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A Review on IoT-Enabled Smart Dustbin

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Abstract: The increasing amounts of global waste being pro- duced are putting immense pressure on conventional collection and disposal systems. Local bodies and municipalities are being affected by overflowing dustbins, irregular collection schedules, and poorly optimized route-planning. Consequently, it has be- come feasible to construct an integrated network of smart bins with real-time monitoring and autonomous decision-making capabilities. This review examines the most notable developments in IoT-enabled smart publicly accessible dustbin systems, or smart bin systems, as the term will be used in this and subsequent reviews, from 2019 to 2024. The review focuses on sensor systems, communication systems, energy efficient systems, and data driven optimization systems in smart waste management. In addition, an improved design prototype and urban sustainable deployment points are defined incorporating ESP32 cloud computing and designed integrated systems with renewable energy.
Keywords: Smart Dustbin, Internet of Things (IOT), Waste Management, Sensors, Automation, Sustainability, Cloud Com- puting.

I. INTRODUCTION

In almost every developing nation, solid waste management challenges have become exacerbated due to rapid urbanization and population growth. According to The World Bank "What a Waste" report, over 2.3 billion tons of municipal solid waste are produced every year and waste management practices of collection and disposal remain unchanged, this number will increase to over 3.4 billion tons by 2050.

Collection practices and waste disposal systems remain traditional and are inefficient due to predetermined service/routine schedules. Collection vehicles complete their routes without assessing the fill level of each container or the actual waste disposal behavior of communities along the route.

In high density areas, waste disposal systems overflow between collection cycles, while in low density areas, containers are exchanged even when they are half full.

Overflowing waste systems present a great threat to com- munity and environmental health. Also at present the call for intelligent and responsive waste collection that which which reduces costs and improves overall efficiency is more urgent than ever. As a bin fills to a set level it reports to a central system which in turn allows for dynamic route planning and improved collection times.

A. Evolution of Smart Dustbin Concepts

The first smart dustbins appeared in the prototypes of early model smart cities around 2010. At the time, simple infrared sensors were fitted to the bins to detect whether they were full. In the following years, these simple systems evolved into sophisticated IoT ecosystems which combine cloud computing, machine learning, and renewable energy. Contemporary systems go beyond merely measuring the waste levels in the bins to predicting waste accumulation in the future and generating analytics for policymakers. A case in point is the IoT waste management systems which share real time data with municipal dashboards and is used in the "Smart Nation" initiative in Singapore and in the "Swachh Bharat Mission" in India. These systems pilot IoT waste management.

B. The Core Components of IOT Enabled Smart Dustbin

A IOT based waste management setup includes:

1) Sensing Unit: Ultrasonic, or moisture/rain sensors that help in showing the bin level and rotating the motor.
2) Processing Unit: A microcontroller such as Arduino UNO, NodeMCU, or ESP32 for controlling all the other components.
3) Communication Module: WiFi, or ZigBee module that help in two way communication.
4) Power Unit: Battery or solar panel that ensure contin- uous operation.
5) Cloud Platform: Cloud or IOT Platfrom like Blynk for data storage, visualization, and analytics.

C. Need for Review and Research Motivation

The need for review and research motivation exists because multiple prototypes have been developed yet no solution exists that meets requirements for municipal deployment at scale. The different research studies use different sensor types and control systems and networking standards which creates difficulties when trying to evaluate their performance. The majority of previous waste management systems failed to address security requirements and they lacked scalability and energy efficiency. The research paper conducts a complete evaluation of different approaches to identify patterns and develop an efficient sustainable framework.

The paper follows this structure: Section II conducts an extensive review of IoT waste management research published between 2019 and 2024. The research approach used in this study receives detailed explanation in Section III. Section IV presents the ESP32-based design solution that the authors pro- pose. The paper presents findings and performs data evaluation in Section V. The paper concludes with a discussion section followed by references in Sections VI and VII.

