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# A Scalable IoT-Based Solution for Waste Monitoring and Management in Railways

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***Abstract*—This paper presents the design and implementation of an IoT-enabled smart sanitation system for public restrooms and septic tanks, focusing on real-time waste monitoring and odor control. The proposed solution addresses sanitation challenges commonly observed in high-footfall environments such as railway stations and remote rural areas, where manual inspections are inefficient and unreliable. The system is built around the ESP32 microcontroller, which integrates various sensors including infrared, gas, and temperature sensors to continuously track parameters such as waste levels and harmful gas concentrations like ammonia and hydrogen sulfide. A rule-based algorithm processes this data to activate exhaust fans, deploy odor neutralizers, or send notifications to cleaning personnel via a mobile app when threshold levels are exceeded. Additionally, Bluetooth and cloud communication modules enable remote monitoring and predictive maintenance, reducing manual labor and emergency interventions. A prototype developed and tested under controlled conditions demonstrated high reliability in early waste detection, odor management, and automated response execution. The system showed potential for scalability and low-power operation, making it suitable for deployment in both urban smart city infrastructure and underserved rural regions. The results affirm the system's capability to improve hygiene standards, reduce pollution, and support national initiatives like Swachh Bharat Abhiyan.***

***Keywords*— *IoT-enabled sanitation, ESP32, Smart restroom system, Odor control, Septic tank monitoring, Predictive maintenance***

## I. Introduction

Maintaining hygiene and proper sanitation in public and remote areas remains a pressing concern in developing countries, especially in densely populated environments such as railway stations, buses, and other high-footfall public restrooms. Traditional maintenance techniques rely heavily on manual inspection and scheduled cleaning, which are often inefficient, delayed, and resource-intensive. This results in frequent occurrences of waste overflow, foul odors, and unclean conditions, which compromise user comfort and pose significant public health risks [1]. Moreover, septic tank monitoring is typically neglected until issues such as clogging, gas accumulation, or full capacity arise, which can lead to system failures or environmental hazards [2]. Recent advances in smart technologies have opened new avenues to tackle such challenges. The integration of the Internet of Things (IoT), embedded systems, and wireless communication has enabled the development of intelligent, automated systems for real-time monitoring and control of public utilities. In particular, microcontrollers like the ESP32 with its dual connectivity options (Wi-Fi and Bluetooth), low power consumption, and cost-effectiveness are ideal for smart sanitation applications [3]. When coupled with sensor technology and cloud-based analytics, these systems can revolutionize hygiene management by ensuring timely interventions and efficient resource utilization. The motivation for this work stems from the increasing demand for sustainable and automated sanitation systems that require minimal manual intervention and are adaptable to various environments. Public facilities in under-resourced or rural areas often lack the infrastructure or workforce to support frequent maintenance. Meanwhile, urban locations are challenged by scale and rapid user turnover. A scalable IoT-based hygiene monitoring system would help solve both issues by automating the data collection, decision-making, and alerting processes. The objective of this study is to design, develop, and test a smart restroom and septic tank hygiene management system that is capable of real-time data acquisition and intelligent actuation. The proposed system is designed to monitor key hygiene indicators, including odor levels, gas concentrations, temperature, and waste fill levels, through the use of embedded environmental sensors. A rule-based decision-making algorithm processes this sensor data to initiate context-sensitive actions, such as activating exhaust fans, deploying odor neutralizers, or sending notifications to sanitation personnel via a Bluetooth-connected mobile application. In addition to real-time responsiveness, the system incorporates mechanisms for fault detection, energy-efficient operation, and wireless remote access through cloud-based platforms. By analyzing historical usage trends and tank conditions, the system also supports predictive maintenance, thereby reducing the need for emergency interventions and enabling better resource planning. The key contribution of this paper lies in the development of an end-to-end sanitation management system that combines ESP32-based sensor processing, wireless communication, cloud analytics, and mobile app-based remote monitoring. The prototype demonstrates a functional, low-cost, scalable solution for smart public hygiene systems. It also serves as a proof-of-concept for integrating automation into sanitation workflows, which is in line with the goals of Swachh Bharat Abhiyan and smart city initiatives [4].

