Research Article

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A Novel Automated Solution for Biomedical Waste Management

P. Padmapriya[1*], D. Banupriya[1], J. Saminathan[1], John William[2], Manoharan Loganathan[3] and R. Pavithra[4]

[1]Department of Biomedical Engineering, SRM Institute of Science and Technology (Deemed to be University), Ramapuram Campus, Chennai, TN, India

[2]Department of Computer Science and Engineering, CK College of Engineering and Technology, Cuddalore, TN, India

[3]Department of Electronics and Communication Engineering, Hindustan Institute of Technology and Science, Coimbatore, TN, India

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*padmaprp1@srmist.edu.in

ABSTRACT

Efficient management of biomedical waste is essential for ensuring public health and environmental safety. With the growing volume of biomedical waste, effective segregation methods are increasingly necessary. This project focuses on developing an automated biomedical waste segregation device utilizing Arduino technology and sensors. The device categorizes biomedical waste into three distinct types: dry, wet, and metal. An infrared motion sensor identifies the type of waste based on preprogrammed characteristics, while an LCD provides real-time updates on the segregation status. Extensive testing with various types of biomedical waste has demonstrated the device's ability to accurately and efficiently allocate waste to the appropriate bins. Leveraging Arduino and sensor technologies, this system offers a cost-effective and practical solution for biomedical waste segregation. This innovation holds particular promise for addressing waste management challenges in developing countries, where effective biomedical waste handling is a pressing issue. In summary, this project illustrates the potential of using Arduino-based systems for biomedical waste segregation. The device has proven to be reliable, efficient, and economical, offering significant benefits for both public health and environmental safety.

Keywords: Arduino; Biomedical waste segregation; Environmental safety; Infrared motion sensor; Public health.

1. INTRODUCTION

The automated biomedical waste segregation device marks a paradigm shift in waste management. By leveraging automation and technology, it provides an innovative solution to a pressing global challenge. As the world moves toward greater sustainability and environmental care, this device represents a significant step forward, ensuring a safer and cleaner future for all. (Saha *et al*. 2017) Waste management is defined as the strategy for managing solid waste and offering feasible solutions to repurpose items that do not belong to garbage. It involves utilizing waste as a valuable resource while ensuring safe and economical disposal of materials. For over a century, researchers have been working on waste management and, for the past forty years, on waste utilization analysis. There are eight key techniques for waste management: reduction and reuse, animal feeding, recycling, composting, fermentation, landfilling, incineration, and land application. Recent advancements have integrated IoT solutions to enhance the efficiency of waste management processes at various stages. (Khan *et al*. 2021) The rapid growth in the global population has led to inadequate waste management, causing environmental pollution and health issues. Traditional waste collection practices, involving weekly pickups, often result in overflowing bins and street litter. To address this, a smart and efficient waste management solution utilizing IoT and machine learning is proposed. The system employs an Arduino UNO microcontroller, ultrasonic, and moisture sensors. Image processing techniques assess waste levels at dumping sites, and a hardware prototype demonstrates the proposed model's potential for creating clean, pollution-free cities. (Kumari *et al*. 2018) Waste management has emerged as a critical global challenge due to population growth, urbanization, and changing lifestyles. This paper introduces an IoT-enabled solution for automating and optimizing waste management processes. The proposed system alerts users and authorities when bins reach capacity or detect unusual conditions, such as elevated temperature or humidity. A multi-layered architecture supports data collection, providing dashboards and alerts to help manage waste efficiently while reducing manual intervention. (Fernandez-Gonzalez *et al*. 2020) Organic waste is the dominant component of municipal solid waste, and its recycling presents an alternative to landfills, supporting goals outlined in the European Circular Economy Package. This study reviews scientific literature from 1980–2019, highlighting advancements in composting technologies, particularly those aimed at reducing environmental emissions. It emphasizes the growing focus on using organic waste for biogas production, reflecting a shift towards sustainable waste