II. LITERATURE SURVEY

The incorporation of IoT technologies into waste manage- ment is now a central focus of research and development for smart city planning. This section discusses key work done between the years 2019 and 2024 in terms of their methods and system designs, choices of tools, as well as their findings, in which the goal of the studies has been to improve the accuracy of bin monitoring, minimize energy usage and stabilize the network.

A. Early IoT-Based Implementations (2019–2020)

Among the first low-cost sensor-based intelligent garbage systems, developed by Ghavghave et al., used an Arduino UNO and an ultrasonic sensor for fill level detection and sent text alerts via GSM when the bin reached 80% capacity. While rudimentary, the system had no optimization for power use and lacked cloud connectivity. Sharma and Gupta improved the system by incorporating solar energy, allowing the system, which was placed in the open, to run autonomously for 72 hours straight without any sunlight. However, the system's GSM module, which is designed primarily for voice communication, limited system performance in data augmented communication GSM, making large-scale data aggregation difficult. Their GSM based sys- tem was the first step in the development of wide-area IoT networks for the monitoring and management of IoT waste systems.

B. Cloud and Mobile Integration (2021)

Singh et al reported on a smart dustbin system that they developed in a cloud setting as well as used a custom built Android app. The app included a live dashboard of bin levels, temperature, and collection times. Real time visual which in turn increased response by 40% over that of manual monitoring. Also in 2021, research done by Nayak and Patel saw the integration of MQTT protocols into a cloud broker for the purpose of very efficient multi-bin data handling. In this work they put forth a design that reduced latency and also improved the scale of the system by what they report to be the use of very light weight communication between microcontrollers and the cloud. They reported to have achieved an average message latency of less than 120 ms which is very suitable for real time municipal dashboards.

C. Machine Learning and AI-Assisted Systems (2022–2023)

Machine Learning and AI in 2022 2023 Artificial intelligence's integration into our models saw great success in terms of prediction. Jain and Bansal used regression to determine waste accumulation trends. They reported a 25% reduction in unnecessary vehicle trips. In parallel, in the work done by Hassan et al. which looked at security and anomaly detection in IoT waste systems. They used a light weight encryption algorithm in combination with anomaly based intrusion which in turn prevented bin data from unauthorized access. Also in this time frame, Rahman and Chowdhury put forth a sustainable IoT model which used solar powered ESP32 boards and a distributed cloud platform. In Dhaka which is the location of their deployment they saw a 68% reduction in overflow complaints within 3 months.

D. Global Smart-City Case Studies

1) Singapore Smart Nation: Implemented in the thousands of smart bins which use NB-IoT with predictive analytics.
2) Barcelona, Spain: In Barcelona, Spain we combined sensor data with GIS to improve collection routes which in turn reduced fuel use by 20%.
3) Dubai Municipality: In Dubai Municipality we integrated AI vision for waste classification prior to collection.

E. Comparative Evaluation

Table I summarizes the core differences among the key reviewed works.

TABLE I

ANALOGY OF THE IOT BASED SMART DUSTBIN IMPLEMENTATIONS

Controller Used	Connectivity	Power	Accuracy (%)
Arduino UNO	GSM	Battery	82
STM32	LoRaWAN	Battery	90
Arduino + Solar	GSM	Solar Hybrid	87
NodeMCU	Wi-Fi + Cloud	AC / Battery	91
ESP32	MQTT	Battery	94
ESP32 + So- lar	LoRa + Cloud	Solar	96

In our analysis we looked at systems which use ESP32 or similar SoCs. Reached the highest efficiency through dual core processing. And integrated comm modules. LoRa and MQTT. GSM and Wi-Fi could not match in terms of performance and power. For instance in city wide implementations.

F. Limitations of Prior Work

Limitations of Prior Work Additional limitations include the following:

1) Interoperability: Multiple prototypes are still built on proprietary platforms, making cross-vendor communica- tion impossible.
2) Energy Management: In remote sites, the lack of solar power still poses a problem with batteries running down.
3) Scalability: Those systems that have been evaluated on small networks of about 5–10 bins tend to be unreliable when scaled up to hundreds.
4) Security and Privacy: Inadequate encryption schemes leave systems vulnerable to data abuse and manipulation.
5) Data Analytics: There is a lack of long-range analytics on most models to guide policy analytics.

