



Research Article

Smart Garbage Segregation System Prototype Development

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Abstract

This paper presents the development of a TRL4-level prototype for a Smart Garbage Segregation System. This system has three functionalities in a single prototype: waste identification, waste segregation and smart data collection and management. It utilises capacitive proximity, inductive proximity, and moisture sensors effectively to identify and segregate various types of waste. It also collects valuable data for further analysis using an air quality sensor along with the other three sensors and IoT. The high accuracy of these sensors demonstrates reliable functionality in real-world scenarios, contributing to sustainability goals. The proposed prototype of the Smart Garbage Segregation System represents a significant step toward intelligent waste management solutions that address the growing challenges of waste disposal in urban environments while promoting environmental sustainability.

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INTRODUCTION

In the contemporary world, the exponential growth of urban populations and industrial activities has led to an unprecedented surge in waste generation ^[1, 2]. The issue of municipal solid waste generation is becoming increasingly critical, with predictions indicating a dramatic rise from 2.1 billion tonnes in 2023 to approximately 3.8 billion tonnes by 2050 ^[3]. This sharp

increase highlights the urgent need for comprehensive and effective waste management strategies. The management of this waste presents a significant challenge, especially in rapidly urbanising areas where infrastructure often struggles to keep pace with the increasing demands. Without substantial improvements in waste management, the annual cost could surge to USD 640.3 billion by 2050, emphasising the urgent

need for action to mitigate both financial and environmental impacts. Implementing effective waste prevention and management strategies could potentially lower these costs to USD 270.2 billion annually by 2050 [3, 4].

Traditional waste management methods such as open dumping, landfilling, open burning, and inadequate segregation are proving to be unsustainable as urban areas expand and waste volumes grow [5-7, 8]. Assessing the negative human and environmental health impacts of the prevalent solid waste management practices, the future of urbanisation. It finds that these practices, including mixed waste handling, inadequate storage and transport, and uncontrolled disposal, lead to significant pollution, land degradation, and public health risks, disproportionately affecting marginalised groups.

As cities evolve, there is a pressing need to implement more efficient waste management systems that not only handle the volume of waste but also minimise environmental impact and maximise resource recovery [9, 10]. Also, there is a critical need for more efficient systems to meet the Sustainable Development Goals (SDGs). Smart garbage management, which utilises advanced technologies like sensors and data analytics, directly supports several SDGs by improving waste collection efficiency, increasing recycling rates, and reducing environmental harm. This approach contributes to SDG 11 by promoting sustainable cities, SDG 12 by encouraging responsible consumption and production, and SDG 13 by cutting emissions from landfills. Additionally, it helps achieve SDG 6 by preventing water pollution and SDG 14 and SDG 15 by safeguarding ecosystems from waste-related damage [11, 12].

Many researchers have explored smart garbage management solutions that use advanced technologies like sensors and data analysis to address the inefficiencies and environmental challenges associated with traditional waste management systems. These smart solutions aim to optimise the collection, sorting, and recycling of waste, ultimately contributing to more sustainable urban environments.

One of the core technologies in smart waste management is the deployment of Internet of Things (IoT) sensors. These sensors are installed in waste containers to monitor their fill levels in real-time. By providing continuous data on waste accumulation, these sensors enable municipal waste management services to optimise collection schedules and routes. This not only reduces the frequency of waste collection trips, leading to lower fuel consumption and reduced greenhouse gas emissions, but also ensures that bins or containers are emptied before they overflow, thus maintaining public hygiene and reducing the risk of pest infestations [13, 14].

Another significant advancement in smart waste management involves automated sorting systems, which utilise machine learning algorithms and robotics. These systems are designed to automatically sort recyclables from non-recyclables and separate different types of materials such as plastics, metals, and glass. Machine learning models are trained to recognise and categorise waste materials with high accuracy, while robotics handles the physical separation process. This technological integration enhances the efficiency of recycling operations,

minimises contamination in recyclable materials, and increases overall recycling rates [15, 16].

However, these solutions still face numerous challenges, including inefficient collection systems, high contamination rates, inadequate recycling facilities, and environmental hazards due to improper disposal [6]. To address these issues, smart cities implement several strategies using data analytics, which further amplify the effectiveness of smart waste management systems by providing valuable insights into waste generation patterns and optimising management strategies. Through advanced data analytics, municipalities predict future waste generation trends, plan more effective waste diversion strategies, and tailor public engagement campaigns to promote responsible waste disposal that improves waste management efficiency and fosters greater community involvement in sustainability initiatives [17].

