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A Low-Cost Multi-Sensor IoT System for Real-Time Segregation of Polymer Waste

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Abstract

Segregation of solid waste is a critical aspect of waste management, especially in settings where technical and financial constraints limit the adoption of sophisticated technologies. The proposed low cost, sensor-driven smart waste sorting system combines a variety of sensing technologies with an integrated decision-making system. The system employs an inductive sensor, moisture sensor and capacitive sensor to measure the physical properties of waste items, allowing segregation into metal, wet and dry polymer classifications. On the other hand, a rule-based decision system was created in Arduino to interpret the sensor data in real time, avoiding complicated ML approaches. A simple data pre-processing technique using sensor readings averaging was also introduced to enhance accuracy. The waste bins were also monitored through an IoT-based remote monitoring system. The system performed satisfactorily under different environmental conditions with 90 different samples with a 96.7% accuracy for metal, 90% for wet waste, and 86.7% for dry polymer waste. The average processing time was 1.5 to 2 s per item which means that it is fast enough to be usable. The research proves the feasibility of real-time waste separation with no complicated algorithm in a cost-effective way. The multi-sensor system achieves a good compromise between accuracy, simplicity, and scalability, suitable for deployment on a small, low-scale and low-cost.

Keywords: Waste segregation, IoT, multi-sensor system, arduino, polymer detection, smart waste management

INTRODUCTION

As society grows more urban and the population becomes more dense, more and more solid waste is being generated. This poses a problem for waste management in general. Within this problem, the absence of source separation and recycling is a major problem. Waste segregation is more complicated, laborious and time-consuming if there is no distinction of waste types.

The segregation of polymer waste, often referred to as plastics, encompasses the classification and sorting of plastic waste from other municipal waste categories, including organic waste, metals, mixed dry waste, glass, and similar types. Polymer waste typically involves polyethylene terephthalate (PET) bottles; polyethylene (PE) bags, films and sacks; polypropylene (PP) bottles, buckets, drums, and containers; and plastic packaging, among others. The segregation of polymer waste is important as plastics are non-biodegradable and need recycling through specific processes for their reuse or recovery. When polymer waste is mixed with wet waste or contaminated waste during segregation, the quality of the recyclable waste is reduced leading to a large amount of recyclable polymers going to landfill or being incinerated, thereby wasting resources and potentially polluting the environment. [1–2].

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Since most plastics take a lot of time to biodegrade and break down, the improper disposal of polymer and plastic waste may have a significant negative environmental impact. The waste ends up in a landfill site and in the drainage system, river, or ocean and remains there for a long time. This can lead to drain blockage that contributes to flooding in cities. Moreover, animals may ingest plastic waste and cause themselves severe harm or may even die in the case of marine and terrestrial waste ecosystems. Eventually, plastics can degrade into microplastics. These plastics, then, can be easily ingested and get into the food chain and have negative effects on human health. Moreover, plastic waste burnt openly also emits harmful fumes as well as greenhouse gases and adds to air pollution and global warming. Therefore, segregation and recycling of polymers is very important to minimize damage and achieve sustainable waste management of resources and waste [1–3].

In recent times there have been various ways to deal with this challenge, especially in the field of smart waste segregation. These technologies could include the Internet of Things (IoT), machine learning, or image classification technology to identify and sort out the types of waste automatically. While these methods can be highly configurable and have higher levels of classification performance, they tend to have higher energy requirements, network connectivity issues, and require more consistent operating conditions. Hence, their usage in low-cost and low-resource scenarios can be difficult.

On the other hand, simpler sensor-based systems have also been considered as a viable alternative because of their low cost and ease of installation. However, these systems often use a single sensing dimension, and are therefore unable to account for the variability and complexity of real-life waste streams. For instance, certain materials (such as plastics) can lack strong and consistent features for classification using a single type of sensor, resulting in classification errors.

To this end, there's a need for a trade-off solution that would enable effective waste segregation without making the system too complex. The current study meets this need by offering a multi-sensor system for waste segregation that incorporates various types of sensors and an efficient decision-making algorithm. The platform considered for the system is an embedded system, which makes the system feasible for real-time applications with low computational power.

This work is focused on the classification and segregation of dry polymer waste, which can be challenging to sort using traditional approaches. The proposed system, by taking into account several physical properties of the material, seeks to enhance classification accuracy and reliability.

Additionally, the inclusion of IoT features allows for basic sensing, which in turn enables system monitoring. The purpose of this study is to propose a feasible, low cost and scalable design for waste segregation. The main focus of designing the system was to run the system in the places such as a classroom, workplace, and local townhouse where sensors and internet connectivity are not always easily obtained.

RELATED WORK

In today's world, urbanization and industrialization have resulted in a considerable increase in the quantities of waste generated. This increase in the volume as well as variety of solid waste presents several environmental and operational issues. Waste collection and sorting processes today are still largely manual, inefficient, and laborious. They also frequently result in poor waste disposal. In order to tackle these issues, there are a few proposed automated segregation system for waste. They utilize advanced technologies such as Internet of Things (IoT), Artificial Intelligence (AI), and embedded system in a bid to improve their performance in terms of efficiency, accuracy, and environmental impact.

Research on this topic was initially focused on sensor-based waste separation systems which employed sensors such as moisture sensors, inductive sensors, and proximity sensors to distinguish between waste types namely wet, dry, and metallic waste. The systems were relatively cheap and simple

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and were designed to be developed on microcontroller platforms. These systems have the disadvantage that, while they can sort wet and dry waste and metallic waste from non-metallic waste, they cannot be used to sort out different types of materials, such as polymers, because they share the same physical properties as those of the other materials to be segregated. A few vision-based methods relying on image processing and deep learning have been suggested as a solution to this problem which provides improved classification performance, but are computationally demanding and may not be suitable for real-time and low cost applications.