## II. BACKGROUND

The maintenance of public sanitation facilities has long been a logistical and operational challenge, particularly in densely populated or remote areas. Traditional sanitation systems rely heavily on manual monitoring and scheduled maintenance, which often leads to delayed responses, unhygienic conditions, and inefficient use of resources. In public restrooms and railway systems, the accumulation of waste and emission of unpleasant odors go unchecked until a physical inspection is performed, by which time the situation may have already escalated to a health hazard [1].

Manual sanitation systems typically employ fixed schedules for cleaning and waste disposal without regard to actual usage patterns. As a result, resources are often misallocated either wasted on underused facilities or insufficient in high-demand areas. Overflowing septic tanks and restrooms with inadequate ventilation contribute to the spread of harmful bacteria and offensive odors, which are both public health and environmental concerns. Moreover, due to the absence of any early warning or alerting mechanism, maintenance teams are unaware of critical issues until they are visually or olfactorily obvious to users [2].

Recent technological advancements have paved the way for smarter sanitation solutions, with the Internet of Things (IoT) emerging as a transformative approach. IoT systems integrate sensors, microcontrollers, and wireless communication to enable real-time monitoring of various environmental and operational parameters. For example, sensors embedded in garbage bins or restroom facilities can detect fill levels, temperature, humidity, and the presence of harmful gases such as ammonia and hydrogen sulfide. Once the data exceeds certain thresholds, automated mechanisms like alerts, fans, or odor neutralizers can be triggered [3][4].

Automated sanitation systems such as smart bins and self-cleaning toilets have been introduced in smart city initiatives. These systems often leverage microcontrollers like ESP32 or Arduino, paired with GSM or Bluetooth modules for communication. Notably, gas sensors enhanced with deep learning algorithms have shown improved accuracy in odor detection, addressing traditional challenges like cross-sensitivity and environmental drift [5]. Implementations in railway environments have already demonstrated the efficacy of IoT-enabled waste management systems by providing real-time updates and remote access to waste disposal data [6].

Despite these innovations, widespread adoption remains limited due to high deployment costs, lack of standardization, and the absence of scalable, energy-efficient solutions. Therefore, there is a critical need for low-cost, modular systems that can be adapted to diverse sanitation environments. By leveraging affordable hardware, wireless connectivity, and cloud analytics, modern systems can not only automate routine tasks but also enable predictive maintenance, ensuring issues are addressed before they escalate [7].

In summary, the integration of IoT technologies into public hygiene infrastructure addresses the major shortcomings of traditional systems. It introduces scalability, responsiveness, and data-driven management, all of which are essential to meet the hygiene demands of modern urban and rural environments.

## III. LITERATURE SURVEY

### A. *Hygiene Guardian: Proximity-Activated Sanitizing Dustbin with AI Vision*

This paper presents an innovative smart dustbin system that automatically opens its lid when it detects human proximity using an ESP32 camera module. The bin also includes a disinfectant spray mechanism for surface sanitation, aimed at minimizing contact and reducing contamination risk. AI-based visual detection is used for responsiveness. While the system improves user hygiene and interface interaction, it lacks integration with predictive analytics and multi-sensor environmental monitoring essential for large-scale sanitation infrastructure.

### B. *Highly Sensitive Detection of Ammonia in Water by a Fabry–Perot Interferometer Based on Sparse Sampling and Vernier Effect*

This research proposes a novel sensor system for detecting ammonia in water, using a Fabry–Perot Interferometer (FPI) and leveraging the Vernier effect for high sensitivity. The system avoids the need for external reference cavities and achieves up to 16.1 times sensitivity enhancement. Though primarily used for liquid ammonia sensing, the core technology has implications for sanitation systems requiring accurate detection of gaseous ammonia, a key odor component in septic tanks and restrooms.

### C. *Automated Toilet Cleaning System*

This work focuses on an Arduino Uno–based automated toilet cleaning system for use in public toilets at stations and terminals. The system employs ultrasonic sensors, screw rods, pumps, and DC motors to facilitate continuous toilet cleaning with minimal human involvement. It emphasizes basic automation but lacks advanced features such as odor detection, cloud connectivity, or remote alerting capabilities, which are essential for intelligent hygiene management in complex environments.