management practices. (Gondal *et al*. 2021) Urbanization poses significant challenges for waste management as cities face increasing waste volumes. Traditional manual methods are inefficient and costly, necessitating automated waste classification systems. This study proposes a hybrid AI-based model utilizing a multi-layer perceptron and convolutional neural network (CNN) for real-time waste categorization. A camera-based system captures images of waste for classification, enabling effective recycling and landfill reduction. (Abou-Nassar *et al*. 2020) The integration of advanced technologies like IoT, blockchain, and cloud computing has revolutionized various sectors, including waste management. This study introduces a Blockchain Decentralized Interoperable Trust (DIT) framework that enhances reliability, security, and interoperability in IoT-based waste systems. The framework addresses semantic gaps and ensures trustworthy data exchange within interconnected networks. (Kumar *et al*. 2021) Smart cities demand robust waste segregation systems to tackle environmental pollution and promote recycling. This research utilizes the YOLOv3 algorithm in the Darknet neural network framework for classifying six waste categories: cardboard, glass, metal, paper, plastic, and organic waste. Results confirm YOLOv3's superior accuracy compared to its variants, validating its potential for efficient waste classification in real-world scenarios (Chauhan *et al*. 2021). The generation of hazardous healthcare waste, especially during the COVID-19 pandemic, has underscored the need for effective disposal methods. This paper identifies seven key principles for a smart healthcare waste management system, integrating circular economy perspectives to recover value from disposables. The DEMATEL method evaluates these principles, addressing the dual challenges of waste recovery and infection prevention. (Malik *et al*. 2019). Supply chain complexities demand reliable systems for tracking product life cycles. TrustChain, a blockchain-based trust management framework, assigns dynamic reputation scores to supply chain participants, ensuring traceability and integrity. This approach provides a robust solution to data trust issues, enhancing transparency in supply chain operations. The challenges of implementing blockchain and IoT in food supply chains highlight concerns related to information quality and trust. Based on a meat supply chain project, it suggests solutions that emphasize practical applications over fundamental truths, redefining the perception of data authenticity. Leveraging insights from an Australian meat export initiative to China, the study advocates for a shift from historical indicators to forward-looking insights to enhance trust and promote behaviors aligned with desired outcomes (Powell *et al*. 2021). Proportionate Data Analysis (PDA) as a method for managing heterogeneous healthcare data transmissions in IoT-assisted healthcare systems. PDA leverages linear regression to categorize data streams into variations and errors, facilitating efficient handling of diverse data. By periodically differentiating and classifying time intervals, it ensures a high service response rate by separating errors from variations. The method's performance is evaluated using metrics such as accuracy, identification ratio, delivery efficiency, variation factor, and processing time (Kumar *et al*. 2022). Proportionate Information Examination (PDA) for handling heterogeneous medical services information transfers in IoT-helped medical care frameworks. PDA utilizes direct relapse to group information streams into varieties and mistakes, empowering proficient treatment of shifted information. Intermittent separation and order of time stretch to keep a high help reaction proportion by isolating blunders from varieties. The technique's presentation is surveyed utilizing measurements like precision, distinguishing proof proportion, conveyance, variety of components, and handling time (Gao *et al*. 2020). A fog-assisted Computational efficient Wearable sensor network (FCE-WSN) for monitoring athletes' health using IoT technology. Wearable devices continuously monitor heart rate, respiratory frequency, and movement cadence during physical activity. Data collected by sensors is transmitted to an IoT-connected Ethernet module, allowing authorized individuals to access and track athletes' health via the Internet. The analytical model presented minimizes computing costs while maintaining health data accessibility in fog and cloud computing environments. The system's performance is evaluated using a queuing-based assessment method, demonstrating its user-friendliness, reliability, and cost-effectiveness for regular use (Li *et al*. 2020). The potential of smart cities and connected communities to enhance waste management practices. It introduces a conceptual framework for an integrated waste management system comprising three key components: infrastructure for capturing product lifecycle data, innovative business models leveraging this data to minimize waste, and sensor-based systems for efficient waste segregation and collection. The framework underscores the importance of aligning waste management with the entire product lifecycle, highlighting the value of lifecycle data in waste reduction and recovery optimization. The study also examines the role of tracking and data-sharing technologies in addressing waste management challenges and identifies critical success factors for implementing the proposed framework. Additionally, it offers recommendations for future research in this field (Esmaeilian *et al*. 2018). The transformative potential of the Internet of Things (IoT) and cloud computing in addressing the challenges of solid waste management in urban areas experiencing rising waste generation due to population growth. It provides a comprehensive review of waste management models and IoT infrastructures discussed in existing literature. Emphasis is placed on enhancing efficiency, minimizing collection costs, and fostering citizen participation. The study presents an IoT-based reference model and evaluates existing solutions to highlight key methodologies and identify research gaps in this domain. (Pardini *et al*. 2019). an innovative waste management

approach that leverages machine learning and graph theory to predict waste levels in trash bins, optimizing waste collection routes for greater efficiency. Deployed at Ton Duc Thang University in Vietnam, the system utilizes LoRa modules for data transmission to assess performance. The proposed solution offers benefits such as low cost, user-friendliness, and time savings through effective route optimization for waste collection (Khoa *et al*. 2020). This paper presents an Internet of Things-enabled control system that uses a flyback DC-DC converter with active clamping to manage a 250 W photovoltaic system. Real-time monitoring and output voltage regulation are implemented by an ESP32 microcontroller, which sends data to a web server. The system improves adaptability by allowing users to remotely modify converter output. Flexible voltage control, online performance tracking, and effective power conversion are some of its main benefits, which make it a good option for intelligent PV systems. Strong potential for scalable solar applications was indicated by the results, which showed steady operation and successful IoT integration (Silva *et al*. 2020). The study "Smart Garbage Monitoring System using Internet of Things (IoT)" suggests a smart technology-based, effective approach to urban waste management. The system uses an Arduino microcontroller, ESP8266 Wi-Fi module, GSM, and ultrasonic sensors to monitor garbage levels in real time and send alerts via a web interface. By doing away with manual monitoring, it saves money, time, and labour. A buzzer sounds and a GSM warning is sent to local authorities when bins exceed a predetermined threshold. With the help of programs like "Swachh Bharat Abhiyan," the system encourages hygiene and stops overflow. With its optimised collection routes, the design provides an affordable, scalable, and energy-efficient solution for efficient urban garbage management (Chaware *et al.* 2017). It describes a low-cost smart garbage can for public areas that uses PIR, ultrasonic, and Arduino Nano sensors. In addition to logging data and giving user feedback via audio messages, it detects fill levels and, when full, sends SMS notifications via GSM. The system, which is battery-operated with optional solar charging, improves user involvement and sanitation effectiveness. It is appropriate for scalable smart waste management solutions due to its straightforward design and dependable operation (Samann *et al.* 2017). Using a mixed methods approach that includes field studies and surveys, the research identifies key practices such as following project drawings, reducing design changes, providing waste skips for specific materials, and maximizing on-site material reuse. Factor analysis revealed four key factors influencing waste management practices: contractual provisions, waste segregation, material reuse, and efficient logistics. The study provides strategies for implementing each practice, offering guidance to construction site managers and workers in reducing waste generation (Ajayi *et al*. 2017). This study examined consumer recycling behaviour by examining the effects of recycling receptacle placement and quantity on plastic bottle disposal in three university campus buildings. In contrast to other research, this study did not rely on signage to encourage recycling and instead carefully regulated the quantity of bins. The results showed that recycling rates were not significantly impacted by merely adding more recycling containers or altering their appearance in public spaces. However, when bins were positioned directly inside classrooms, there was a noticeable rise in the recycling of plastic bottles, underscoring the significance of thoughtful bin location in encouraging ecologically conscious behaviour. (O'connor *et al*. 2010).