An innovative solution to waste management challenges is the development of a smart garbage monitoring, segregation and smart collection system designed for integration with IoT environments and capable of performing advanced analytics.

The development of such a low cost comprehensive "3-in-1" prototype for waste segregation that combines real-time IoT data collection, advanced analytics, and automated sorting capabilities is still in progress and not widely deployed [1, 18, 19, 16] designed an Automated Waste Segregator (AWS) for efficiently sorting house-hold waste into metallic, wet, and dry categories using advanced sensing technologies. The designed system uses an IR proximity sensor to initiate the sorting process, followed by a metal detection system and a capacitive sensing module to differentiate between metallic, wet, and dry waste. After identification, a circular base rotates to align the appropriate container, allowing the waste to be dropped into its designated compartment for separate collection and processing. [20] proposed a fully automated indoor waste management system using intelligent disposal outlets and a movable waste collecting robot. Ultrasonic sensors monitor bin levels, triggering the robot via Zigbee to locate and empty full bins using RSSI and a Wave Front Algorithm [21]. introduced an innovative IoT-based smart garbage monitoring system designed to optimise waste management processes. This system employs infrared (IR) sensors strategically placed within waste bins to accurately monitor the level of garbage. When the garbage reaches a predetermined threshold, the sensors trigger a notification that includes both the current status of the bin and its geographic location. This critical information is transmitted in real-time via Wi-Fi and GSM networks to a centralised web server, enabling waste management authorities to access up-to-date data on bin capacities across various locations. In addition, the system incorporates GPS tracking for collection vehicles, allowing for efficient routing and scheduling of garbage collection. [22] developed an autonomous indoor waste disposal robot with improved path planning using Fuzzy Logic Control. The robot designed using proximity, sound, and infrared sensors and controlled by a microcontroller unit for effective waste management [23]. presented an Automated Waste Control Management System (AWCMS) using IR sensors, GPS, and a

GSM module to monitor waste levels and locations. A central control unit with a GUI displays the bin status and location, enabling efficient and timely waste collection and disposal [24]. Proposed an IoT-based smart waste segregation and management system using ultrasonic, moisture, and metal sensors to detect and classify metal, plastic, degradable waste and moisture levels. The data is uploaded to the cloud in real-time, enabling efficient waste collection and disposal. [25] proposed an automated household waste segregator using a PIC16F877 microcontroller to simplify the process. To achieve effective waste identification and separation, the system is equipped with an array of sensors, including infrared (IR) sensors, moisture sensors, and metal sensors to identify and separate waste into metal, wet, and dry categories [26] proposed an IoT-based smart waste management system that uses ultrasonic and force sensors to detect bin fill levels and weight, respectively, triggering an alert via GSM to an Android app with GPS location. This enables efficient garbage collection by informing the appropriate vehicle about the location of full bins, thus improving hygiene and supporting cleaner environments. Although separate components of this system are operational, such as IoT-enabled waste bins in cities like Seoul and San Francisco for optimising collection routes, data analytics in Toronto for enhancing recycling strategies, and automated sorting systems in Japan and the Netherlands, there is no fully integrated solution that combines all three elements into a single prototype. This paper explores the prototype design of

such an integrated approach to waste management, considering an office environment. The prototype is called “smart garbage segregation system (SGSS)” and combines three core functionalities: waste identification, sorting, and data management. This prototype is developed to address all critical scaling issues and is tested in a relevant laboratory environment. Therefore, this prototype design stage can be assigned Technology Readiness Level 4 (TRL4). The organisation of the paper is as follows: Section 1 reviews relevant literature discussing the motivation behind the prototype design and paper organisation, Section 2 details the prototype design methodology, Section 3 presents the results, and Section 4 concludes with a summary of the findings.

Prototype Design methodology

The 3-in-1 SGSS prototype design of a TRL 4 level combines three core functionalities: waste identification, sorting, and data management. Designing a prototype for a smart garbage segregation system at TRL4 involves creating a functional model that demonstrates the key components of waste identification, sorting, and data management. This prototype, as shown in Figure 1, will utilise capacitive proximity sensors, capacitive moisture sensors, inductive proximity sensors, an air quality sensor and machine learning algorithms. Below is a detailed breakdown of each component and how they work together.