Aruchamy et al. (2024) [4] explored hybrid polymer composites incorporating bio-fillers such as palmyra palm leaflet fibers, coconut sheath fibers, and tamarind shell powder to improve both the mechanical and environmental attributes of composites. The polymer matrix was epoxy resin, and a composite fabrication technique was used for developing composite materials from the natural bio-reinforcements. The composite materials were evaluated for their mechanical properties including tensile strength, flexural strength, impact strength, inter laminar shear strength, hardness, and the water absorption behavior of the developed materials were measured.

The results indicated that the addition of natural fibers and bio-fillers in the proper amounts helped to enhance the performance and mechanical strengths of the composite materials, which would lead to environmentally friendly and efficient use of the material. The paper also discussed the potential of using composite materials, which are lightweight and high strength, to replace metal in industrial applications, thereby reducing the environmental impacts of the manufacturing process and the use of such materials. However, the management of waste, recycle mechanism, and tracking of the polymer waste materials were not explored in the work.

Ayrilmis and Kanat et al. (2024) [5] explored the idea of waste manhole cover powder and medium density fiberboard sawdust as reinforcing filler materials for recycled polypropylene based polymer composites. They were interested in the use of the polymer composites for sustainable material applications. They analyzed how different fillers affected the mechanical strength, thermal stability, and water absorption properties of the recycled polymer composites.

As the fillers were increased, it was found that there was an increase in the bending strength and stiffness of the polymer composites with the composite material displaying good thermal stability and low water absorption behavior. The work proved that waste-based polymer material had good potential for sustainable applications. In addition, it was found that recycled polymer materials had different physical and structural behavior under the effect of different materials.

This work and other similar works indicate that polymer wastes must be handled carefully in order to enable a good understanding of the properties of materials, and intelligent material waste segregation and identification system should be designed so as to separate polymers and polymer materials so that these materials can be reused for recycling and other purposes.

Ramasubbu and Kayambu et al. (2024) [6] investigated the employment of waste-based reinforcing constituents in recycled polymer composites while assessing their physical, thermal and moisture absorption properties in relation to different formulations. Changes in the polymer content as well as the proportion of the filler are found to influence the structural, as well as the physical properties of a polymer. The experimental results reveal that despite the addition of the waste materials in polymer composites, the recycled composites perform steadily and therefore encourage environmentally friendly waste management and recycling.

In this case, polymers possess identifiable material properties. Thus, the results can be utilized in applications that involve material identification such as the smart separation of waste materials for recycling, where polymer-containing waste dry materials are identified and separated using the sensor-based approach for the effective management of the waste materials.

According to Palanisamy and Murugesan et al. (2024) [7], it is imperative that sustainable polymer composite materials are studied for their ability to minimize the damage posed to the environment when compared to traditional synthetic materials. They provide a review of polymer composite material characteristics and processes along with a discussion of the importance of correct recycling and handling techniques to minimize environmental impact. In addition to this, various properties of the materials are discussed, such as structure and mechanics, along with their relevance to material handling processes. They also discuss the importance of waste handling and segregation and how it could potentially reduce the amount of damage caused to the environment through improper polymer waste disposal.

However, while their work focuses on the environmental perspective of sustainable polymer composite materials and the recycling aspects, there is relatively less focus on automated real-time segregation systems and automated monitoring of polymer waste. The above observations can be seen as a justification for the development of sensor-based and IoT-based systems as a means to increase the efficiency of automated segregation and recycling.

Palanisamy and Kalimuthu et al. (2022) [8] carried out research that produced sustainable, natural fiber reinforced polymer composites with kenaf and banana fibers in epoxy resin. The research also considered the influence of different fiber concentrations on composites' material properties, as well as the moisture absorption characteristics and mechanical durability of polymer composites. The study revealed that the efficient use of polymer applications is dependent upon material composition, appropriate polymer processing, and use of sustainable materials. The study emphasized that effective polymer management, and the recycling of waste polymer materials, are necessary for sustainable waste processing and waste environmental management.

The research however concentrated on the development of polymer composite fabrication and polymer composites performance characteristics; the research did not focus on the development of an automated polymer waste material identification, segregation, and monitoring system. Therefore, it would be useful to utilize polymer waste material segregation through intelligent sensor technology and the Internet of Things.

However, Alfaidz et al. (2025) [9] presented a method of solving this problem by proposing an Internet of Things (IoT) smart bin with sensor fusion and mobile app support. They state that while single sensor-based systems are not able to distinguish all materials present, using a combination of these sensors can detect the material using multiple different features. Although this has improved classification accuracy, there is a gap in polymer waste segregation research.

Chavan et al. (2024) [10] proposed a sensor and data analytical system to be utilized in real-time in order to enable waste segregation and recycling. According to them, real-time monitoring will allow for the proper collection of waste, which will result in a less environmental burden. Likewise, Suthar et al. (2023) [11] discuss ways in which IoT-based technologies may reduce waste from plastics; thereby highlighting how valuable such technologies might prove in promoting the general practice of sustainable waste management.

Sharma et al. (2025) [12] identify some shortcomings of IoT-based smart dustbins. The authors also describe the benefits, including lower costs and better public health outcomes, but they also point out some disadvantages, including higher upfront costs for deployment, ongoing maintenance costs, and some people's unwillingness to embrace new technologies, and they argue that the real-world practicality and ease of use for these systems must be ensured.

Dhanshe et al. (2025) [13] developed the IntelliWaste Optimization System to make it easier to sort waste with the use of IoT sensors that utilize deep learning for image processing. The device classifies

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waste and also uses ultrasonic sensors to determine when waste bins are full, and provides users with a web interface to visualize the data collected from the waste bins. By integrating both sensors and machine learning, the system can more efficiently carry out its function.

Another system developed by Devi et al. (2025) [14] can incorporate this integration by incorporating the Internet of Things, artificial intelligence, and blockchain to the waste management system. Such a system allows for real-time monitoring, predictive modeling, and secure data tracking that could promote greater transparency and accountability in waste management systems, and in doing so supports circular economy goals of recycling and resource preservation.

