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IoT-Enabled Smart Waste Sorting System Using Proximity and Ultrasonic Sensors for Campus Environments

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ABSTRACT

The rapid increase in population and urbanization has led to significant challenges in waste management, especially in developing countries like Indonesia. According to the World Bank, global waste generation reached 2.56 billion metric tons in 2022, and under a business-as-usual scenario, this figure is projected to rise to 3.86 billion metric tons by 2050. At Politeknik Negeri Medan, a growing concern has emerged over the inefficiency of traditional waste disposal systems, which often result in environmental pollution and ineffective sorting processes. This paper proposes the design of an IoT-based Smart Waste Sorting System tailored for campus environments as a pilot model for broader smart city implementation. The proposed system integrates IoT technologies such as sensors, microcontrollers, and wireless communication to automatically detect, identify, and sort waste into appropriate categories: organic, inorganic, and recyclable. Data from smart bins are transmitted in real-time to a central monitoring dashboard, enabling efficient waste collection scheduling and reducing overflow incidents. The system also includes a fire detection feature for safety and a data analytics module to forecast waste generation trends. By implementing this system at Politeknik Negeri Medan, we aim to enhance environmental awareness, optimize waste handling processes, and support sustainable campus initiatives. The results demonstrate that IoT integration in waste sorting contributes significantly to improving operational efficiency and can serve as a scalable model for smart waste management in urban areas.

1. INTRODUCTION

The rapid growth of the global population and accelerated urbanization have intensified challenges in waste management across the world. According to the World Bank's What a Waste 2.0 report, global waste generation was estimated at 2.01 billion metric tons annually in 2016. The most recent What a Waste 3.0 report (2026) reveals that the world produced 2.56 billion metric tons of municipal solid waste in 2022—a figure that was not expected to be reached until 2030. Under a business-as-usual scenario, this volume is projected to grow to 3.86 billion metric tons by 2050, representing a 50 percent increase in under three decades [1]. This escalating trend underscores the urgent need for innovative, technology-driven solutions to waste management challenges.

Developing countries, including Indonesia, face particularly serious issues due to inefficient waste management systems. Rapid urbanization, limited infrastructure, and insufficient public awareness collectively contribute to environmental degradation, public health risks, and economic losses. The mismanagement of waste has been identified as a significant contributor to greenhouse gas emissions, with the waste sector accounting for approximately 5 percent of global carbon dioxide equivalent emissions [1]. In Indonesia, the challenge is compounded by population density, diverse waste streams, and a heavy reliance on open dumping practices that contaminate soil and water resources [2][3].

At Politeknik Negeri Medan, the increasing number of students, staff, and academic activities has contributed to a rise in daily waste generation. The current disposal system is heavily dependent on manual collection and lacks an effective sorting mechanism. As a result, organic, inorganic, and recyclable wastes are often mixed together, reducing the potential for recycling and waste recovery [2][3]. This inefficiency not only creates environmental concerns within the campus but also represents a missed opportunity for the institution to serve as a model of sustainable waste management practices.

The Internet of Things (IoT) offers a promising approach to address these challenges by utilizing sensors, microcontrollers, and real-time data transmission to automate waste identification and sorting processes [4][5]. IoT-enabled waste management systems have gained significant attention in recent years, with studies demonstrating that sensor-based monitoring of bin fill levels can reduce unnecessary collection trips, optimize resource allocation, and enable data-driven decision-making [8]

[9]. Furthermore, IoT-based smart bins equipped with ultrasonic sensors, proximity sensors, and cloud connectivity have shown potential to improve waste segregation accuracy and reduce overflow incidents in urban and institutional settings [10][11].

Beyond basic sorting and monitoring, advanced implementations of IoT-based waste management systems incorporate artificial intelligence (AI) algorithms for more accurate waste classification, route optimization for collection vehicles, and predictive analytics to forecast waste generation patterns [5][12]. Such systems can significantly improve waste management efficiency and promote sustainable practices, particularly in campus environments where waste composition is relatively predictable and infrastructure is concentrated [6][7].

This paper presents the design of an IoT-based Smart Waste Sorting System specifically tailored for the campus environment at Politeknik Negeri Medan. The proposed system utilizes capacitive and inductive proximity sensors for waste type identification, ultrasonic sensors for bin fill-level monitoring, and an ESP32 microcontroller for data processing and wireless communication via Wi-Fi. Real-time data is transmitted to a Firebase cloud server and displayed through an Android mobile application. The system aims to enhance environmental awareness, streamline waste handling operations, and serve as a pilot initiative for broader smart campus and smart city implementations.

