ISSN (Online):3048-5088

International Journal of Advancement and Innovation in Technology and Research (IJAITR)

Volume 3, Issue 1, (Jan-Jun) 2026

AEROBINS: Intelligent Odor-Controlled Waste Management using IoT and Machine Learning

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[1]***Abstract*— Cleanliness is not only the things that we see, it is also the things that we sense, breathe, and keep for the future. Rapid urbanization and increased waste production have resulted in bad odors that, besides causing health hazards, are also damaging the environment. Most of the currently available smart waste programs only keep track of how full the bins are and do not pay attention to the very important aspect of odor detection. Since an odor is the earliest indication of decomposition and a source of diseases, thus, its treatment is necessary. This is an AI-powered Smart Waste Management System that uses predictive analytics to keep off the waste from being smelly, which is the essence of the project. The system installs gas sensors, environmental sensors, and ultrasonic fill-level detection that are linked through ESP32 to a cloud platform for real-time monitoring. It is a machine learning model that anticipates the generation of odors due to the decomposition of the waste before the occurrence of the event, thus, making it possible to intervene on time and also to collect the waste in an optimized way. By integrating odor prediction with AI-based route optimization, the device becomes a means of improving hygiene, reducing human labor, and being a reliable partner for a sustainable Smart City future**

***Index Terms*— Smart Waste Management, Internet of Things (IoT), Gas Sensor Array, Decomposition Monitoring, BME688, MQ-04, Ultrasonic Sensor**

I. INTRODUCTION

The Internet of Things (IoT) has completely changed urban systems, as communication of real-time data between sensors, devices, and cloud platforms has become possible for intelligent automation. As for waste management, the majority of smart bins just keep track of their fill levels, while neglecting odors and toxic gas emissions—signs that not only show the waste is rotting but also that become a source of health hazards. AeroBins came up with an AI-driven, IoT-based odor-controlled waste management system to break through these constraints. Their system integrates various sensors, such as the ESP32 microcontroller (the main controller of the system with built-in Wi-Fi), HC-SR04 ultrasonic sensor for fill level measurement, BME680/BME688 for temperature, humidity, pressure, and VOC monitoring, and MQ-4 gas sensors for toxic gas detection, and a NEO-6M GPS module for location tracking, etc. Data coming from sensors are sent to the cloud, where machine learning algorithms process them to forecast odor intensity, identify the release of hazardous emissions, and even find the best routes for waste collection. Those bins that are prioritized by the system are the ones with the greatest health risk i.e. high for toxic gases, medium for full bins, and low for partially filled ones, while citizens also have the opportunity to report problems through QR-based feedback. By using intelligent sensing, AI analytics, and community engagement, AeroBins becomes a promoter of cleaner, safer, and more sustainable waste management in smart cities.

II. LITERATURE REVIEW

A. Smart Waste Management and IoT Integration

The integration of the Internet of Things into the process of waste management revolutionizes conventional systems by allowing real-time monitoring and automation of the processes of waste collection. Smart bins fitted with IoT sensors will be able to monitor their fill levels and transmit the data obtained to cloud servers for route optimization in order to utilize available resources efficiently [1], [2]. Most of them are still reactive, focusing mainly on the detection of waste volumes while completely disregarding the chemical pointers to decomposition that give rise to odor and gas emissions. There is a reported need for multi-sensor, predictive systems to progress toward proactive waste management [3]. Such intelligent frameworks will improve operational efficiency, reduce environmental impact, and contribute to enhancing the living standard of citizens in urban areas.

B. Gas and Air-Quality Sensing for Odor Detection

Odor development on waste bins is characterized by the emission of gases: methane (CH_4), ammonia (NH_3), and VOCs [4]. Modern sensors, such as the BME688, allow for simultaneous measurement of VOC levels together with temperature and humidity, ensuring an integrated concept in air-quality assessment in the context of waste environments [5]. Among gas sensors, MQ-4 sensors are popularly used for methane detection, although calibration remains necessary given their cross-sensitivity to temperature and humidity [6]. On this basis, investigations have shown that integrating gas sensors together with environmental data, such as humidity and temperature, can provide higher accuracy in odor prediction while increasing system reliability [7]. Thus, sensor fusion can play an important role in early odor detection and environmental monitoring.