Predictive analytics has proven to be a powerful method of optimizing waste management. Suganya et al. (2025) [15] apply linear regression and IoT data to predict and schedule garbage collection. The authors show strong results and argue that data-driven decision-making contributes to more efficient waste management.

With regard to automation of waste collection systems, Oorkavalan and Subramaniyan (2015) [16] studied the use of machine learning techniques along with robotic technology to automate waste sorting. Their approach detects various waste items through smart-classifiers and sorts them automatically with little need for manual handling. This could make high-throughput waste processing much more efficient, though there are costs to implementing and operating the systems, not to mention other considerations including technical difficulties, data privacy issues, and regulations, suggesting that robotic automation might be more suitable in industrial-scale environments and less so in public collection systems.

Sankar and Fathima (2024) [17] developed the IoTBinCap algorithm to optimize waste collection; this method gathers data from IoT sensors placed inside bins. Their system processes data from these sensors to optimize garbage collection schedules based on the current status of the waste bins and thus can eliminate empty routes that would have otherwise been taken for full bins. The resulting dynamic waste collection can result in energy savings, cost savings, and environmental protection from pollution. The research shows that data-based optimization has great potential to make IoT systems much more efficient.

Oise et al. (2025) [18] take an analytical perspective on the use of IoT and deep learning to facilitate waste management. They discuss potential benefits and challenges of machine learning for waste classification, noting that machine learning models depend on high quality data in large amounts, and that the black box nature of such models makes the results difficult to interpret and could lead to challenges in implementation. The authors also argue that interpretability tests are necessary for these systems so that reliability and scalability of results can be determined.

In terms of real-world implementation, Wasai and Yohannis (2025) [19] studied the use of IoT-based smart waste bins in practice. They found that while the waste bin systems perform well overall in terms of accuracy, several factors impact their success. In particular, environmental factors such as light and humidity, coupled with sensor aging, can influence the system’s performance. User behavior also impacts performance; specifically, incorrect use of the waste bin affects the system’s performance. The implication is that IoT-enabled waste bin systems must be designed to account for real-world conditions and user behavior.

To improve the system’s capability by adding functionality, for example odor control and fire detection capabilities, in addition to waste bin separation capabilities, Vinnarasu (2024) [20] propose the development of the EnviroTech system. These added capabilities increase the safety and usability of the system, making it better suited for use in public settings. This additional functionality suggests the potential for smart waste bins to act as versatile devices for environmental monitoring.

To extend the technology stack to multiple technologies, Ikenna et al. (2025) [21] combine IoT, Artificial Intelligence (AI), robotics, and blockchain technologies. Their design promotes data sharing between the various system components and automation for the waste processing stages. They found that the combined use of these technologies could potentially lead to more efficient waste collection, less contamination, and higher recycling rates, but also that the system design and implementation complexity could increase.

Yadav et al. (2025) [22] discuss the value of AI-based predictive analytics in waste management applications. They demonstrate how machine learning-based predictive models use historical data and real-time information from the sensors to predict waste disposal patterns. Such predictions facilitate proactive decision-making by improving planning operations and resource allocation, as well as enabling sustainable public practices in the form of minimizing the environmental impact of operations.

Idoko et al. (2024) [23] discuss the technological challenges of scalability of IoT-driven waste management systems. The study identifies critical factors that could be hindering widespread adoption, namely low levels of internet connectivity, lack of standards adoption, and incompatibility between different systems. These barriers would reduce the effectiveness of communication and the overall reliability of the systems as they scale.

Recent automation advancements are further exemplified by WasteXpert Auto (2025) [24], which utilizes robotics, IoT, and AI to facilitate the identification and sorting of waste in real time. This system boasts high efficiency levels when deployed within laboratory settings thanks to its automated sorting mechanism. However, the widespread implementation of such systems is limited by their high operational costs, energy demands, and maintenance requirements.

Sosunova and Porras [25] conduct a systematic review of IoT-based waste management systems to explore architectural considerations in this field. They identify that effective IoT-based waste management systems require integrating a network of sensors, communication networks, and data management and visualization platforms to be able to develop an efficient system, while stressing the importance of engagement of relevant stakeholders including the end-users, local authorities, and operators of the system.

In a similar vein, Shaikh and Ali (2025) [26] propose a system integrating IoT, AI, blockchain, predictive analytics, and geofencing technologies as a solution for waste management. Their solution leverages geospatial-based technology to improve monitoring and resource allocation. They demonstrate that combining technologies can help solve the multiple challenges of the contemporary waste management.

Last, but not least, Sharma and Kashyap (2025) [27] discuss the use cases of the system, assessing the impact of smart waste bins on waste management and public sanitation. They found there are many advantages and disadvantages such as high initial capital cost and low users acceptance that must be addressed to successfully implement them.

Singh et al. (2024) [28] also describe the creation of smart bins with gas sensors that can determine waste types by measuring gas emissions, which provides another way of sorting waste, specifically for organic matter and decomposable waste although it is not well suited for polymer waste.

Additionally, Arpitha et al. (2025) [29] have designed an automatic waste segregation system that uses different sensors and actuators under the control of an Arduino microcontroller, demonstrating that relatively inexpensive embedded systems can perform basic segregation, and could therefore be appropriate in low resource scenarios.

Ushasree et al. (2024) [30] examine IoT-based smart bins for landfill management and indicate that they can be effective in reducing waste overflowing since waste volumes can be constantly monitored to determine when waste collections need to be done. It also supports on-time waste collection planning so as to avoid waste collection on empty trucks, increasing recycling possibilities but network stability and maintenance requirements are some of the constraints that hamper its scalability. From this extensive review on literature, it is clear that the IoT and AI-based systems for waste management have made great progress. Yet, there are limitations such as the detection of polymer waste, the issue of scalability, cost efficiency, and real-time deployment. The existing systems are often very complex or do not have a good multi-sensor decision making for an easy deployment. Thus Table 1 demonstrates the review of the gaps in the current studies and the requirement of the proposed system.

This summary illustrates the necessity of an IoT-enabled intelligent waste segregation system that is affordable and scalable with enhanced polymer sensing capabilities, and this forms the basis of the research objectives.