### D. *Catalyzing Domestic Waste Management: A Deep Learning and IoT Enabled Smart Bin*

A smart bin architecture is proposed that uses a Raspberry Pi platform and a ResNet50 convolutional neural network (CNN) to classify waste in real time. The system achieves up to 95% classification accuracy and automatically routes waste into biodegradable and non-biodegradable compartments using motorized gates. While the work is focused on waste segregation, the use of AI and IoT integration demonstrates how intelligent automation can enhance the performance and efficiency of waste systems, including those used in public restrooms.

### E. *IoT Enabled Garbage Maintenance for Railway Hygiene System*

This study introduces a railway-specific waste monitoring system that utilizes ultrasonic, IR, and moisture sensors connected to an Arduino Uno to monitor garbage levels in real time. Alerts are sent to staff through a wireless interface when bins approach capacity, enabling efficient waste collection and route optimization. The system addresses core issues in waste accumulation but does not incorporate gas sensing, odor neutralization, or cloud-based data analysis, which are important aspects of comprehensive smart hygiene systems.

## IV. METHODOLOGY

The proposed IoT-enabled sanitation monitoring and odor control system is designed to provide real-time detection, automated alerts, and remote waste management in public restrooms and railway environments. This section describes the overall system approach, sensor integration, data processing using the ESP32 microcontroller, and wireless communication through cloud and Bluetooth platforms. The system is aimed at reducing manual interventions, enhancing hygiene, and enabling data-driven predictive maintenance.

The methodology adopts a modular and scalable design approach, making the system easily adaptable to varying environmental conditions and infrastructure sizes. At its core, the system integrates multiple sensing components to detect key hygiene-related parameters such as tank fill level, odor intensity, temperature, humidity, and presence of harmful gases (e.g., ammonia and hydrogen sulfide). These sensors are interfaced with the ESP32 microcontroller, which serves as the central processing and control unit. The ESP32 was chosen for its low-power operation and built-in support for both Bluetooth and Wi-Fi, enabling dual-mode communication for real-time monitoring and remote control.

A simplified block diagram of the system is illustrated in Figure 1 (Block Diagram of Recommendation), which should be included in this section. This figure represents the hardware architecture, depicting components such as IR sensors, power supply modules, Bluetooth transceivers, waste tanks, and control relays/motors for disposal.

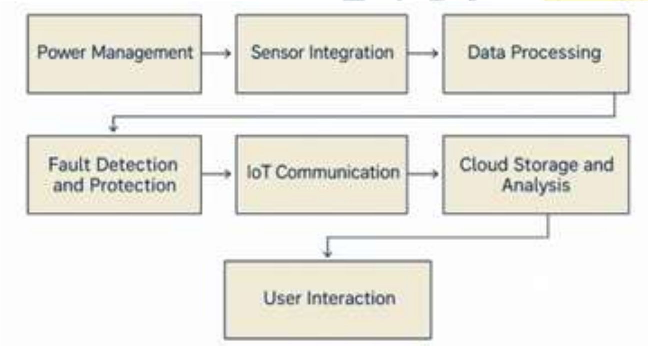


Figure 1: Block Diagram

### *A. Power Management*

Reliable power distribution is critical for uninterrupted system operation, especially in environments like moving trains or remote stations. A dedicated power management module regulates the power supply to all components. This includes the ESP32 microcontroller, IR sensors, gas sensors, relay modules, Bluetooth units, and motor drivers. The system uses a low-power design to extend battery life or reduce power draw from onboard supplies. Voltage regulation is achieved using step-down converters and surge protection circuits to safeguard sensitive electronics.

### *B. Sensor Integration*

The core functionality of the system relies on continuous monitoring of sanitation parameters. The IR sensors measure the fill level of waste bins and tanks, while gas sensors (e.g., MQ-135 or MQ-137) detect harmful gases and odor-causing substances. Temperature and humidity sensors help track environmental changes that may affect waste decomposition or sensor performance. All sensors are configured to transmit analog or digital signals to the ESP32, which converts them into readable data points.

Sensor readings are taken at regular intervals and passed through threshold evaluation logic. For instance, a tank level above 70% or an ammonia concentration beyond a predefined limit triggers specific system actions.