C. Machine Learning to Predict Odors and Assess Risks

Recent research has demonstrated that ML can transform WM from reactive to predictive: it is able to forecast when an odor will form and identify high-risk bins before problems arise [8]. Algorithms identified to successfully analyze multisensor data include Random Forests, Support Vector Machines, and Artificial Neural Networks; they predict odors and gas concentrations with high accuracy [9]. Such models perform traditional threshold-based methods by identifying complex patterns indicative of early decomposition [10]. ML systems go further in enhancing environmental safety and supporting efficient collection strategies based on data-driven insights.

D. Route Optimization and Sustainable Operations

Dynamic route optimization, guided by real-time IoT data, greatly enhances operational efficiency related to waste collection services. It is found that intelligent routing decreases fuel consumption, traffic congestion, and hence greenhouse gas emissions. The integration of urgency parameters like gas concentration or odor risk levels allows for the development of optimized collection schedules that give priority to those bins posing the greatest threats to the environment and health. Such AI-enabled routing systems align with the sustainability objectives of balancing environmental protection with economic efficiency.[11]

III. PROPOSED SOLUTION

In the urban areas of today, the uncontrolled waste and release of odors can be considered as the silent yet serious signs of environmental neglect, which require more intelligent and sustainable solutions. To deal with this problem, AeroBins comes up with a smart waste management system powered by AI and IoT, which can detect, evaluate, and change waste conditions automatically in the real world. It employs MQ-4 for detection of methane, BME688 for air quality and VOC measurement, and an ultrasonic sensor for fill-level monitoring, all linked with an ESP32 microcontroller. The data gathered are transferred to a cloud platform where machine learning algorithms forecast odor generation and locate the bins with the highest risk for the earliest intervention. In case of abnormal gas concentrations or strong odors, AeroBins instantly notifies the municipal authorities via a dashboard and uses AI-driven route optimization to locate the collections that need to be done first. Also, a QR-based citizen feedback system enables users to report odor or overflow issues, thereby facilitating community participation. By integrating multi-sensor intelligence, AI analytics, and citizen engagement, AeroBins is enabling waste management that is cleaner, healthier, and more sustainable in smart cities.

IV. SYSTEM ARCHITECTURE

The AeroBins system architecture has been designed to set up a smart, IoT-enabled, AI-driven waste monitoring and odor detection framework that operates in real-time. The system architecture of AeroBins consists of five major layers:

1.Sensing Layer: It features a BME680 sensor capable of detecting a wide range of environmental parameters like the temperature, humidity, and gas concentration. Methane (CH_4) detection is carried out with the help of an MQ-4 sensor, while the ultrasonic sensor is used for the measurement of the waste fill level. All sensors have been carefully positioned in the dustbins or nearby to record the data that is both up to the minute and accurate.

2. Processing Layer: The ESP32 microcontroller is responsible for the collection and preprocessing of sensor data, it also carries out calibration and, finally, sends the data to the cloud in a secure manner via Wi-Fi or MQTT protocols.

3.**Cloud Layer**: The data collected are then sent to a cloud-based platform like ThingSpeak, Firebase, or AWS IoT Core. The layer is responsible for data storage, visualization, and advanced analytics. The machine learning model in the cloud analyses the sensor data, predicts odor intensity, assigns priority levels to bins, and creates the shortest routes taking into account the location as well as the severity
.

4.Application Layer: The web or mobile interface allows the local government officials to monitor the live data, get notifications and view the optimized collection paths. If the set limits are exceeded, warning signals are produced and instantly sent to the authorized persons.

5.Feedback Layer: This layer provides citizens with an opportunity to participate in the process by QR code scanning. Feedback is kept and analyzed to constantly upgrade the system performance and prediction accuracy.

Such a modular design architecture offers advantages in scaling, easy upkeep, and the ability to make decisions in real-time which is what makes AeroBins a reliable and eco-friendly solution for smart city waste management.