Table 1. Research gap analysis of existing waste management systems.

Author (year)	**Key contribution**	**Identified gap**	**Research need**
Aruchamy et al. (2024)	Developed sustainable hybrid polymer composites	No automated waste segregation system	IoT-based polymer segregation system
Ayrilmis and Kanat et al. (2024)	Developed recycled polymer composites using waste fillers	No intelligent polymer identification	Sensor-based polymer classification
Ramasubbu and Kayambu et al. (2024)	Evaluated recycled polymer composite properties	No real-time segregation approach	Smart IoT-enabled waste monitoring
Palanisamy and Murugesan et al. (2024)	Reviewed sustainable polymer recycling practices	Limited automated segregation focus	Intelligent polymer segregation system
Palanisamy and Kalimuthu et al. (2022)	Developed natural fiber reinforced polymer composites	No IoT-based waste segregation	Sensor-based recycling management system
Alfaidz et al. (2024)	Sensor fusion-based smart bin	No focus on polymer-specific detection	Material-specific classification (polymers)
Chavan et al. (2024); Suthar et al. (2024)	IoT-based monitoring & recycling optimization	Limited classification intelligence	Smarter decision-making mechanisms
Sharma et al. (2025)	Smart dustbin challenges	High cost, usability issues	Low-cost, user-friendly design
Dhanshe et al. (2025)	AI + IoT (deep learning-based classification)	High computational requirements	Lightweight real-time models
Devi et al. (2025); Ikenna et al. (2025); Shaikh & Ali (2025)	IoT + AI + Blockchain integration	High system complexity	Simplified, scalable hybrid systems
Suganya et al. (2025); Yadav et al. (2025)	Predictive analytics in waste management	Focus on prediction, not segregation	Improve real-time segregation accuracy
Oorkavalan & Subramaniyan (2025)	Robotics-based segregation	Expensive, low scalability	Cost-effective automation alternatives
Sankar & Fathima (2024)	Route optimization (IoTBinCap)	Focus only on collection efficiency	Improve waste identification at source
Oise et al. (2025)	Review of AI-based systems	Lack of explainability, dataset issues	Interpretable and practical models
Wasai & Yohannis (2025)	Real-world IoT implementation	Environmental dependency	Robust adaptive systems
Vinnarasu et al. (2024)	Smart bin with safety features	No improvement in classification logic	Enhanced sensing mechanisms
Idoko et al. (2024)	IoT scalability challenges	Interoperability and connectivity issues	Standalone embedded solutions
Singh et al. (2024)	Gas sensor-based detection	Limited to organic waste	Polymer-focused sensing
Arpitha et al. (2025)	Arduino-based segregation system	Basic classification only	Multi-sensor intelligent logic
Ushasree et al. (2025)	IoT-based landfill optimization	Monitoring-focused, not detection	Pre-segregation improvement

Research Gap

The data comparison in Table I highlights that even though substantial research has been carried out on IoT-based and artificial intelligence (AI) smart waste management, many issues still exist in the current work. Most of the work is centered on machine learning or deep learning algorithms, which demand heavy computational processing, adequate resources, and higher expenses for implementation. Although sensors are a low-cost alternative to machine learning or deep learning methods, most of the research concentrates on a single or few sensing mechanisms. It has been observed that during the classification of heterogeneous and partially mixed wastes, the performance of such systems degrades. The sensing mechanisms do not always distinguish between polymers, thus, there is a lack of consistent classification performance for the polymer category as well.

Also, it was noted in several research papers that research has been carried out for the purpose of waste monitoring, monitoring at the waste bin, or optimization of waste collection. While there are some advantages to these approaches, it is not emphasized much for the purpose of smart waste segregation at source, which is crucial for the improvement of the recycling system and reduction of post-collection handling cost of wastes. Moreover, most approaches do not focus on reducing the cost of the system, the continuous need for Internet connectivity to perform segregation, limitation in scalability, and the influence of ambient conditions for reliable performance of the systems that are deployed in a controlled environment are not considered. Many times, the waste material to be detected may not be clearly distinct, the environmental conditions in the field may be different, and a variety of mixed material compositions can be present. This implies the lack of extensive exploration in combining different sensing mechanisms that can be deployed for a specific low-cost and low-computation embedded platform.

In addition, there is limited research done on the sensing of polymer category wastes and segregation of dry polymer wastes. This highlights the requirement of a cost effective and scalable system that combines different sensing mechanisms and processes the outputs using a low computation embedded system to perform waste segregation in real time for specific polymer waste, which is the motivation of the current research work and will be discussed in this paper.

Research Objectives

The objective of this work is to develop and implement a low-cost and IoT-based smart waste segregation system capable of performing polymer classification using a multi-sensor-based embedded approach. Specifically, the research work presented is focused on the following objectives:

1. To design a multi-sensor waste segregation system for IoT based smart waste management on Arduino.
2. To improve the recognition of dry polymer wastes using capacitance sensing and other sensors.
3. To create a real time sensor based embedded classification method.
4. To evaluate the feasibility and functionality of the designed system in a real time scenario.

METHODOLOGY

The design of the proposed system was driven by a desire to develop a functional and cost-effective system for segregating waste and can withstand real-life application. Unlike some previous work, this work relies on a simpler scheme of sensors to acquire information on waste characteristics, which is then analyzed locally by a processor to take a decision to act upon.

The system design started with considering several approaches for waste categorization including a vision-based approach and a scheme that relies on the usage of a single sensor for classification. Both these options were considered at the start as they appeared to be a good starting point. However, after conducting further investigations it is noticed that the vision-based techniques are computationally expensive and require the usage of additional components to ensure proper illumination. Thus, an affordable system based on the use of multiple sensor signals to determine the category of the incoming waste material was considered.