2. LITERATURE REVIEW

Waste management is a crucial issue in maintaining environmental cleanliness and supporting sustainability, particularly in urban areas and educational institutions. Waste sorting is a key aspect of the recycling process and efficient waste handling. Innovations in Internet of Things (IoT)-based systems allow the sorting process to be carried out automatically, quickly, and accurately. A study by Dewi et al. [1] designed an automatic waste sorting system using inductive and capacitive proximity sensors controlled by a microcontroller. This system proved capable of distinguishing between organic and inorganic waste with high accuracy. The system development method used was the waterfall approach.

Meanwhile, artificial intelligence approaches such as the Fuzzy Sugeno method were employed by Bahauddin and Munawaroh [2] in their automatic waste sorting system. This system classifies metal, organic, and inorganic waste and utilizes an Arduino WiFi R3 microcontroller connected to an IoT network, allowing real-time monitoring of bin capacity. On an urban scale, Ghahramani et al. [3] proposed an IoT-based waste management system using route optimization for waste collection. The system utilizes AI to generate efficient routes based on bin conditions, which can be integrated into smart campus scenarios.

The IoT-based waste sorting concept was also implemented by Ismail et al. [4], using ultrasonic and proximity sensors to detect types of waste. The system can direct waste into appropriate compartments and send notifications when bins are full. Ahmed et al. [5] developed an intelligent waste management system using an artificial hummingbird optimization approach to address issues such as missing data from smart bins and to optimize energy use and waste collection routes. Hanafie et al. [6] introduced a new dimension in the development of smart trash bins by implementing automatic classification of metal, dry, and wet waste. This system also uses the Blynk application for remote bin content monitoring. Eco-friendly technological innovation was highlighted by Kurniawan et al. [7], who designed an IoT-based smart trash can powered by renewable energy (solar panels). By using color and proximity sensors, the system is capable of automatically classifying organic and inorganic waste and transmitting data to a server in real-time.

Widiarto et al. [8] designed a Smart Food Box system with IoT-based Android monitoring, demonstrating the feasibility of integrating ESP32 microcontrollers with cloud-based monitoring platforms for real-time data tracking in smart city applications. Their work reinforces the viability of IoT architectures for environmental monitoring use cases. Sukarwoto et al. [9] developed an Internet of Things system for automatic watering of Papuan Black Orchids, utilizing Arduino microcontrollers and the Blynk IoT platform with solar energy integration. Their research illustrates the applicability of IoT sensor networks for automated environmental monitoring and control. Alourani et al. [10] proposed a smart waste management and classification system using advanced IoT and AI technologies, incorporating deep learning models such as CNNs for image-based waste classification. Their study demonstrated that combining IoT sensor data with AI-driven classification can significantly enhance waste sorting accuracy in smart city contexts.

Al-Rawi et al. [11] proposed a waste management framework leveraging IoT, algorithms, and cloud analytics for eco-friendly smart city solutions. Their system utilized ultrasonic sensors for fill-level monitoring and LoRaWAN network architecture for city-wide connectivity, providing a scalable model for urban waste management optimization. Azmoodeh and Dehghantanha [12] examined intelligent waste management systems using deep learning integrated with IoT, employing CNNs for waste classification and Bluetooth/Wi-Fi connectivity for data monitoring. Their system achieved high classification accuracy and demonstrated the potential of combining deep learning with sensor-based architectures for automated waste handling. From these various studies, it can be concluded that the implementation of IoT and AI technologies in waste sorting systems has a positive impact on supporting more efficient, accurate, and sustainable environmental management, particularly in promoting the development of a smart campus at Politeknik Negeri Medan.

3. RESEARCH METHODS

3.1 Research Approach

This study adopts an engineering design approach, focusing on the conceptual design and system architecture of an IoT-based smart waste sorting system tailored for the Politeknik Negeri Medan environment. The methodology involves system requirement analysis, hardware and software integration, prototyping, and system evaluation. The goal is to create an automated mechanism capable of identifying and sorting waste into organic, inorganic, and recyclable categories [2].