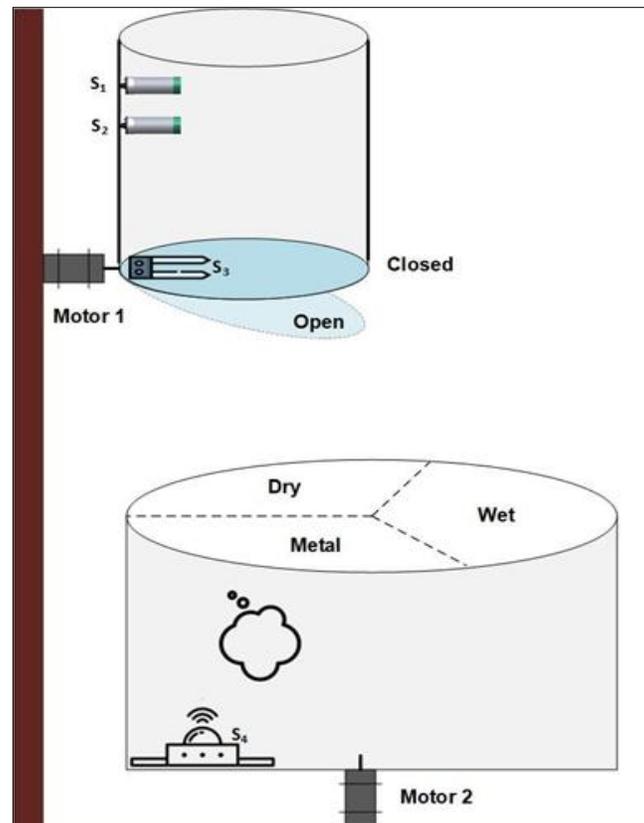


Fig 1: Diagram of the proposed Smart Garbage Segregator (SGSS) (S1: capacitive proximity sensors, S2: capacitive moisture sensors, S3: inductive proximity sensors, S4: air quality sensor, M1: Motor1, M2: Motor2)

Waste Identification

The first step in the prototype is waste identification, which utilizes capacitive proximity sensor. This sensor S1 is placed on the left side of the entrance of the bin, as shown in Figure 1. It measures the capacitance changes caused by the presence of various waste in proximity. When waste is placed in the system, the capacitive proximity sensor is used to detect the presence of waste, wet and dry waste, as well as metal waste, based on their dielectric properties.

1. **Wet Waste:** Capacitive sensors can detect wet waste as a result of its higher dielectric constant compared to dry waste. The presence of water significantly affects the capacitance measurement.
2. **Dry Waste:** Dry materials typically have a lower dielectric constant, allowing the sensor to differentiate them from wet waste. The change in capacitance can be measured when dry waste is present.
3. **Metal Waste:** Capacitive sensors can also detect metal, but they may not be as effective as they are with organic materials. Metals can influence the electric field around the sensor, causing a change in capacitance, although the detection range may vary depending on the type and thickness of the metal.

By calibrating the sensor with a diverse dataset of common waste types, the system can effectively identify the type of waste. The output of the capacitive proximity sensor is then sent to the Arduino board, which processes the data and prepares it for sorting decisions.

Waste Sorting

Once the waste has been identified, the next phase involves sorting, which is done by using one inductive proximity sensor and one capacitive moisture sensor.

Inductive proximity sensor, S2, is placed below the capacitive proximity sensor on the left side of the entrance of the bin, as shown in Figure 1. It detects metallic objects, by generating a magnetic field that can sense conductive materials. The sensor output a low signal when no object is detected and a high signal when a metallic object is within the sensing range hence allowing the system to efficiently segregate metals from other waste types.

The capacitive moisture sensor S3, on the other hand, assesses the moisture content of waste. Capacitive moisture sensors measure changes in capacitance caused by the presence of moisture. They consist of two conductive plates separated by a dielectric material. When moisture is present, it affects the dielectric properties and increases the capacitance. The sensor can measure this change to determine moisture levels. Hence, it can distinguish between wet and dry waste, ensuring that dry and wet waste are separated and sent to the respective waste bins.

The sorting mechanism involves servomotors as actuators M1 and M2 that physically separate the waste into designated bins based on the data received from the sensors. For example, if the system identifies a metal object, M2 will rotate the bin, and M1 will open the flap that leads to a metal collection bin. The flowchart in Figure 2 shows how the integration of these sensors allow the dynamic sorting of various types of waste.