1.1 Research Gap and Novelty

The urgent demand for an automated device for biomedical waste segregation arises from the significant challenges posed by improper biomedical waste management, combined with the increasing need for sustainable solutions in healthcare and environmental protection. Improper handling and disposal of biomedical waste present severe risks to public health and safety. Biomedical waste, which includes infectious agents, sharps, and pharmaceuticals, can transmit diseases and create major health hazards if not managed properly. Practices such as indiscriminate disposal or mixing biomedical waste with municipal solid waste can lead to contamination of water, soil, and air, thereby threatening human health and the environment. Given these risks, it is essential to adopt effective waste management strategies to safeguard public health. Moreover, the rapid expansion of healthcare facilities, research labs, and diagnostic centers has led to a sharp rise in biomedical waste generation. With a growing global population and continuous medical advancements, this trend is expected to intensify in the future. The volume of biomedical waste poses significant logistical and operational challenges for waste management authorities and healthcare facilities. Traditional waste segregation methods, relying on manual labor and visual inspection, are not only time-consuming but also prone to errors. This highlights the urgent need for automated solutions that can streamline the waste segregation process, improve efficiency, and reduce the workload on healthcare staff. The environmental impact of improper biomedical waste management is also a critical concern. Biomedical waste contains hazardous substances, such as heavy metals, cytotoxic drugs, and radioactive materials, which can persist in the environment for long periods and enter the food chain. Inadequate disposal methods, including improper landfilling or incineration without sufficient emission control, can lead to soil and water contamination, air pollution, and ecosystem disruption. As environmental awareness increases, there is a growing consensus for sustainable waste management practices that minimize harm and promote resource conservation. Beyond addressing immediate health and environmental concerns, the introduction of an automated biomedical

waste segregation device has broader implications for healthcare sustainability and regulatory compliance. By ensuring correct waste segregation at the source, healthcare facilities can optimize waste management processes, reduce the risk of regulatory violations, and enhance operational efficiency. Effective segregation also paves the way for recycling and resource recovery, helping to recycle valuable materials and reduce reliance on raw resources.

The need for an automated waste segregation device is driven by interconnected challenges related to public health, environmental sustainability, and regulatory compliance. Such a device offers a technological solution to streamline waste management, mitigate risks, and promote sustainable practices in healthcare and beyond. In addressing these complex challenges, innovative solutions like automated waste segregation devices play a crucial role in building a healthier, more sustainable future.

In summary, this project illustrates the potential of using Arduino-based systems for biomedical waste segregation. The device has proven to be reliable, efficient, and economical, offering significant benefits for both public health and environmental safety. In the modern era, with growing concerns about environmental sustainability and public health, the management of biomedical waste has become a critical priority. Biomedical waste generated by healthcare facilities, research labs, and even households often contain hazardous materials that require specialized handling to prevent risks to human health and the environment. This calls for innovative solutions that simplify and enhance the segregation and disposal of biomedical waste. This project introduces an automated biomedical waste segregation device, a groundbreaking system designed to transform waste management practices. Utilizing cutting-edge technology, this system ensures precision and efficiency in segregating waste, setting new standards for biomedical waste handling. At the heart of the system is an Arduino microcontroller, known for its versatility and reliability. Coupled with an array of advanced sensors, the device categorizes biomedical waste into three main types: dry, wet, and metal. This process is enabled by a sophisticated methodology that combines sensor inputs and predefined parameters to identify the waste type accurately.