### *C. Data Processing and Rule-Based Decision Making*

The ESP32 microcontroller processes raw sensor data using a rule-based algorithm implemented in C/C++. This decision-making engine is designed to:

- Compare sensor readings against preset thresholds.
- Activate actuators such as exhaust fans or neutralizer pumps.
- Send Bluetooth messages to connected mobile applications.
- Trigger visual/audible alerts (e.g., buzzer or LED indicators).

This ensures that each sanitation-related event (e.g., overflow, odor spike) is handled autonomously and promptly. The rule-based system is modular, allowing future updates to incorporate fuzzy logic or AI-enhanced decision-making.

### *D. IoT Communication Layer*

For wireless transmission, the ESP32 uses Bluetooth for short-range mobile app communication and Wi-Fi/GSM (optional) for long-range cloud interaction. Bluetooth is used to relay live bin status to the staff through an Android application, which displays the current tank condition (e.g., “Filled,” “Empty,” “Moderate”). Notifications and alerts are issued in real time, minimizing the chances of overflow and sanitation failure.

For remote monitoring and predictive analytics, collected sensor data is uploaded to a cloud storage platform (e.g., Firebase or Thing speak). This enables long-term performance tracking, trend analysis, and optimization of cleaning schedules.

### *E. Fault Detection and Safety Mechanism*

To ensure operational robustness, the system includes a fault detection module that identifies sensor malfunctions or communication failures. This is done by monitoring the consistency of sensor readings and response signals. If an anomaly is detected (e.g., no data received for a set time), the system isolates the affected module and raises an alert. This prevents mis operation and ensures user safety.

### *F. Mobile App and User Interaction*

A dedicated mobile application provides sanitation staff with intuitive access to real-time data via Bluetooth. They can monitor bin status, receive alerts, and manually initiate disposal if necessary. The interface includes a dashboard showing tank fill levels, odor concentration, and system health indicators.

## V. SYSTEM ARCHITETCTURE

The proposed project, titled "A Scalable IoT-Based Solution for Waste Monitoring and Management in Railways," presents an integrated system designed to automate the process of waste monitoring and disposal within train coaches. The system architecture is built around the ESP32 microcontroller, which serves as the central unit, interfacing with water level sensors, motors, pumps, relays, and cloud platforms to ensure efficient and real-time waste management. The overall system is depicted in Figure 2.

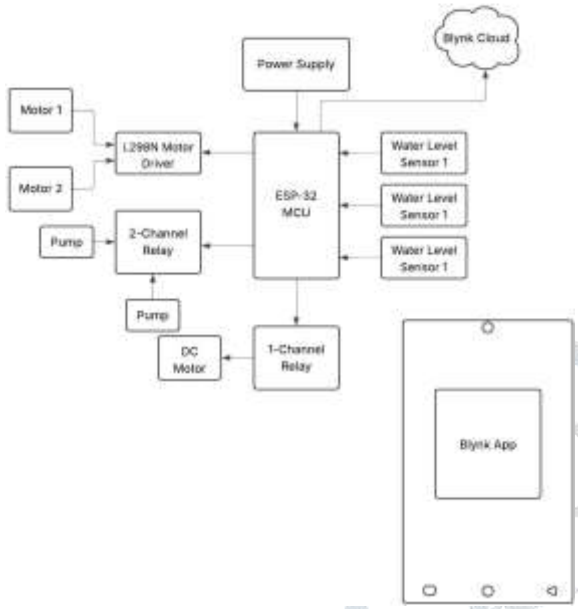


Figure 2: Proposed System Architecture for IoT-Based Waste Management

This At the core, the ESP32 MCU receives continuous input from three water level sensors, each installed in different waste or water compartments inside railway trailers. These sensors detect the waste level categorized into low, medium, or high and forward the data to the ESP32, which processes and evaluates the need for waste disposal.

The system includes two pumps connected via relay modules (2-channel and 1-channel), which are activated automatically when the sensors detect that the tank has reached the critical (high) level. These pumps drain the compartments without manual intervention, thus preventing overflow. Simultaneously, two motors are employed for mechanical actions such as lifting or discharging waste. The motor directions (forward/backward and up/down) are controlled through an L298N motor driver, allowing flexible physical motion as required.