During preliminary trials and testing, it was found that the single-sensor based methods are generally prone to inaccurate waste classification. To address this issue, the design of a classification system that is based on a scheme that combines the readings from a number of distinct physical sensors was proposed. The system is comprised of the integration of number of sensors that are capable of sensing different waste-related physical properties into an embedded controller. Multiple sensors are used as each of them will be able to detect certain physical property. When their individual information is added together, it forms the basis for waste classification. For example, the inductive sensor is used to detect the waste objects that contain metal parts, the moisture sensor determines the object's moisture content, while the capacitance value of the waste object determines the dielectric nature of a particular material (e.g., dry polymer wastes).

Based on this, Figure 1 also shows that the proposed system operation can be divided into three different operational stages: the sensing stage, the decision-making stage, and the actuation stage. In the sensing stage, a data acquisition unit is employed to obtain the necessary sensor data that will be processed later. The decision-making stage then takes the sensor data as input in order to determine what category of the waste material is passed through the detection zone. This processing is then carried out by the microcontroller that uses logic equations to identify the different categories of waste materials. The actuation stage is triggered by the output of the microcontroller. Depending on the type of waste detected, an actuation device such as a servo motor, or DC motor may be activated to push the waste in to the appropriate waste bin. The connection between the sensors, Arduino board and the actuation device is illustrated in Figure 1. This shows that sensor data is used to generate an actuation signal to control the waste bin mechanism that will separate different waste types from each other.

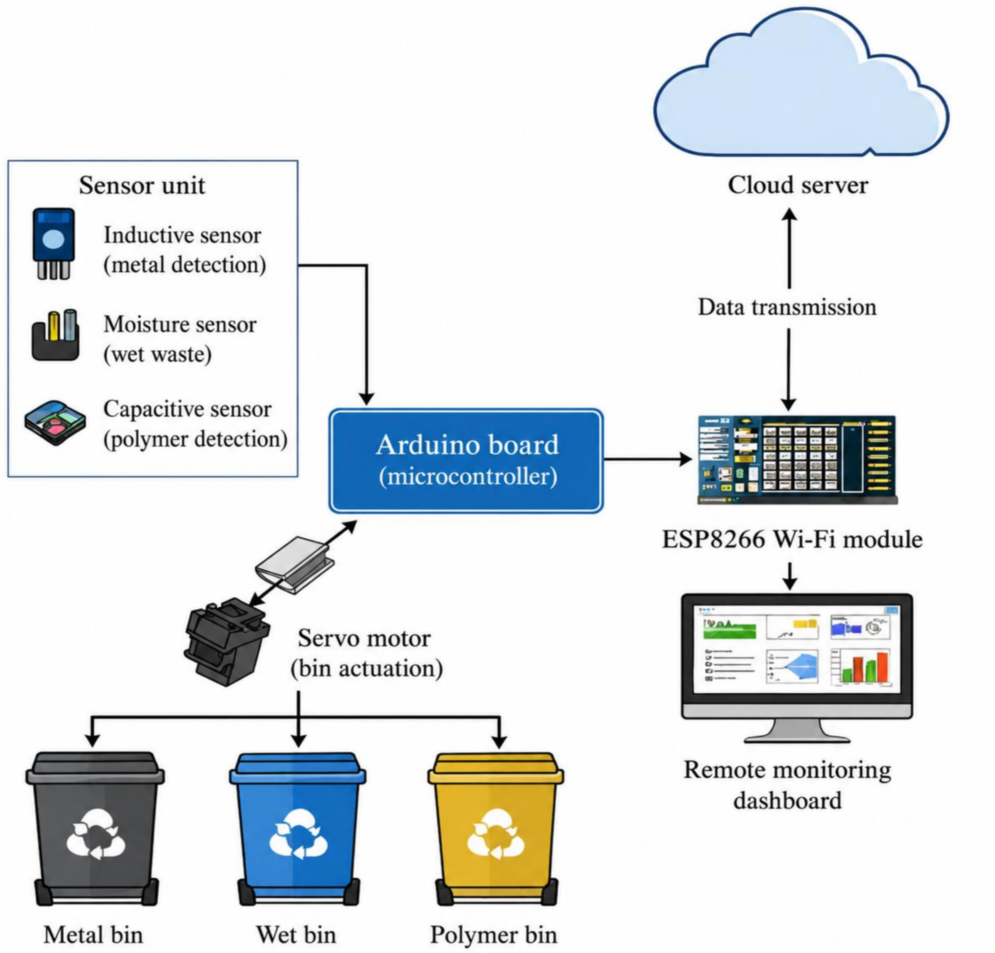

Figure 1. System architecture of the proposed multi-sensor IoT-based system.

Waste categorization is performed using the sensors and based on that the sequential decision making approach was used. This strategy gives priority to the detection of materials that can be unambiguously identified, such as metals detected by the inductive sensor, while it then proceeds to evaluate waste features that are more variable, such as those of water or plastics detected by moisture and capacitance sensors, respectively. The use of a sequential decision scheme simplifies the decision-making procedure and thus improves the efficiency of the system. This approach is characterized by its straightforwardness, repeatability, and flexibility. The system is simple to deploy and manage, without the need for elaborate computer systems. In addition, the design of the proposed system allows for the future incorporation of further equipment, including sensors or microcontrollers, according to requirement and application.

Data Acquisition using Sensors

The proposed approach to waste segregation system relies mainly on the effective data acquisition with different sensors. This system is based on utilizing a variety of sensing types for different parameters instead of single parameter based on the preliminary findings of using sensors individually in real-life scenarios of mixed waste and waste items of various shape and sizes.

The inductive sensor is used to detect metallic wastes due to the inductive nature of sensing, it detects metals regardless of dirtiness on metal items. During testing, it was observed that the sensor readings were stable and repeated with the same object, hence it is used as the first stage of sensor based classification.

The moisture sensor is used for the purpose of finding wet waste in the proposed system by measuring the presence of moisture, however certain situations were observed where partially dried food or slight dirtiness of plastic waste provided intermediate sensor values during testing. Thus, the readings are sampled for short durations to obtain the average values and avoid fluctuations and improve on the stability of classification for the system.