In addition, we have integrated one air quality sensor, S4 at the bottom of the bin for garbage bin to significantly improve the ability to detect and identify foul odors associated with waste decomposition. This sensor monitors the air quality parameter of methane gas which is commonly released from organic materials. By providing real-time air quality data, the sensor can trigger alerts for timely waste collection and management, helping to mitigate unpleasant odors and prevent health hazards.

Smart Data Collection and Management

The last part of the prototype is data management, which uses machine learning to make waste identification and sorting better and more efficient.

By collecting data from the sensor assembly during the identification and sorting process, the system continuously learns and improves its waste classification algorithms.

For the developed prototype, sensor assembly data is transmitted to the Think Speak Internet of Things platform, where it is analyzed using Random Forest model. Random Forest model is one of the most commonly used due to its effectiveness in both classification and regression tasks. It is also robust and provides insights into feature importance, allowing it to handle both categorical and numerical data effectively, making it ideal for diverse sensor datasets. This analysis focuses on historical data to identify patterns in waste generation and composition, enabling fine-tuning of sensor calibration and sorting thresholds. In addition, the collected data are visualized through a user interface, offering insights into waste management trends, such as the temporal volume of various types of waste processed.

This visualization feature is instrumental for waste management authorities, facilitating informed decision making and supporting initiatives aimed at reducing waste generation and enhancing recycling rates. By linking real-time sensor data to predictive analytics, the system not only optimizes operational efficiency, but also contributes to sustainable waste management practices.

By integrating these three functionalities, identification, sorting and management into a single prototype, the system effectively demonstrates its capability to automate waste segregation while collecting valuable data for analysis. This comprehensive approach not only enhances efficiency, but also supports future scalability and real-world testing, aligning with the goals of TRL4 development.

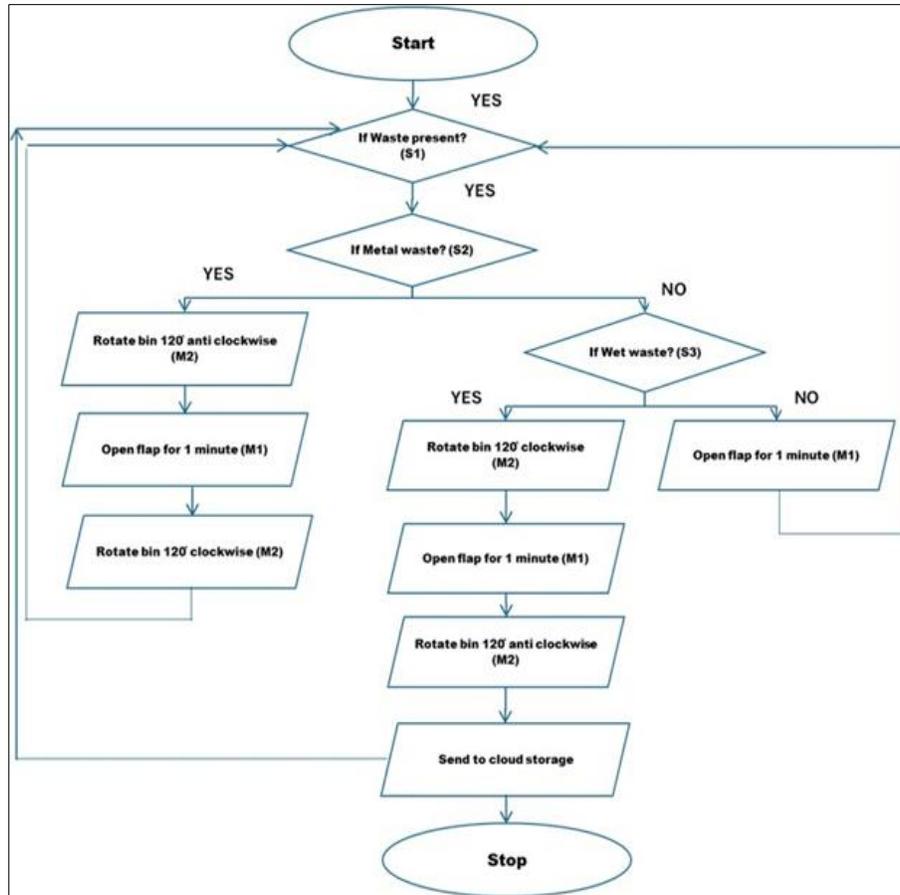


Fig 2: Flow Chart

RESULTS AND DISCUSSION

The development of the SGSS prototype effectively integrated capacitive proximity sensors, capacitive moisture sensors, inductive proximity sensors, air quality sensors, IoT and a

Random Forest algorithm. This combination enabled efficient waste identification and segregation and real-time monitoring, providing significant information on waste characteristics and management.