The system operates seamlessly. When waste is introduced, the sensors quickly analyze its properties. The Arduino microcontroller processes this data through intricate algorithms, enabling rapid and accurate decision-making. The waste is then automatically directed to the appropriate compartment—dry, wet, or metal—ensuring precise segregation with minimal human intervention. A user-friendly LCD interface provides real-time feedback on the segregation process, offering transparency and operational efficiency. This visual feedback builds user confidence and ensures the system's reliability in various applications. The benefits of this automated waste segregation system are significant. By automating the process, it minimizes human error and the risks associated with manual segregation, such as cross-contamination and exposure to hazardous materials. Proper segregation also paves the way for effective disposal practices, protecting public health and the environment. This device's adaptability allows it to integrate seamlessly into existing waste management infrastructures, whether in healthcare facilities, research institutions, or community environments. Its scalability makes it a versatile solution for diverse settings and requirements.

Our proposed system is a major improvement in waste management, especially in the area of biological waste segregation, which is frequently disregarded or not sufficiently handled by automated systems already in use. The majority of earlier solutions use IoT bin-level tracking or vision-based AI models to classify general municipal waste (such as plastic, glass, and organic). The sensitivity, specificity, and adaptability needed to handle hazardous biological waste—which includes infectious, moist, dry, and metallic components—are usually lacking in these systems.

The following are our system's primary novel contributions:

1.1.1 Application Specific to Biomedicine

Our system is specifically designed for the segregation of biomedical waste, meeting the urgent demand for the safe treatment and disposal of hazardous waste associated with healthcare. As far as we are aware, this is among the first biomedical waste segregation systems based on Arduino that incorporates several sensors for effective and secure classification.

1.1.2 Physical Property-based Three-category Segregation

We take a novel and practical strategy by dividing biological waste into three categories: dry, moist, and metal. Our approach employs moisture sensors, infrared sensors, and inductive metal detectors to classify waste according to inherent physical properties—moisture content and metallic presence—that are essential to the handling of biomedical waste, in contrast to earlier systems that mostly depend on visual or compositional analysis.

1.1.3 Sensor Fusion with IoT Communication and Real-time Feedback

High accuracy and dependability are ensured by integrating several sensors under the control of an Arduino microcontroller. Additionally, the system employs the MQTT protocol through NodeMCU for bin-level monitoring and real-time updates, enabling

authorities to react swiftly to the buildup of hazardous trash. During operation, an LCD interface gives users instant visual feedback.

1.1.4 Practical, Scalable, and Low-cost Design

The system's scalable and cost-effective architecture makes it ideal for implementation in healthcare facilities with limited resources. Our hardware-based approach guarantees safe segregation with less operating expense and human interaction than expensive AI/CNN-based systems.

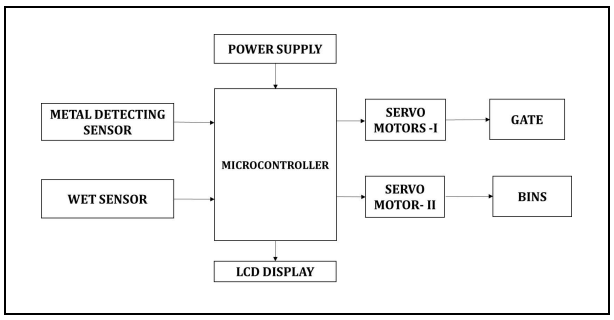


Fig. 1: Schematic overview of the automated waste segregation prototype

2. PROPOSED METHODOLOGY

The smart waste management system represents an innovative approach that keeps our environment clean, green, and free from unpleasant odors. This advanced system fosters a healthy ecological balance while preserving the beauty of our communities. By automating the waste collection process, it reduces the need for manual labor, offering a more efficient and cost-effective solution. A key advantage of this system is its real-time communication between the smart segregation units and municipal departments. This feature helps reduce traffic congestion, ensuring a smoother flow of vehicles. As a result, it lowers air pollution, noise pollution, and other environmental hazards linked to traffic jams.

Automated biomedical waste segregation is another vital component of the system. It eliminates the need for manual segregation, which can be hazardous for workers exposed to infectious diseases and toxic substances. By automating this process, the system minimizes health risks and work-related stress, creating a safer working environment for waste management personnel. Ultimately, the innovative waste management system plays a crucial role in reducing environmental pollution. It ensures waste is separated, processed, and disposed of in an eco-friendly manner, minimizing its impact on the environment. By reducing the amount of waste that ends up in landfills and oceans, it helps combat climate change, protect biodiversity, and conserve natural resources. Overall, this system is a game changer in waste management, contributing to a cleaner, greener, and healthier environment for both current and future generations. In the proposed waste management system, two bins are designated for dry and wet waste, ensuring easy replaceability for routine cleaning. The system utilizes a dry-wet sensor, set with a moisture threshold, to detect the moisture content in waste. When waste is placed, the sensor triggers the relay, which activates a servo motor to rotate and move the waste into the respective bins in both clockwise and anticlockwise directions.

IR sensors continuously monitor the bin levels and send notifications to municipal authorities when the bins are nearing full capacity. Additionally, an MQ sensor detects odors and gas concentrations, contributing to environmental monitoring. Data collected by the Arduino UNO through the sensors is transmitted to the cloud via a node MCU, with the embedded C programming ensuring smooth system operation. User information is displayed on LCD screens, and bin status updates are communicated to authorized personnel using the MQTT protocol, enabling effective waste management and prompt action.