The capacitive sensor is used for the purpose of finding dry plastics based polymer waste in the system as it is designed to respond to changes in dielectric properties of the material. During testing for various polymer materials, the system provides different approximate values of capacitance, however it was observed that clean and dried plastic materials provided stable readings, and mixed or layered material provide varied readings but still can be used in conjunction with other sensors.

The polymer waste materials are identified through capacitive response in combination with other sensor responses. Different polymer materials exhibit different capacitance as they have different dielectric characteristics depending on their molecular composition and structure. When a material is placed at the sensing point of the sensor, it alters the electric field in the proximity of the sensor's sensing surface, leading to a change in the measured capacitance, the difference in capacitance response of different polymer materials helps differentiate polymer waste from other dry wastes as well as metallic and wet waste [31–32].

However, the purpose of using the capacitive sensor here is to identify the polymer wastes from dry waste and segregate them as a separate waste class in the proposed waste segregation system, rather than classifying the polymer waste types into various polymer types. In order to reduce the error and to further validate the capacitive response of a sensor in real-world conditions, the rule-based decision making of a system is performed with moisture sensor and inductive sensor outputs as well. With the help of multiple sensors, the classification accuracy and reliability are increased. Additionally, the error due to the noise level, external contamination, or environmental conditions is effectively reduced [31–32].

In addition to the three sensors, the system is equipped with a ultrasonic sensor to detect the bin fill

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level. While the sensor has no function in the waste classification but is useful to monitor the system and for better functioning. In order to improve the efficiency of data acquisition, a simple filtering method was used in software to sample and average sensor values within short durations instead of taking instantaneous values. It was observed that this helped to reduce noise levels and stability of the classification of waste.

Data Processing and Decision Logic

In the proposed system, waste classification is achieved by implementing a rule-based decision-making policy on the Arduino microcontroller. The purpose of this phase is to interpret the information provided by the sensors in the data acquisition system and decide on a particular type of waste in a reliable way.

In the initial stages of development, it was found that the direct classification based on the raw sensor readings was not always reliable as it could be affected by small variations and environmental conditions. To resolve this problem, an initial stage of data acquisition was introduced where several sensor readings are taken in a short period of time and an average is used as the input to the decision making process. This helps to smooth out variations and enhance stability.

In the decision-making process, a sequence of decision making is adopted, as shown in Figure 1. This order was established after experimentation and it was discovered that some waste types, such as metals, are detected with greater certainty than others. This can help boost the overall detection accuracy of the system.

The classification is done in the following way:

1. The inductive sensor reading is checked. A high output value signifies a metal waste and the object is classified as metal.
2. If the item is not metal, the moisture sensor value is compared to a threshold value. A high value is a sign of wet waste.
3. If the sample is dry, the value of the capacitive sensor is checked. If this value is within the experimentally determined range for polymer materials, then the waste is identified as dry polymer waste.
4. If the sensor reading does not fall into any of the clear categories, the waste is classified as dry waste to prevent incorrect classification.

As depicted in Figure 2, the system evaluates the sensor readings in a sequential manner. The sorting process starts with metal detection, then proceeds to moisture detection and finally dry polymer using capacitive sensors. Depending on the result of this process, the system sends control signals to trigger the sorting system and route the waste into the corresponding waste bin. When sensor responses are ambiguous, a default classification is used to prevent misclassification.

Testing revealed overlapping sensor responses in some extreme scenarios, such as partially wet plastic or mixed waste. In such scenarios, the threshold limits were refined, and moisture information was deemed more important than capacitance values in case of conflict between the two sensors. This increased the confidence of the decision logic in real world situations.

Actuation Mechanism

The actuation mechanism of the proposed system separates the waste physically following the decision given by decision logic, through the actuation mechanism where a servo motor positions the waste into its respective waste collection chamber. A servo motor was chosen for this purpose as it offers angular control and is compatible with Arduino.

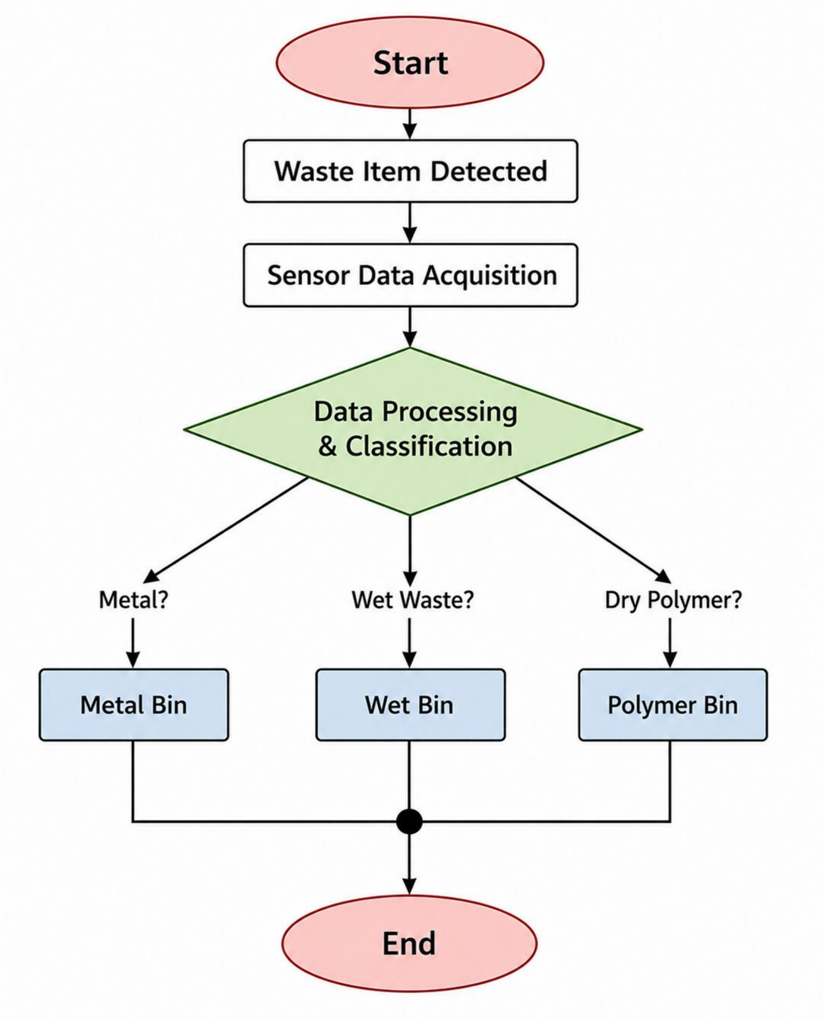

Figure 2. System flowchart of the proposed waste segregation system.