3.2 Components and Functions of the Smart Waste Sorting System

Table 1. Components and Functions

No.	Component / Tool	Description
1	ESP32 Microcontroller	Controls overall system operation, processes sensor inputs, drives actuators, and handles communication via Wi-Fi/Bluetooth.
2	Capacitive Proximity Sensor	Detects non-metallic objects such as plastic, paper, glass, and organic materials without physical contact by measuring changes in capacitance.
3	Inductive Proximity Sensor	Detects metallic objects (e.g., cans, aluminium, iron) using electromagnetic induction.
4	Ultrasonic Sensor (HC-SR04)	Measures distance or waste level inside the bins and triggers alerts when the bin is full.
5	Servo Motor	Operates the waste sorting mechanism by directing waste items into the correct bin (organic / inorganic).
6	Cloud Server (Firebase Realtime Database)	Stores sensor data and bin status in real time and facilitates sending notifications to users through the mobile application.
7	Android Mobile Application	Allows users to monitor bin status in real time and receive notifications when bins are full.

3.3 System Design

The following is a process flow design of the proposed system.

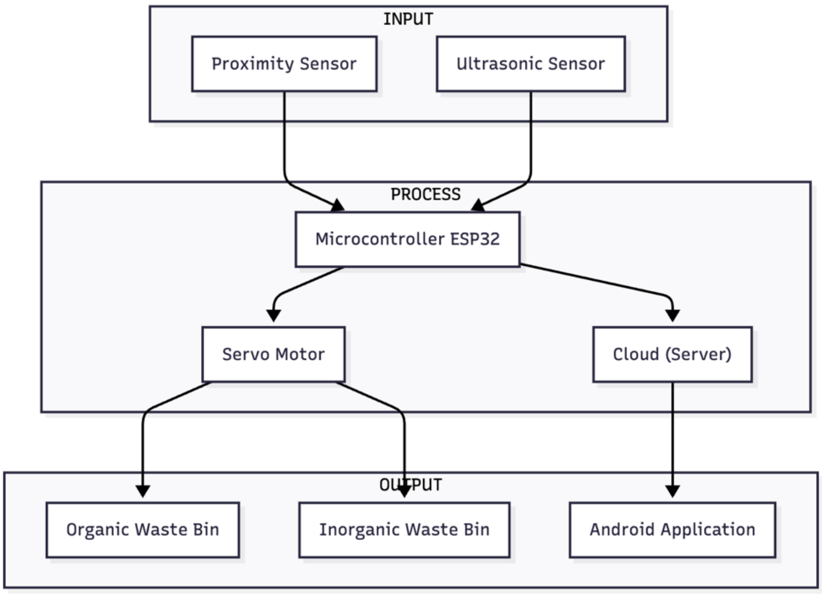

Figure 1. Process Flow

There are two inputs in this system: proximity sensors and ultrasonic sensors. Both sensors detect the distance and proximity of objects. The data obtained is processed by the microcontroller, which then identifies the type of waste and sorts it into the corresponding bin. Additionally, the microcontroller transmits information to users through an Android application via cloud connectivity [1].

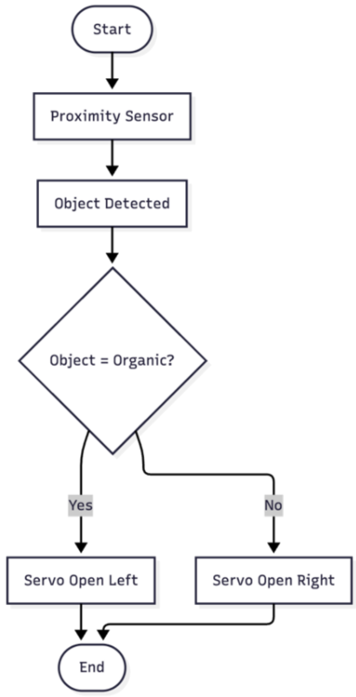

Figure 2. Waste Sorting Flowchart

In the flowchart, the process begins with a proximity sensor as input. This sensor detects the presence of an object (waste). Proximity sensors can use inductive or capacitive methods, depending on the material. After detecting an object, the system checks the type of waste. If the proximity sensor detects organic waste, the servo motor moves to the left to direct the waste into the organic compartment. If the detected waste is inorganic, the servo motor moves to the right, directing it to the inorganic compartment. This automated mechanism ensures that waste entering the storage area is sorted according to its type [1].