Fig.1 The block diagram illustrates the system's components and their interactions. The sensors identify the type of waste, while the Arduino board processes the data to activate the corresponding actuator, directing the waste into the correct bin. The LCD offers real-time feedback on the waste segregation process. Designed for ease of use, the system provides a user-friendly interface, making it an ideal solution for efficient biomedical waste segregation.

Sensor Deployment: Metal sensors and IR sensors are strategically placed within the waste management system to detect metal objects and monitor the fill levels of the bins.

Data Collection: The sensors gather data about the presence of metal waste and the current waste levels in the bins, which are then transmitted to the Arduino microcontroller for processing.

Processing and Decision-making: The Arduino microcontroller processes the sensor data, classifying the waste as dry, wet, or metal, and determines the appropriate action to take based on predefined thresholds and algorithms.

Actuation: After processing the data, the Arduino activates the servo motor, triggering the segregation mechanism. The motor rotates to guide the waste into the correct bin based on its type (dry, wet, or metal).

Feedback and Display: The Arduino provides real-time feedback to the LCD, updating users or operators on the status of the waste segregation process.

2.1 System Requirements

2.1.1 Arduino Uno

The Arduino Uno is an open-source microcontroller board based on the ATmega328P microcontroller (MCU), developed by Arduino.cc and first released in 2010, as shown in Fig. 2. It is equipped with a variety of digital and analog input/output (I/O) pins that can be interfaced with various extension boards (shields) and other circuits. The board features 14 digital I/O pins (six of which support PWM output) and six analog I/O pins and is programmable via the Arduino IDE using a Type B USB cable. It can be powered through either a USB connection or a barrel connector, which supports voltage input ranging from 7 to 20V, similar to a standard 9V battery. The Uno uses the same microcontroller as the Arduino Nano and shares header compatibility with the Arduino Leonardo board. The hardware reference design is available under a Creative Commons Attribution Share-Alike 2.5 license and can be accessed on the Arduino website. Additionally, design and production files for some versions of the hardware are also available. Unlike previous Arduino boards, the Uno uses the Atmega16U2 (formerly Atmega8U2) microcontroller as a USB-to-serial converter, replacing the traditional FTDI USB-to-UART chip used in earlier versions, and it communicates via the original STK500 protocol.



Fig. 2: R3 version arduino UNO-compatible board integrated with USB iDuino

2.2 Power Sources

The USB connector on the Arduino Uno operates within a voltage range of 4.75 to 5.25V. Official Uno boards are equipped with a USB-B connector, though third-party boards may feature mini-USB, micro USB, or USB-C connectors. The 5.5mm/2.1mm barrel jack connector on official Uno boards supports an input voltage range of 6 to 20V, with 7 to 12V being the recommended range. The maximum voltage for third-party Uno boards can vary depending on the manufacturer, as different voltage regulators with varying maximum input ratings may be used. The power supplied through this connector is routed through a series diode before connecting to the VIN pin to protect against accidental reverse voltage conditions. The VIN pin, located on the board's header, accepts power within the same voltage range as the barrel jack. However, since this pin lacks reverse voltage protection, it can be used to either supply or receive power. When powering the board through the VIN pin, an external series diode is needed if the barrel jack is also in use. Conversely, when powered by the barrel jack, power can be drawn from the VIN pin.

2.3 LCD

The 16x2 LCD (Green) display is an essential component for adding visual output to your Arduino projects. If you need to display a small amount of data, this 16x2 LCD is an excellent choice. It features a 16-character by 2-line display with crisp, high-contrast dark text on a green background with backlight illumination, making it easy to read. This cost-effective and straightforward display integrates a 16x2 white-on-RGB liquid crystal display (LCD) into your project, which is ideal for Arduino-based applications. The display can be easily connected to a microcontroller like Arduino in either 8-bit or 4-bit mode, depending on the number of available microcontroller pins. While the LCD only displays text, it serves as a helpful user interface for showing data such as battery status or distance to an object. The green backlight makes this LCD especially suitable for projects requiring clear, easy-to-read out.

2.4 IR Sensor

The IR sensor is one of the most widely used sensors in electronics, with numerous applications both domestically and industrially. The IR module consists of an IR transmitter and a receiver. Operating on a voltage of 5V, this module has an obstacle detection range of up to 5cm, which can be extended to 15cm. The IR sensor can detect the presence of objects or any motion in its surroundings. The working principle of the IR module is straightforward. When powered, the IR transmitter continuously emits infrared waves. If an obstacle is present in the path of these waves, they are reflected to the receiver, allowing the sensor to detect the obstruction. This ability to detect objects or motion makes the IR sensor highly versatile in various applications.

2.5 Metal Sensor

An Inductive Proximity Sensor is a non-contact electronic sensor designed to detect metals. The detection range of this sensor depends on the type of metal being detected. It operates based on a coil and an oscillator, which generate an electromagnetic field around the detection area. When a metallic object enters this field, it causes a reduction in the oscillation amplitude. This change in amplitude is detected by a limit circuit, which results in a corresponding change in the sensor's output.