To ensure a stable operation, a regulated power supply unit provides the necessary DC voltage to all components. Voltage regulators (e.g., 7805) step down the voltage to required levels for the ESP32 and other modules. For communication, the ESP32 uses its inbuilt Wi-Fi to connect to the Blynk Cloud Platform. Through the Blynk mobile application, railway personnel can monitor the fill levels of each trailer, receive real-time alerts, and remotely control motors or pumps using virtual buttons and sliders. The app also displays whether compartments are empty or full and shows pump activation status.

This modular architecture supports manual override and automated functionality, making it both flexible and robust. Its scalable design ensures that it can be deployed across multiple railway coaches, contributing to India's Swachh Bharat and smart infrastructure goals. Overall, the system offers a low-power, cost-effective, and real-time solution for intelligent waste handling in rail transport environments.

## VI. IMPLEMENTATION AND ALGORITHM

The implementation of the proposed IoT-based waste management system is carried out through the integration of hardware components, control logic, and cloud-based monitoring. The system operates using the ESP32 microcontroller, which connects with water level sensors, pumps, motors, and the Blynk Cloud to provide automated and remote management of waste tanks in railway coaches.

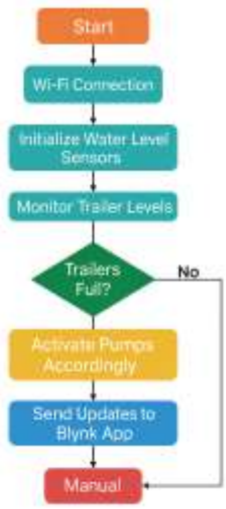


Figure 3: Flowchart for Waste Management System Operation

### *A. Step-by-Step Working*

1. System Initialization and Wi-Fi Connection: Upon startup, the ESP32 attempts to connect to the designated Wi-Fi network. If unsuccessful, it retries until a stable connection is achieved.
2. Sensor Initialization: Three water level sensors are initialized to monitor the fill status of tanks. These sensors detect three distinct levels: LOW, MEDIUM, and HIGH.
3. Monitoring and Decision Logic: The ESP32 continuously monitors sensor data. When a HIGH level is detected in any tank, it triggers the activation of the corresponding pump via relay modules.
4. Pump and Motor Control: The system uses relay modules to switch pumps ON/OFF and a L298N motor driver to control the direction and operation of motors for waste handling. If multiple tanks are full, both pumps operate simultaneously.
5. Mobile App Integration via Blynk: The Blynk mobile app allows real-time visualization and manual control of pumps and motors. It uses virtual pins (V0–V5) to activate pumps, control motor directions (forward, backward, up, down), and receive trailer status updates.
6. Loop and Re-evaluation: After executing any control action, the system loops back to monitoring the sensors, ensuring continuous and dynamic waste management.

### *B. Control Logic & Algorithms*

The control algorithm follows a threshold-based rule:

- If trailer level == HIGH → Activate pump → Notify app
- If manual input received via app → Perform action accordingly
- Continue monitoring unless interrupted

Sensor values are processed using digitalRead() functions, and actions are taken using digitalWrite() based on the status. Non-blocking logic via millis() ensures real-time responsiveness.

*C. Power Optimization and Fault Handling*

The ESP32 is programmed to detect sensor disconnection or Wi-Fi failure. In such events, it retries connections or enters a safe fail state. Power consumption is minimized through use of energy-efficient relays and non-blocking code execution.

*D. Odor Detection and Future Integration*

While odor detection (e.g., using MQ135 sensors) is not included in the current phase, the architecture supports its integration. Threshold-based gas detection can be implemented using similar logic and alert mechanisms through the Blynk app.

## VII. RESULTS AND TESTING

The proposed "A Scalable IoT-Based Solution for Waste Monitoring and Management in Railways," was developed and tested in a prototype lab environment using hardware such as ESP32 microcontrollers, water level sensors, pumps, relays, and the Blynk IoT platform for monitoring and control. The objective was to validate the system's functional accuracy, real-time responsiveness, and efficiency in comparison with traditional manual waste management methods.