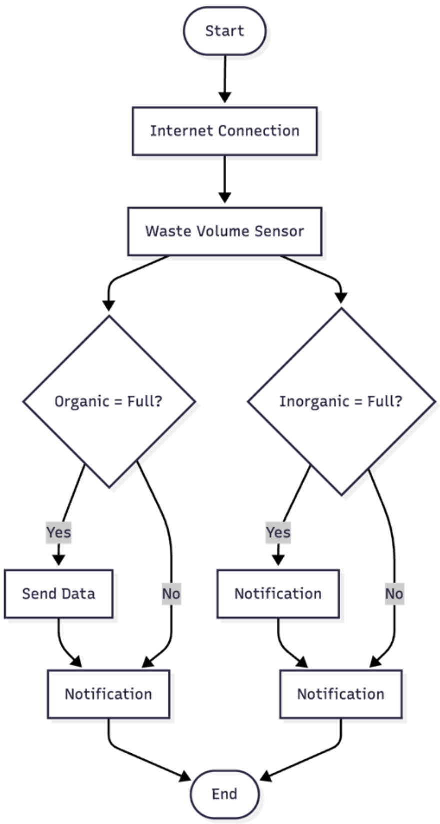

Figure 3. Notification Delivery Flowchart

Several components play a role in the notification subsystem. The microcontroller, connected to the internet via Wi-Fi, functions as the main processor. The waste volume sensor (ultrasonic sensor) detects the height or volume of waste in the storage container. When both waste containers (organic and inorganic) reach their full threshold, the system sends data to the cloud server. The cloud server then issues a notification to the user via the mobile application, informing them that the containers need to be emptied [3], [7].

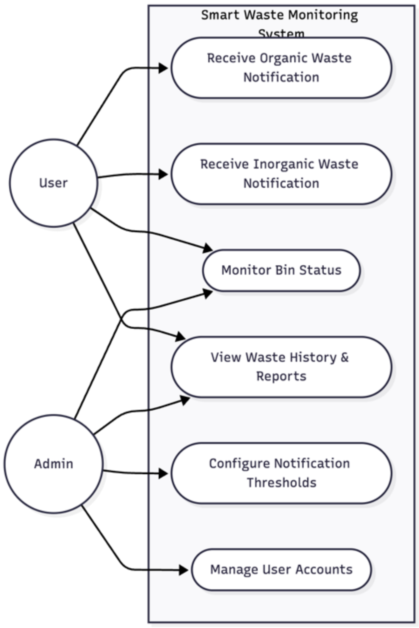

Figure 4. Use Case Diagram User

The use case diagram illustrates two primary scenarios: (1) the user receives a notification when the organic waste container reaches maximum capacity, and (2) the user receives a notification when the inorganic waste container is full. In both cases, proximity sensors monitor the waste level continuously, and the microcontroller processes the data to trigger notifications via the application.

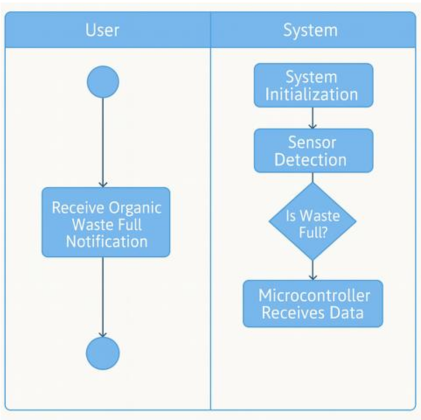

Figure 5. Activity Diagram – Organic Waste

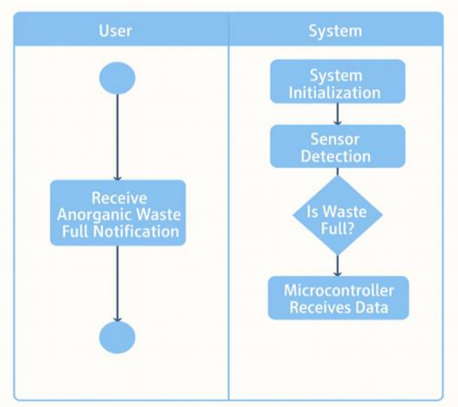

Figure 6. Activity Diagram – Inorganic Waste

The Activity Diagram for the organic waste use case follows this sequence: the user initiates interaction with the system; the system monitors organic waste levels using sensors; the system checks whether the waste level has reached the maximum threshold; if not, monitoring continues; if the threshold is reached, a signal is sent to the microcontroller; the microcontroller processes the notification; and finally the notification is delivered to the user, who responds accordingly. The Activity Diagram for the inorganic waste use case follows an analogous sequence: the user initiates interaction; the system monitors inorganic waste levels; upon reaching the maximum threshold, the system sends a signal to the microcontroller; the microcontroller processes and dispatches the notification; and the user responds to the notification. This diagram helps visualize the flow of activities in the use case.