The detection range is more extended for ferrous metals, while non-ferrous metals, such as copper, reduce the detection range by about 60%. The sensor typically provides two output states, which is why it is also known as an inductive proximity switch. Typical applications of inductive sensors include metal detectors, traffic signaling, and various industrial automation processes.

3. PROJECT IMPLEMENTATION

Implementing a waste segregation system involves the use of various sensors, microcontrollers like Arduino, and actuators like servo motors to efficiently sort dry waste, wet waste, and metal waste is illustrated in Fig.3. A brief overview of how these components work together.

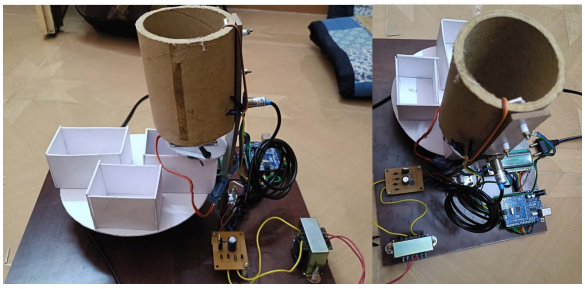


Fig. 3: Working prototype of the waste sorting system

Proximity Sensors based on electromagnetic induction can detect the presence of metal in the waste. When metal is detected, the sensor sends a signal to the microcontroller to initiate the segregation process for metal waste. IR sensors can detect the presence of an object by emitting ultrasonic sound waves and then receiving the reflected waves. In a waste segregation system, IR sensors can be used to detect the level of waste in the bins, ensuring that the segregation process is initiated when the bin is full. The Arduino microcontroller processes the input from the sensors and triggers the appropriate actions based on the detected waste type and bin levels. It interfaces with the various components of the system and controls the segregation process. An LCD can be used to show real-time information, such as the status of each bin, notifications, and system diagnostics. It provides a user-friendly interface for monitoring the segregation process. Servo motors can be employed to actuate the segregation mechanism, directing the waste to the appropriate bins based on the input from the sensors and the Arduino. The detecting component is the part of the downpour sensor that recognizes the presence of precipitation. It may be a capacitive, resistive, or optical sensor. When the sensor is detected, the sensor sends a signal to the microcontroller to initiate the segregation process for wet waste. The transformer helps us to step down DC current through the system.

3.1 Details of System Testing: Materials Used

The prototype testing phase did not employ actual biomedical waste for safety and ethical concerns. Rather, we used simulated biomedical waste samples, which are very similar to the physical and sensory properties of real biomedical waste that is usually produced in hospital environments. These comprised:

- **Wet Waste:** To replicate bio-contaminated dressings, use moist cotton, gauze soaked in saline, and tissue paper.
- **Dry Waste:** Paper-based disposables, gloves, and packaging materials.
- **Metal Waste:** Samples of stainless steel and aluminium were used to simulate sharp instruments, such as metal forceps or scalpel blades.

3.2 Trial Protocol and Configuration

A controlled laboratory setting was used to test the system. Ninety trials in all were carried out, including thirty for wet trash, thirty for dry waste, and thirty for metal waste. One item was put into the input bin for each trial, enabling the system to identify, process, and separate the garbage according to its characteristics.

3.3 Work Flow

The calculation of the undertaking is as follows, and it is explained in a flow chart in Fig. 4.

Step 1: Turn on the system

Step 2: The microcontroller, all the motors, and sensors are switched on.

Step 3: Put the waste in the main bin; the waste is sensed by the proximity sensor to detect if it is a metal or not.

Step 4: If the waste is metal waste, then motor-II rotates 90 degrees, and the gate will be opened to put the desired bins.

Step 5: If not metallic waste, the proximity sensor turns off, and it meets the raindrop sensor that decides whether the waste is wet waste or dry waste by checking the moisture content of the waste.

Step 6: If the waste has some humidity, it is detected as wet waste, and motor II rotates 45 degrees, and the gate is open to put the desired bins.

Step 7: If not wet waste, then the waste is dropped into the dry waste bin.

Step 8: At long last, the waste is dropped into the individual canisters, and the isolation cycle is finished.

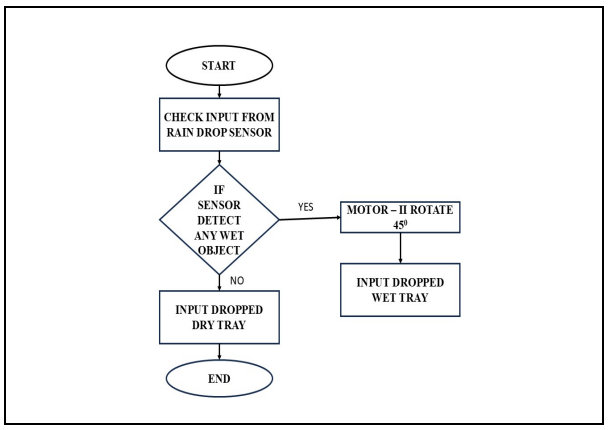


Fig. 4: Flow chart of proposed system for biomedical waste segregation

4. RESULTS AND DISCUSSION

The wet waste sensor is deployed in a gate, which is designed to collect damp waste, as shown in Fig. 5. When the sensor detects an object as wet waste, it sends a signal to the system, which then responds by carrying over the corresponding bin to collect the waste.