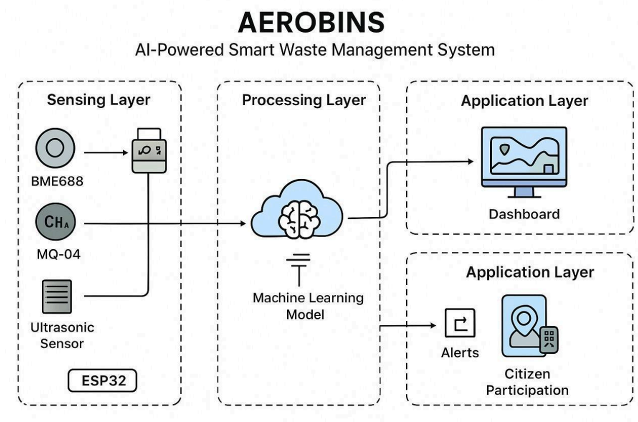

Fig.1. AeroBins architecture

V. METHEDOLOGY

To build a cleaner and smarter urban ecosystem, the AeroBins methodology combines IoT intelligence, cloud computing, and machine learning to revolutionize real-time odor detection and waste management. The system makes use of BME688, MQ-4, and ultrasonic sensors connected to an ESP32 microcontroller to continuously monitor air quality parameters, toxic gases, and bin fill levels. The data gathered is sent to the cloud in a secure manner via Wi-Fi/MQTT, where machine learning algorithms analyze odor intensity and gas concentrations to estimate the health risks.

On the basis of these insights, AI-based route optimization dynamically prioritizes bins and generates the most efficient collection routes for municipal vehicles. At the same time, real-time alerts are sent to the authorities when thresholds are exceeded, and a citizen feedback system based on QR codes facilitates the active engagement of the community. Such a comprehensive system guarantees that waste will be handled in a timely manner, that environmental hazards will be reduced, and that there will be a sustainable smart city environment

A. Hardware Components

1.1. **ESP32**

At the center of the Aerobin's intelligent sensing system is the ESP32, a high-performance, low-cost microcontroller. We chose this component mainly for its powerful dual-core processor and its built-in Wi-Fi and Bluetooth features, which are crucial for our project's IoT functionality. In the Aerobin design, the ESP32 acts as the main processing unit. Its main job is to connect directly with various sensors, including the primary odor sensor, like the MQ-135, and the ultrasonic sensor for fill-level detection. The ESP32 gathers raw data from these components, processes it in real-time, and then uses its built-in Wi-Fi module to send this information, such as current PPM levels and bin fullness percentage, to our cloud server. This smooth data transmission is the foundation of our system, allowing for real-time monitoring and analytics presented to the user.[1]

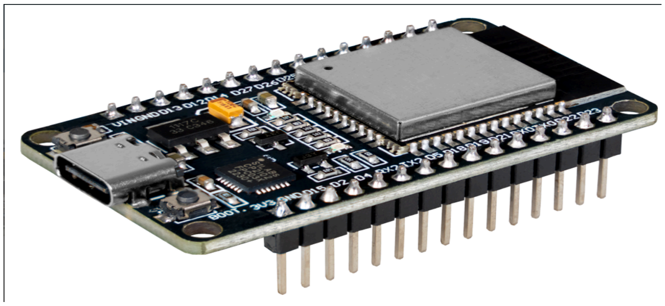

Fig.2. ESP32

1.2. **ULTRASONIC SENSOR**

We use an ultrasonic sensor shown in fig no. works in the Aerobin to check how full it is without ever touching the trash. It works similarly to a bat's sonar. This small sensor, which combines a speaker and microphone (called a transducer), sits at the top of the bin and points down.It sends out a quick sound 'ping' that is too high-pitched for us to hear. This sound travels through the air, hits the top of the waste, and bounces back as an echo. The sensor listens for that echo to return. .A small computer chip inside measures how long it took for the sound to make the round trip—down and back up. This measurement is called the 'Time of Flight' (ToF). Using that travel time, the system can easily calculate the distance to the trash. This tells us how much empty space is left at the top of the bin. Once we know the empty space, we can easily determine how full the bin is as a percentage, which is the key information we need for pickups.[2]

Fig.3. Ultrasonic Sensor

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1.3. **BME688**

For the important task of environmental analysis, our system uses the Bosch BME688, a 4-in-1 environmental sensor. This component acts as the main "nose" of the Aerobin. It quantifies the air quality inside the waste container by measuring gas levels, temperature, humidity, and barometric pressure. Its main function relies on a Metal Oxide (MOx) gas sensor, which is very sensitive to various Volatile Organic Compounds (VOCs) and Volatile Sulfur Compounds (VSCs), such as hydrogen sulfide and ammonia. These compounds are the primary byproducts of anaerobic decomposition and the main source of bad smells in waste.