The developed prototype moves the servo motor to a set position, where each position represents a particular type of waste (i.e., metal, wet waste or dry polymer waste). Once a waste is detected and categorized, it is fed by the microcontroller to the servo motor in order to rotate. Initial testing shows that an accurate positioning of the servo motor is very important in achieving the objective of segregation. Even a small error in angle might lead to improper segregation of the waste from one another in different waste chambers. Therefore, the servo angle values were set up after various trials to give correct functioning with the optimal angles.

The mechanical design involves a chute or flap connected to the servo shaft to direct the waste, which is allowed to fall from the sensing chamber into the designated waste bin. Once the waste is put in the bin, the servo motor is returned to its home position, completing one cycle. There is a time delay between each operation, in order for the mechanical parts to settle down and to ensure that the items do not overlap with each other.

Another problem noticed while testing was the diversity of size and shape of waste. For example, a thin plastic waste sometimes swayed off the chute because of wind or misalignment. To mitigate this, the chute was modified to control the guidance better. In summary, the actuation mechanism provides an effective means to automate segregation. With the classification system based on sensors, the complete process of classification and segregation can proceed continuously.

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IoT Integration

The proposed system uses Internet of Things (IoT) capabilities for remote monitoring and reporting. While waste classification and segregation is primarily done locally on the Arduino, IoT integration enables a better overview into system operation and utilization.

In the developed prototype, a Wi-Fi device (such as the ESP8266) is attached to the Arduino and communicates with a cloud service. The device is used to transmit system information such as waste type classified and status of waste collectors. These information is transmitted at regular intervals, or once the waste is classified depending on the system settings. Design considerations prioritized minimizing reliance on internet availability, as it might not be readily available in many places where the system might be deployed. For this purpose, the system can perform all its functions, including sensing, decision-making, and actuation, even in offline.

IoT connectivity is just a support, not mandatory to the functioning of the waste segregation system. A rudimentary user interface on the cloud, displaying the number of items identified, types of items identified (metal, wet, polymer), and bin fullness can be provided to monitor waste. This helps in identifying trends in waste accumulation, thereby aiding in schedule planning of waste collection. In addition, alerts can be triggered when the bin fullness crosses a threshold, thus increasing the effectiveness of waste management operations.

During experiments, it is noticed that a very high data upload rate results in increased network and energy consumption. Hence, the system uploads the data only on detecting a significant change in bin status or at regular intervals of a certain number of learning cycles using a simple optimization algorithm. Thus, the role of the IoT subsystem in the proposed system is meant to be a minimal and supporting role. This helps in making the system cost effective, more reliable and efficient while being able to provide useful monitoring and data accessibility.

RESULTS AND ANALYSIS

The experiments were designed in order to evaluate the proposed system under more realistic scenarios rather than ideal cases. Different kinds of waste were considered while performing the experiments, including items with different materials, surface textures and shapes. This enabled us to analyze the behavior of the proposed system under real-world situations typically seen in a waste segregation system. Besides checking the effectiveness in classifying waste, experiments also focused on the performance consistency of the proposed system. In an embedded system, performance consistency matters just as much as accuracy over a long-term usage. Hence, multiple trials were performed for each category and results were carefully noted down.

Experimental Setup

The prototype, including the sensing unit, microcontroller (Arduino board) and actuation unit, were assembled for this experiment. Waste samples were placed at the entry of the system. The samples were placed at the entry such that the entry path is similar for all samples during the experiments. Samples were chosen such that they represent typical waste items found in real world.

Items chosen to represent metal waste include aluminum cans and other small metal objects which may vary in shape and corrosion status. Food scraps and vegetable peels were chosen to represent wet waste. Partially dried scraps of food might be included to represent practical scenarios. Plastic bottles, wrappers and other small thin objects were considered for representing dry polymer waste, which can vary in physical and electrical characteristics.

Overall, 90 samples were used: 30 samples for each type. In each case, sensor responses, classification, and actuation results were recorded. Not only accuracy, but also any anomalies or delays were noted.

Table 2. Classification performance.

Waste Category	Total Samples	Correctly Classified	Accuracy (%)
Metal Waste	30	29	96.7%
Wet Waste	30	27	90.0%
Dry Polymer Waste	30	26	86.7%

Classification Accuracy

The classification accuracy was measured by comparing the result of the system with the actual class of the waste. The results are shown in Table 2.

As can be seen, the system is quite good in detecting metallic waste. This is not surprising, given the inductive sensor gives a very strong and consistent response, which is largely independent of surface conditions.

The results for the detection of wet wastes were also good, but there were some irregularities. Due to some materials being partially dry or having non-uniform moisture content, the readings were close to the threshold, thereby making it difficult to classify. However, averaging the sensor readings overcame the problem.

The classification accuracies obtained for various waste categories in our proposed system are illustrated in Figure 3. It is evident from the figure that metallic waste shows the highest classification accuracy because of the accurate performance of inductive sensing. On the contrary, the performance of the proposed model for detecting dry polymer is less compared to other categories because of a wide range of polymer type in dry waste. Dry polymer waste classification showed slightly low results. Because it doesn't show specific sensor reactions as other two wastes: metals and wet wastes.

The thickness, density and surface finish of the polymer material affected the capacitive sensor measurements, resulting in some misclassifications. However, given the low cost and simplicity of the system, the results obtained are satisfactory.