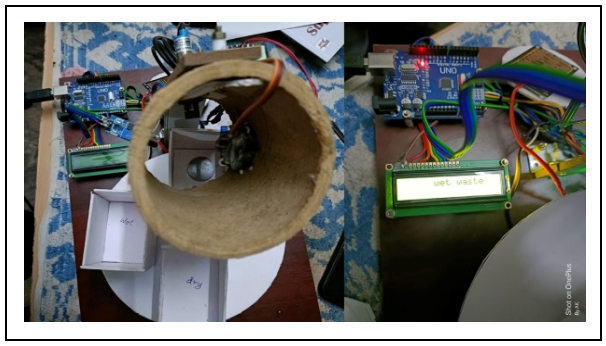


Fig. 5: Identification and segregation of wet waste

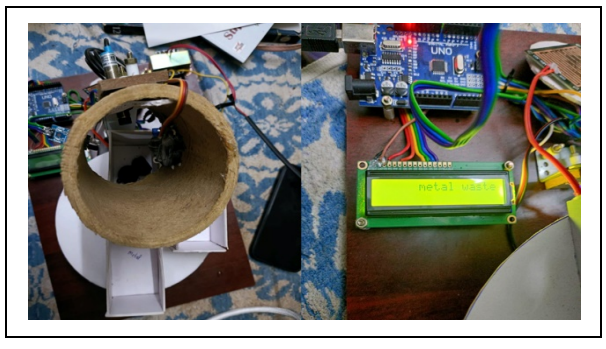


Fig. 6: Segregation of metal waste from the group of various biomedical waste

In the same way, the metal sensor is deployed in a gate, which is designed to collect metal waste, as shown in Fig.6. When the sensor detects an object as Metal waste, it sends a signal to the system, which then responds by carrying over the corresponding bin to collect the waste.

Similarly, the IR sensor is deployed in a gate, which is designed to collect dry waste. When the sensor detects an object as dry waste, it sends a signal to the system, which then responds by carrying over the corresponding bin to collect the waste, as shown in Fig. 7.

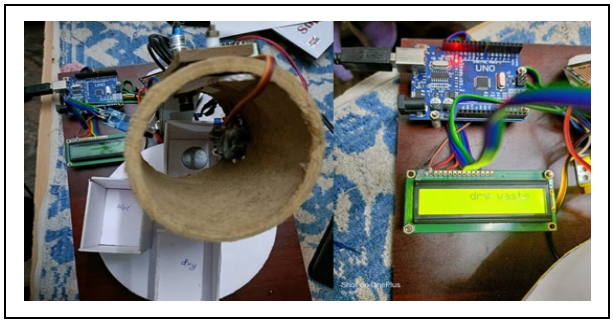


Fig. 7: Dry waste management through segregation

Table 1. Evaluation metrics of the proposed system

Waste Type	Total Samples Tested	Correctly Classified	Accuracy (%)
Wet Waste	30	28	93.3%
Dry Waste	30	29	96.7%
Metal Waste	30	30	100%
Overall	90	87	96.7%

4.1 Performance Evaluation and Accuracy Data

Measures of Evaluation:

- **Segregation Accuracy:** Determined by correctly classifying and rerouting waste to the appropriate bin.
- **Response Time:** The amount of time between waste detection and bin assignment.
- **Sensor Reliability:** The quantity of missing or false positive detections.

In this project, used simulated biomedical waste materials that represented the three desired categories—dry, wet, and metal—in 90 controlled trials in a lab setting to assess the effectiveness of the biomedical waste segregation system. Thirty samples were examined for each category. The average time from waste detection to bin segregation was 3.8 seconds per item.

4.1.1 Number of Errors

4.1.1.1 Total Misclassifications: 3

Due to borderline moisture levels, two cases of wet waste were mistakenly classified as dry. One case of dry waste being misdiagnosed because of a lag in sensor sensitivity.

4.2 System Uptime and Responsiveness

Throughout the testing, there was no downtime and the system ran constantly. Under normal laboratory circumstances, sensor response was continuously dependable.

The system obtained a 96.7% overall segregation accuracy, with sporadic misclassifications occurring when metal objects were partially wrapped or the moisture content was borderline. Each item took an average of three to four seconds to respond to. The sensors showed excellent reliability and repeatability, operating consistently throughout trials as obtained in table 1.

Table 2. Comparison of existing waste segregation systems with proposed biomedical waste segregation device

Author / System	Kumari *et al*. (2018)	Gondal *et al*. (2021)	Kumar *et al*. (2021)	Chaware *et al*. (2017)	Khoa *et al*. (2020)	Proposed System (This Work)
Waste Type Addressed	Municipal solid waste	General waste	General waste	Solid waste	University campus waste	Biomedical Waste
Technology Used	Arduino, Ultrasonic, Moisture Sensor	CNN, MLP (Machine Learning)	YOLOv3 + Darknet	IoT-based smart bin	ML + LoRa modules	Arduino + IR + Moisture + Metal Sensors
Category Segregation	Wet/Dry	Six categories	Glass, Metal, Plastic, etc.	Full/Empty status only	Organic/Inorganic	Dry / Wet / Metal
Target Application	Smart cities, public bins	Urban waste, recycling	Smart city waste management	General use	Educational institutes	Hospitals, Labs, Clinics
IoT/Real-Time Features	Bin-level alert via sensors	Camera-based classification	High accuracy classification	Bin overflow notification	Optimized collection routing	Real-time display + MQTT alerts
Limitations	Not specific to biomedical waste	High cost, needs training data, not real-time	Needs large datasets, not biomedical-specific	No segregation, no biomedical application	Focus on collection, not segregation	Overcomed all existing limitations and give low cost, scable device 1st specific on biomedical waste