The BME688's main advantage is its AI-powered gas scanning ability. With BME688 AI-Studio, we can train the sensor to recognize the specific gas signature of decomposing waste. While in use, the sensor's internal hotplate cycles through different temperatures. This causes the MOx layer's resistance to change based on the specific gas mixture present. The resulting data, which includes gas resistance, humidity, and temperature, is sent via the I2C digital interface to the ESP32. This detailed dataset allows our system to go beyond simple alerts and conduct a more thorough analysis of the decomposition stage, enabling smart waste management.[3]

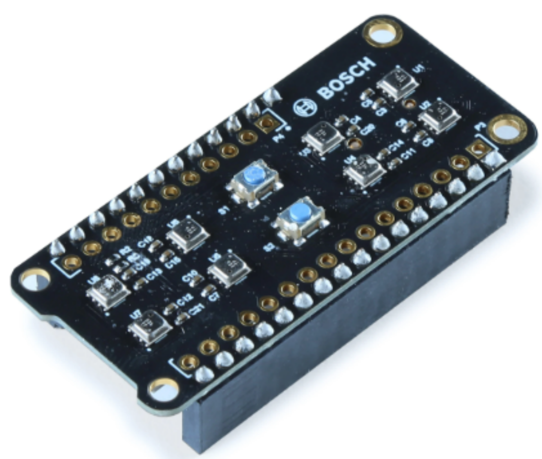

Fig.4. BME6888

1.5.MQ-04

An MQ-04 sensor in the Aerobin "smells" the air inside. This sensor is designed to detect methane gas, a key gas that builds up when organic waste begins to break down in an environment without enough air. This process is called anaerobic digestion. Think of this sensor as an electronic nose. It contains a tiny sensing element that is sensitive to methane. When methane gas from the waste comes into contact with this element, it alters the sensor's electrical resistance. A small computer chip, or microcontroller, continuously measures this resistance. If methane levels start to rise, the resistance changes, and the chip translates that change into a signal. This signal indicates the concentration of methane gas in the bin, usually measured in parts per million (PPM). By monitoring this, we gain insight into the type of decomposition taking place inside the bin. This information is crucial for understanding the composting process and managing any potentially harmful or flammable gas buildup. [4]

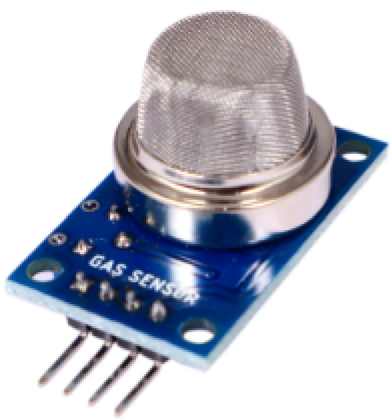

Fig.5. MQ-04 Gas sensor

B. Software, Artificial Intelligence, and Machine Learning Framework

The AeroBins is a system that features an elaborate software and AI-ML framework for predictive waste management and real-time odor analysis. The backend, which is responsible for data processing and API communication, is built by Python (Flask/Django), while the frontend is developed by ReactJS and Node.js for the dynamic visualization of the data. The data repositories used are MySQL/MongoDB, and the analytics dashboards are created by Power BI and Plotly, which provide the real-time insights.

Artificial Intelligence and Machine Learning Components

1.Data Preprocessing: This stage uses the libraries NumPy and Pandas for data cleaning, normalization, and feature extraction.

2.Odor Prediction Model: Algorithms: Random Forest, Support Vector Machine (SVM), and Artificial Neural Network (ANN).

3.Function: Estimates the level of the odor source and the classifies waste bins into different risk categories (Low, Medium, High).

Optimization Algorithm

1.Algorithms: Genetic Algorithm and A* Search.
2.Function: Waste collection routes that are shortest and prioritized are generated.

Anomaly Detection

1Algorithms: Isolation Forest and K-Means Clustering.
2.Function: Identifies the occurrences of unusual gas emissions or abnormal patterns of decomposition.

Alert System

AI-controlled thresholds lead to the dispatch of alerts in real-time to the municipal authorities, who can take immediate action.
The coupling of software intelligence with machine learning in this manner leads to higher accuracy, better efficiency, and increased sustainability in modern waste management systems.