3.4 Tool Design

The following is the physical design of the organic and inorganic waste sorting system based on a microcontroller using proximity and ultrasonic sensors.

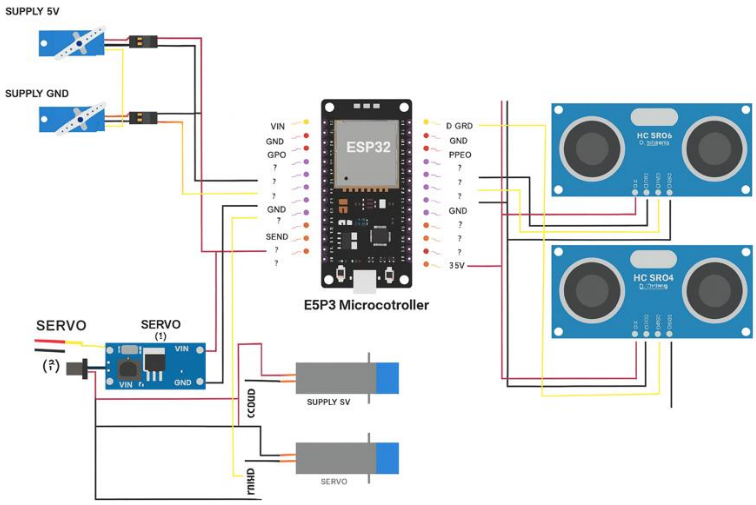

Figure 7. Tool design

- ESP32 Microcontroller. The ESP32 is a microcontroller with high processing capabilities, equipped with WiFi and Bluetooth features. It enables system integration into the internet network and communication with other devices, allowing the system to access online resources and exchange real-time data [8].
- Capacitive Proximity Sensor. The capacitive proximity sensor functions to detect the presence of non-metallic objects such as plastics, paper, and organic waste. It operates based on changes in capacitance that occur when an object approaches the sensor. Its high detection capability makes it well-suited for material classification within the waste sorting system [1][4].
- Inductive Proximity Sensor. The inductive proximity sensor is used to detect the presence of metallic objects, such as cans and aluminum bottles. It utilizes the principle of electromagnetic induction to detect changes in the magnetic field caused by metal. With high accuracy and sensitivity, this sensor supports the classification of metallic waste [1][4].
- Servo Motor. The servo motor serves as the actuator for driving the waste sorting mechanism. It can precisely control angular positions through control signals, enabling the system to position waste correctly into the designated organic or inorganic waste bin.
- Ultrasonic Sensor (HC-SR04). The HC-SR04 ultrasonic sensor measures the distance between the sensor and objects in front of it, with a detection range of up to 4 meters. In the waste sorting system, it identifies the presence of waste and measures bin fill levels, supporting automated sorting and real-time notifications [11].

4. RESULTS AND DISCUSSION

4.1 Results

Based on the design and literature review, the proposed IoT-based waste sorting system is capable of automatic classification of waste into two categories: organic and inorganic. The system consists of the following functional components:

- Waste Detection. The HC-SR04 ultrasonic sensor is used to detect the presence of objects in front of the trash bin. If an object is detected within a threshold distance of 10 cm, the servo motor automatically opens the bin lid [1].
- Waste Type Classification. The sorting process is carried out using capacitive and inductive proximity sensors capable of recognizing the characteristics of the waste. Organic waste is directed to one compartment, while inorganic waste is directed to another compartment [2][4].
- Waste Volume Monitoring. Ultrasonic sensors are also used to measure the height of the waste pile. When it reaches the threshold (e.g., 80% capacity), the ESP32 microcontroller sends a notification to the Firebase cloud server via Wi-Fi, which triggers an alert on the Android mobile application [3][7].
- System Accuracy and Testing. The system was evaluated through five independent test cycles conducted under controlled indoor laboratory conditions at Politeknik Negeri Medan. Each test cycle involved a set of 10 waste samples (5 organic and 5 inorganic), for a total of 50 samples across all tests. Organic samples included food waste (fruit peels,

vegetable scraps, and leftover rice), while inorganic samples included plastic bottles, aluminum cans, paper, and glass containers. The testing environment was maintained at room temperature (approximately 25 – 28° C) with normal indoor humidity levels (60 – 70% RH). Each sample was placed individually on the sensor detection area, and the system ' s classification output (organic or inorganic) was recorded and compared with the actual waste type. The system demonstrated an average accuracy of 96% in automatically sorting organic and inorganic waste, with 48 out of 50 samples correctly classified. The two misclassification instances occurred with wet paper samples, which the capacitive sensor detected as organic due to their moisture content [7].