Response Time Analysis

To determine the real-time capability of the system, the response time was also considered. For this research, the response time is defined as the time taken from the moment an item of waste enters the sensing zone to the time sorting is completed. According to experimental results, the average response time is about 1.5-2 seconds per waste item. This includes the time taken for sensor data collection, sensor data stabilization, decision logic execution and the servo movement.

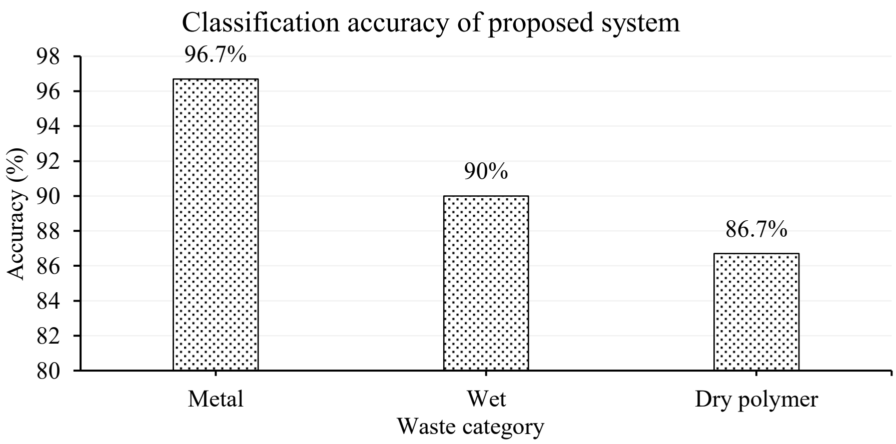

Figure 3. Classification accuracy of the proposed system for different waste categories.

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It was also noticed that the response time was quite similar for various types of waste, as the same process flow is adopted in all cases. There were slight differences when the sensor data required more samples to be taken to stabilize the data. In practical terms, the response time is adequate for low- to medium-waste generation spaces, such as small institutions and controlled public areas. Potentially higher speed systems may require further improvements.

IoT Monitoring Performance

The IoT performance was tested in terms of data transmission and remote monitoring. The Wi-Fi module was tested to transmit classification results and bin status to the cloud. During this stage, we found that the system relied on network connectivity. Data transmission was seamless with stable network connection but experienced delays with intermittent connectivity. However, as the main classification process is performed locally, this did not hinder the main system operation.

To optimise the process, data was only transmitted when major events occurred, such as end of classification or large changes in bin status. This reduced network traffic and also led to power savings.

Discussion

The study suggests that the developed system provides an affordable and feasible approach for automated sorting. The use of multiple sensors and a straightforward decision-making strategy allows the system to classify with reasonable accuracy with limited processing power.

The simplicity and practicality of the system is a key advantage. The simplicity of the system, with commonly available components and simple processing, allows it to be used in resource-constrained environments. The modular design also facilitates future upgrades, such as the addition of new sensors or increased processing power. Some limitations were identified, especially with mixed and uncertain wastes. These are common issues in rule-based systems, and suggest future improvements, perhaps involving hybrid systems or more sophisticated sensors.

Overall, the system achieves its goal of delivering an affordable and real-time waste segregation system, with a good balance between accuracy, simplicity and implementation.

CONCLUSION

This paper described a sensor-based smart waste segregation system that attempts to offer a low-cost and feasible solution for real-time waste segregation. The design is centred on the integration of different sensing technologies and a straightforward rule-based decision-making process, without the need for complex and computationally demanding techniques.

The results suggest that the system can successfully classify various types of waste with satisfactory accuracy. Specifically, the system could reliably identify metallic waste, and with reasonable accuracy could classify wet and dry polymer waste, taking into account the variability of their physical characteristics. The use of multiple sensors, and simple signal processing (such as averaging) helped to stabilise the classification.

The simplicity and practicality of the system are also noteworthy. The choice of an Arduino-based platform and low-cost sensors enables the system to be deployed in small-scale applications such as schools, offices and community areas. Furthermore, the Internet of Things (IoT) feature of the system allows remote monitoring of the bins to help improve waste management strategies.

The proposed system shows acceptable performances in most cases, but in few cases where there was a mixture of waste, or the waste was a little contaminated, the accuracy dropped. Thus, better sensing and decision-making techniques could be considered for further enhancement of proposed system. The proposed system can be further enhanced either by adding more sensors or using lightweight intelligent methods, without adding much complexity to the system. This prototype can be a starting point towards the development of similar systems, that may be customized and scaled depending upon the application and industry needs.

FUTURE SCOPE

The system as proposed in this study proved to be a good solution for waste segregation under the tested conditions. However, it can still be improved. The current system uses just a set of sensors and simple decision-making rules, but it has the potential to do much more. While these rules are currently adequate to achieve the expected result, the ability of these simple rules in differentiating between waste streams with ambiguous properties remains unproven.

One possible improvement would be the incorporation of a wider range of sensors in order to better capture characteristics of the waste. For example, the optical or visual sensing could aid in discriminating between different types of plastic and plastic composites, especially where electrical parameters are not distinguishable. Another possible approach would be the study of adaptive decision making. Currently, the system relies on experimental threshold values, which could change under different conditions. Lightweight machine learning approaches could be implemented to provide adaptive decision-making to the system to make it more robust and reliable.

The mechanical design of the proposed system could also be improved in terms of actuation mechanism to handle waste items of different sizes, shapes and weights better. Further development of mechanical structure to increase durability and adaptability can also make the system better suitable to deploy in different environments. Finally, the IoT-based monitoring could also be exploited for more meaningful purposes than just monitoring the system operation. By integrating with centralised waste management system using data analytics, it can monitor and analyze waste generation patterns in real time. This can be utilized by waste collection companies for better resource planning.

The current work, as presented in this paper, provides a basic prototype for a waste management system. With further enhancement in sensing and intelligent systems in a phased manner, it can evolve into a much more intelligent system to deal with the complexities of modern waste.

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