initial Quantity	Description	Shredding Time
1	1 Bottle	550 ml plastic bottle	1 minute 5 seconds
2	8 Bottles	550 ml plastic bottles	9 minutes 45 seconds
3	5.304 L	Leaves (organic waste)	2 minutes 12 seconds

Table 2 explains the results of the waste shredding process testing using the prototype developed in this study. It presents data on the initial amount of waste, the type of waste being shredded (such as 550 ml plastic bottles and dry leaves), and the time required for each shredding scenario. The results show that organic waste (leaves) is shredded more quickly than plastic waste, which takes longer, especially in larger quantities. This table highlights the efficiency and limitations of the shredding system based on the type and volume of waste processed.

Table 3. Waste Compaction Results

No	Quantity	Description	Initial Volume (cm ³)	Final Volume (cm ³)	Time Taken
1	10 bottles	Plastic	12.285 L	0.5 L	6 minutes 30 sec
2	5.304 L	Leaves	5.304 L	0.192 L	1 minute 25 sec

Table 3 explains the detailed measurements of the initial and final volumes and the time taken for each type of waste during the compression process. The volume reduction test demonstrated that 10 plastic bottles with an initial volume of 12.285 liters were compressed to 0.5 liters in 6 minutes and 30 seconds, while 5.304 liters of leaves were reduced to 0.192 liters in 1 minute and 25 seconds. These results indicate that the compression tool effectively reduces the volume of both plastic and organic waste by over 95%, with leaves being compressed faster due to their softer texture compared to plastic. This highlights the tool's efficiency in minimizing waste volume, which can improve waste management processes.



CONCLUSION

The design and testing of the Smart Waste Sorter and Shredder with Pressing System demonstrated that the device can automatically sort plastic and leaf waste using a combination of ultrasonic, infrared proximity, and capacitive proximity sensors. The shredding system effectively processes plastics with low to medium thickness (approximately 0.3–0.5 mm) but is less effective on thicker plastics. The pressing feature works as intended, compacting shredded waste for easier packaging and space-saving. Additionally, the Arduino Uno-based control system successfully manages the operation of servos, stepper motors, and sensors, although additional electrical protection is needed to prevent short circuits.

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