*A. Test Scenarios (Prototype Validation)*

The system was evaluated under various simulated trailer conditions:

- Single Trailer Full: When only Trailer 1 was filled, the corresponding sensor triggered Pump 1 through Relay 1. The Blynk app displayed "Trailer 1 Filled" instantly.
- Multiple Trailers Full: When both Trailer 1 and 2 were full, both pumps activated simultaneously. The system responded correctly, displaying the appropriate status on the app.
- Manual Override: Via the Blynk app, pumps and motor direction (up/down, forward/backward) were manually controlled. All commands were executed with minimal delay (<1 sec).

*B. Sensor Accuracy and Alert Timing*

The water level sensors performed with 100% accuracy across all trials. Timing metrics were recorded to evaluate responsiveness:

| **Condition** | **Sensor Response** | **Pump Activation** | **App Alert Delay** |
|---|---|---|---|
| Trailer Filled | < 1 sec | < 2 sec | ~1 sec |
| Manual Pump Activation | - | < 1 sec | Immediate |

Table 1: Sensor Response and Alert Timing Performance

*C. Visual Demonstrations*

Figure 4: Smart Waste Management Prototype


Figure 5: Blynk App Interface

These visuals reinforce the claim that the system is interactive, reliable, and well-integrated between hardware and user interface.

*D. Comparison with Traditional Methods*

Unlike traditional railway waste systems which rely heavily on manual inspections and fixed cleaning schedules this smart solution offers a real-time, condition-based approach. In conventional methods, waste overflow is often only noticed after passenger complaints or during scheduled cleaning rounds, leading to hygiene issues and poor user experience.

The IoT-based system overcomes these limitations by continuously monitoring waste levels and automatically alerting authorities when thresholds are crossed. Moreover, the ability to trigger waste disposal remotely eliminates unnecessary manual labor and enhances efficiency. The speed of response, automation, and scalability make this system significantly superior in both operational and hygienic outcomes.

## VIII. DISCUSSION

The testing and evaluation of the Smart Waste Management System confirm its potential to improve sanitation practices in railway environments through IoT-based automation. The system's real-time monitoring, automatic waste disposal, and mobile interface functionalities address several limitations of traditional manual systems.

The prototype successfully detected tank fill levels using water-level sensors and activated pumps via relay modules when thresholds were exceeded. Data was transmitted to the Blynk mobile application with minimal delay, enabling remote supervision and manual override. These results confirm the system's effectiveness in reducing overflow incidents, streamlining operations, and improving hygiene.

Key Benefits: The system delivers multiple practical advantages:

- Automation eliminates the need for routine manual checks and reduces human effort.
- Timely Alerts ensure proactive disposal of waste before tanks overflow.
- Improved Hygiene through continuous monitoring and rapid response.

- Cost-Effective Deployment due to the use of affordable components like ESP32 and relays.
- Remote Access via the Blynk app increases convenience and operational efficiency.

Limitations: Despite its strengths, the system has a few notable constraints:

- Wi-Fi Dependency: In areas with poor connectivity, real-time alerts may be delayed.
- Sensor Durability: Low-cost sensors might degrade over time when exposed to moisture and waste residues.

Scope for Improvement: Several enhancements could increase the system's robustness and adaptability. Integrating solar power or battery backup would enable deployment in remote or mobile settings. Using more durable sensors resistant to corrosion or waste material buildup would improve long-term accuracy. Additionally, adding data analytics for predictive maintenance can help schedule cleaning more efficiently, preventing system failures. GPS integration could support location-based monitoring and waste collection planning.

## IX. CONCLUSION

The project titled "A Scalable IoT-Based Solution for Waste Monitoring and Management in Railways," introduces an innovative and efficient approach to addressing sanitation issues in the railway sector. Utilizing IoT components such as the ESP32 microcontroller, water level sensors, relay-operated pumps, and the Blynk mobile application, the system enables real-time monitoring of waste levels, automated waste disposal, and remote user control. The successful prototype demonstrated accurate tank level detection, timely pump activation, and user-friendly mobile updates, minimizing manual inspections and preventing tank overflows. Its low power consumption and scalable design make it ideal for deployment across multiple coaches and stations. The solution aligns with national initiatives like Swachh Bharat Abhiyan and Smart Cities Mission, enhancing cleanliness and operational efficiency in public transport.

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