Table 1: Waste Item Classification

Waste Item	Metallic	Wet	Dry
Aluminium Foil	Yes	No	No
Steel Spoon	Yes	No	No
Cans	Yes	No	No
Coins	Yes	No	No
Key	Yes	No	No
Old Batteries	Yes	No	No
Paper Clips	Yes	No	No
Paper	No	No	Yes
Polythene	No	No	Yes
Glass	No	No	Yes
Wood	No	No	Yes
Cardboard	No	No	Yes
Packaging Paper	No	No	Yes
Dry Fabric	No	No	Yes
Wet Fabric	No	Yes	No
Banana Peel	No	Yes	No
Wet Tissue	No	Yes	No
Food Wrapper	No	Yes	No
Oil Impregnated Paper	No	Yes	No
Food Scrap	No	Yes	No
Plant Debris	No	Yes	No

This study aimed to evaluate the feasibility and performance of our smart garbage segregation system using a dataset comprising the List of item categories as in Table 1. The dataset was carefully created to represent a diverse range of real-world scenarios, including variations in lighting and object orientation. We have considered accuracy as our evaluation metrics. Mathematically, accuracy is calculated as:

$$\text{Accuracy} = \frac{\text{Correct Classifications}}{\text{All Classifications}} \quad (1)$$

The capacitive proximity sensor was used to detect various types of materials on the basis of their dielectric properties. The results showed an accuracy of 92% in identifying the waste entering the bin.

The inductive proximity sensor successfully identified metallic objects in the waste, achieving an accuracy of 88%. It consistently detected aluminum and steel, which are vital for recycling processes.

The capacitive moisture sensor assessed the water content in the waste, effectively distinguishing between wet and dry waste with an accuracy of 90%. This provided essential information about the composition of organic waste.

The air quality sensor monitored methane gas and issued alerts when concentrations exceeded safety thresholds. This provides readings that reflect the concentration of methane in the air, typically measured in parts per million (ppm). 1% methane equals 10,000 ppm for the air quality sensor used in the prototype.

Table 2: Summary of Sensor Performance

Sensor Type	Accuracy (%)
Capacitive Proximity Sensor	92
Inductive Proximity Sensor	88
Capacitive Moisture Sensor	90
Air Quality Sensor	99

Table 1 shows the classification of waste that may enter the bin in the chosen environment, and Table 2 shows the performance of the sensors used for the developed prototype. This data is displayed in the user interface using IoT. Random Forest model is used to predict waste generation patterns. This model is trained on the collected data from the sensors.

Figure 3 shows the developed prototype, where the integration of multiple sensors demonstrated a robust capability to identify, separate and analyse waste effectively. The high accuracy of the capacitive proximity sensor, inductive proximity sensor and moisture sensor highlights their effectiveness in identifying and segregating different waste types, which is essential for efficient recycling processes. The air quality sensor's ability to monitor harmful gas emissions adds another layer of safety and environmental awareness, ensuring that waste management practices do not adversely affect public health. Furthermore, the application of machine learning algorithms enhanced the system's capability to analyse historical data and predict waste generation trends. This predictive insight can inform future

waste management strategies, ensuring more effective allocation of resources and improving recycling rates.



Fig 3: Prototype of proposed Smart Garbage Segregator (SGSS)

CONCLUSION

This prototype effectively showcases its operations under essential environmental conditions, demonstrating reliable functionality in real-world scenarios. By integrating three core functionalities into a single system, the prototype automates waste segregation while simultaneously collecting valuable data for analysis. This comprehensive approach not only enhances operational efficiency but also supports future scalability and practical testing, aligning with the objectives of TRL4 development. Future work will focus on advanced sensor fusion techniques, alternative machine learning algorithms, real-time adaptation mechanisms, and enhancing the user interface to improve accuracy, performance, and user engagement in the system. Although there are some limitations, the system offers a promising foundation for developing more advanced and intelligent waste segregation solutions.

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