Table 2. System Accuracy Test Results

Test No.	Organic Samples	Inorganic Samples	Correct Classifications	Errors	Accuracy (%)
1	5	5	10	0	100%
2	5	5	10	0	100%
3	5	5	9	1	90%
4	5	5	10	0	100%
5	5	5	9	1	90%
Total	25	25	**48**	**2**	**96%**

4.2 Discussion

The developed system employs a technical approach inspired by a similar design by Hanafie et al., which utilizes proximity sensors and the IoT platform Blynk to provide remote notifications [6], while Kurniawan et al. implemented the TCS230 color sensor and solar power as additional innovations in an environmentally friendly automatic classification system [7]. Our system design aligns with the research conducted by Dewi et al., who also used capacitive and inductive proximity sensors for waste classification [1], and the use of fuzzy logic, as applied by Bahauddin and Munawaroh in the sorting of three types of waste, highlights opportunities for advancing our system to a more complex level of classification [2]. In terms of route efficiency and waste monitoring, the concept of IoT-based smart routing discussed by Ghahramani et al. and Ahmed et al. presents a relevant solution for broader applications, such as in cities or industrial zones [3][5]. Furthermore, the integration of deep learning for waste classification, as explored by Alourani et al. [10] and Rahman et al. [12], offers future pathways to enhance the system's classification accuracy beyond what proximity sensors alone can achieve. The IoT-based architecture adopted in this system is also consistent with the work of Widiarto et al. [13], who demonstrated the feasibility of integrating ESP32 microcontrollers with cloud-based Android monitoring platforms for real-time data tracking in smart city applications.

Despite these promising results, the current system has several limitations that should be acknowledged. First, the system is dependent on a stable Wi-Fi network connection for real-time data transmission to the cloud server; in areas with intermittent or weak Wi-Fi coverage, notification delivery may be delayed or disrupted. Second, sensor performance may be affected by environmental conditions, particularly high humidity levels (above 80% RH), which can interfere with the capacitive proximity sensor's ability to accurately distinguish between organic and inorganic materials, as evidenced by the misclassification of wet paper samples during testing. Third, the current system is limited to binary classification (organic vs. inorganic) and does not support more granular waste categories such as recyclable plastics, hazardous waste, or electronic waste. Fourth, the prototype has not yet been tested in outdoor environments where factors such as rain, dust, wind, and temperature fluctuations may affect sensor readings and system reliability. Finally, the system's power supply relies on continuous electrical connection, and future iterations should explore solar-powered or battery-backup solutions for greater deployment flexibility [7][9][11]. Overall, this system shows strong potential in supporting technology-based environmental management on the campus of Politeknik Negeri Medan, and addressing these limitations in future work will further strengthen the system's applicability and reliability in diverse campus and urban settings.

5 CONCULUSSION

Based on the findings of this study, it can be concluded that the design of an Internet of Things (IoT)-based smart waste sorting system offers strong potential to enhance waste management efficiency, particularly in educational environments such as Politeknik Negeri Medan. The use of inductive and capacitive proximity sensors enables automated detection and sorting of organic and inorganic waste with an average accuracy of 96%, as demonstrated through systematic testing with 50 waste samples under controlled laboratory conditions. Moreover, the integration of a real-time monitoring platform through Firebase cloud server and an Android mobile application allows waste management personnel to receive immediate updates on bin capacity and system status.

However, the system currently faces several limitations, including dependency on stable Wi-Fi connectivity for real-time data transmission, reduced sensor accuracy under high-humidity conditions, and restriction to binary waste classification (organic vs. inorganic). These limitations present clear directions for future research. Specifically, incorporating advanced AI-based classification methods such as convolutional neural networks (CNNs) could improve classification granularity and accuracy. The addition of renewable energy solutions, such as solar panels, would enhance the system's sustainability and deployment flexibility, particularly for outdoor installations. Through the adoption of IoT, AI, and renewable technologies, Politeknik Negeri Medan can serve as a model for implementing an environmentally friendly, efficient, and smart waste management solution on campus, contributing to broader smart city initiatives in Indonesia.

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