4.3 Important New Features of the Suggested System

Unlike general-purpose systems, it is specifically made for biomedical waste. Three categories based on physical characteristics that are pertinent to medical waste (e.g., metal sharps, moist gauze). Accuracy and speed are made possible via sensor fusion with the Arduino microcontroller. Integrated MQTT and LCD for real-time communication and user input. Low-cost and modular, perfect for remote health centres and underdeveloped nations as tabulated in table 2.

Thus, our proposed system can be applied to real time application in following ways:

(a) Point-of-Care Area Deployment

Because the suggested device is small and can be set up on a benchtop or in a corner, it can be used in crucial locations such intensive care units, operating rooms, diagnostic labs, and outpatient departments (OPDs), where it is crucial to separate biological waste quickly and safely.

(b) Decreased Cross-contamination Risks

The system guarantees adherence to biomedical waste handling laws by decreasing human interaction during segregation, lowering the danger of infection transmission to sanitation and healthcare staff.

(c) Integration with present trash Collection Systems

The separated trash is compatible with the hospital's present waste operations since it can be collected straight into typical biomedical colour-coded bins (red, yellow, blue, and white, for example). The system's real-time data (via LCD and MQTT) can also help hospital maintenance departments and biomedical waste handlers keep an eye on fill levels and schedule proper disposal.

(d) Scalability

The modular design allows for easy replication and scaling across departments or multi-floor facilities. For large hospitals, several units can be networked to a single monitoring system or run autonomously, allowing for centralised analytics and waste tracking.

(e) IoT & Future Integration Potential

Real-time waste tracking, maintenance warnings, and data logs for audit or regulatory compliance are made possible by the MQTT protocol and cloud connectivity, which facilitate smooth integration with hospital information systems (HIS). RFID integration or barcode-based waste tracking are examples of potential future improvements.

(f) Low-cost and Adaptable to Various Settings

Made with Arduino and easily accessible sensors, the gadget is affordable and can be easily modified for use in diagnostic labs, big tertiary hospitals, or small clinics.

5. CONCLUSION

The automated biomedical waste segregation system is a fully automated solution designed to classify biomedical waste into three categories: dry, wet, and metal. Powered by an Arduino microcontroller, the system uses sensors to identify the type of waste. Key sensors include an infrared motion sensor to detect waste presence and a load cell to measure the weight of the waste. Upon detecting waste, the system processes sensor data to determine the type of waste. If the waste weight is below a predefined threshold, the system activates a servo motor to direct it into the dry waste bin. For waste exceeding the threshold, the system directs it into the metal waste bin, while wet waste is directed to the wet waste bin using another servo motor. The LCD provides real-time feedback on the segregation process, clearly indicating whether the waste is dry, damp, or metal. This ensures proper waste separation, helping reduce contamination risks and improving safety for both the environment and public health. The system is designed for ease of use and operation, with a modular structure that allows for straightforward maintenance and upgrades. Its energy-efficient design reduces overall operational costs. This system presents an ideal solution for biomedical waste segregation, particularly in developing countries where waste management poses a significant challenge. In conclusion, the automated biomedical waste segregation system offers an innovative, efficient, and user-friendly approach to waste management. The integration of sensors, Arduino, and actuators results in a precise and reliable system with important implications for public health and environmental safety, especially in regions facing critical waste management challenges.

5.1 Future Scope

The integration of Internet of Things (IoT) technology into medical waste management has the potential to revolutionize the process, enhancing efficiency and effectiveness. By leveraging sensors and automation systems, the generation, segregation, and disposal of biomedical waste can be monitored and tracked in real-time. This ensures proper waste classification and disposal, reducing the risk of contamination and improving both environmental and public health outcomes. In addition, the use of advanced technologies such as artificial intelligence (AI), machine learning (ML), and robotics can further optimize waste segregation and disposal. For instance, AI algorithms can analyze waste data to identify patterns, enabling more precise waste separation. Robotics can be employed to automate the segregation process, reducing the need for manual labor and increasing accuracy. The integration of IoT and cutting-edge technologies also enhances overall waste management. Real-time data analysis can identify trends in waste generation, allowing for better resource allocation and planning. Furthermore, the application of these technologies can reduce the overall cost of waste management, making it more affordable for healthcare facilities. In conclusion, the integration of IoT and advanced technologies in medical waste management not only modernizes the system but also boosts efficiency. By enabling continuous monitoring and tracking of waste generation, segregation, and disposal, these innovations reduce the risk of contamination and enhance safety. Furthermore, the use of AI, ML, and robotics streamlines waste management, lowering costs and optimizing operations.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest.

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