VI. RELATED WORK

A. Smart Waste Collection Using RFID and GPS Integration

As explained by the authors, the system is configured to feature garbage bins from different localities as the RFID-tagged smart garbage bins to provide unique identification for every bin. Upon the arrival of the waste collection truck, the vehicle-mounted RFID reader identifies the waste bin by scanning its tag received from the RFID module in it. The truck gets the exact location of the incident from its GPS unit while the data is sent from the vehicle to the control center via GPRS. The control center gets all the information, like the identification of the bin, the location, and the collection status, which are then used and analyzed by a GIS application for addressing the optimization of routes and tracking the monitored area. Combining the GPS technology with RFID is what makes waste networking very effective, the time of operation shortened, and that gives the collection process a higher degree of transparency. [1]

B. AI-Based Smart Waste Bin Using IoT and Gas Sensors
The integrated model of waste management has been created with the help of an ESP32 microcontroller which supports the integration of MQ-135 and MQ-4 gas sensors that are used for the multi-gas detection especially methane, ammonia, and carbon compounds produced by decay of the waste. An ultrasonic sensor is used to gauge the filling of the bin, and the IoT sensor data is sent to the cloud server through Wi-Fi. The AI algorithm gets trained on historical sensor data and it is capable of predicting the intensity of the odor and even recognizing the type of waste decomposition. Once the set points are exceeded, SMS or

app notifications are dispatched to the municipal monitoring office. Integration of AI with IoT raises the level of waste collection's efficiency through enabling predictive maintenance and sending automated alerts so that hygiene and environment could be better controlled .[2]

VII. FUTURE WORK

A. Integration of Adaptive AI and Odor Forecasting Models

Developments to the AeroBins platform will concentrate on the construction of an adaptive AI system that can identify odor signatures in various situations. The deep learning models along with TinyML algorithms make the system capable of performing on-the-fly odor pattern recognition and even predicting odor propagation methods directly on the ESP32 edge device. Thus, it allows for odor detection in the early stages and the scheduling of sanitization activities even before the arrival of the staff or gas hazardous accumulation with minimal cloud dependency.

B. Renewable Energy and Smart Power Management

In order to improve its sustainability, AeroBin shall be equipped with flexible solar panels as well as a smart power management module capable of guaranteeing its outdoor operative continuity. The system will meter the battery level and the sunlight intensity conditions and accordingly vary the sensor sampling rates, thus power will be consumed more economically without the loss of the data quality. The solar-powered concept and the smart power management system will make AeroBin a perfect candidate for those less developed areas where the power grid is still inaccessible.

C. Cloud-Integrated Dashboard and AI Analytics Portal

The cloud-connected web and mobile solution will be the future version of AeroBin envisaged for 24/7 real-time data presentation, analysis, and recording purposes. The sensor data are transmitted through an IoT platform, e.g., AWS IoT Core or Google Cloud IoT, to be visualized interactively via maps and trend charts. The AI analytics portal will accomplish the tasks of automatic odor grade identification, waste collection frequency logging, and provision of municipal cleaning routes.

D. Multi-Sensor Fusion for Environmental Correlation

It's future to AeroBin to consider incorporating temperature, humidity, barometric pressure, and CO_2 sensors along with the waste sensors so that correlations between weather factors and waste decomposition can be established. The multi-sensor fusion will form the base of context-aware models for odor prediction that take into account seasonal and climatic changes. Besides the integration of environmental intelligences, it will also be more accurate and reliable for waste monitoring.

E. Autonomous Collection and Smart Route Optimization

The linking of AeroBin with GPS and RFID modules-installed autonomous or semi-autonomous waste collection vehicles is a futuristic plan. AI-powered route optimization will allow the system to calculate the shortest and therefore most time-efficient routes for waste collection based on bin fill levels, odor intensity, and distance variables. Consequently, there will be less time when the vehicles will be standing idle, smaller amounts of pollutants will be emitted, and a circular smart waste management ecosystem that is fully automated will come into existence.

VIII. CONCLUSION

This project is about AeroBins a smart idea that connects IoT sensors and AI to make waste management easier and faster. The setup works on an ESP32 board that links with BME688, MQ-4, and ultrasonic sensors to find gas levels, odor, and how full the dustbin is. The data go to the cloud, where a simple machine learning model studies the pattern and guesses when the waste may start smelling or decomposing. If bad odor or gas rises above a safe point, the system sends a quick GSM message to the city workers. This helps them clean on time and stops the smell from spreading. The idea behind AeroBin is not just about smart bins but about cleaner surroundings, saving time, and improving the daily life of people in modern cities.

ACKNOWLEDGMENT

We sincerely thank Prof. Nidhi Nigam, Department of Computer Science and Information Technology (CSIT), Acropolis Institute of Technology and Research, for her valuable guidance, insightful feedback, and continuous encouragement throughout this research. We also appreciate the institute's support and resources that facilitated this work. Finally, we extend our gratitude to our peers for their constructive suggestions and to our families for their motivation and unwavering support during the completion of this study.

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