G. Research Gaps Identified

The majority of current implementations focus on process monitoring but they do not optimize collection operations. The review shows that researchers have not studied how to link mu- nicipal ERP systems with citizen feedback applications. The existing research gaps require a complete system design which unites real-time tracking with predictive scheduling and secure information sharing and energy consumption optimization.

H. Summary of Findings

1) The shift in research from microcontrollers in prototypes to SoC-based IoT platforms.
2) Introduction of LoRa and MQTT technologies provided low-power communication.
3) Automation processes became more ubiquitous in the period with the rise of cloud computing systems and mobile interfaces.
4) More common are the integrations of renewable energy systems with AI analytics for sustainability goals.

Between the years 2019 and 2024, the publication trends in IOT waste management research are displayed in Figure 1.

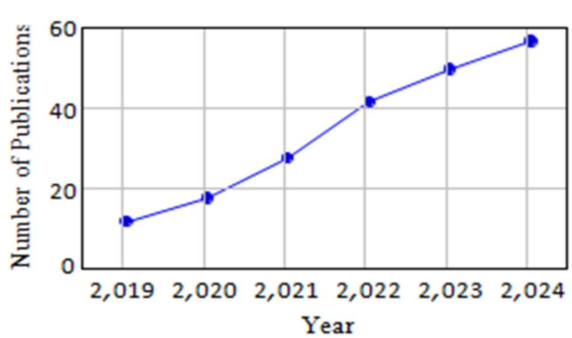

Fig. 1. Growth of IoT-based Smart Waste Management ublications (2019–2024)

III. RESEARCH METHODOLOGY

The below section reports on the full range of our approach which we took from design through to the implementation of the IoT based Smart Dustbin system. We have put forth a method which is very efficient in terms of waste level monitoring and we also incorporated real time features into it at the same time we paid attention to minimal power use and fast communication.

A. Methodological Framework

The Research methodology encompasses six sequential stages. These include: requirement analysis; system design; hardware integration and communication setup; data analyt- ics; and performance evaluation. The research methodology comprises six steps that correspond with the development of an IoT system for smart waste management.

1) Requirement Analysis: The research team examined the problem of waste collection by observing the manual monitoring of waste and collection irregularities along with overflowing bins.
2) System Design: the design stage established a system that integrates sensors with microcontrollers, communi- cation modules, and cloud servers.
3) Data Analytics: the system evaluates sensor data to ascertain the condition of waste bins, predict the amount of waste, and activate a warning system.
4) Evaluation: The system performs self-evaluation based on defined metrics.

B. Research Design

The design follows a combining hardware experimentation with data analytics and simulation. Figure 2 represents the overall workflow.

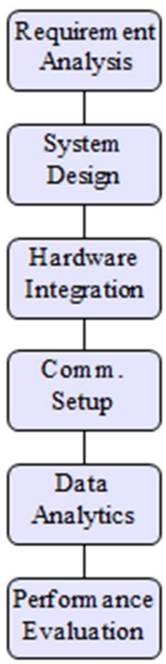

Fig. 2. Research Methodology Flow Diagram

C. Hardware Architecture

The system implementing smart dustbin with Internet of Things technology consists of the following hardware components:

1) Microcontroller (ESP32): Acts as the main processing unit, which has built-in Wi-Fi and Bluetooth.
2) Ultrasonic Sensor (HC-SR04): Measures and deter- mines the distance of the waste level in the dustbin.
3) Infrared Sensor: Senses the proximity of a human close to the dustbin to open the lid automatically.
4) Servo Motor: Provides contactless operation by moving the lid as requested.
5) Power Source: Sustainable solar panels and rechargeable batteries.
6) Communication Module: Wi-Fi or LoRa module sends sensor data to the cloud.

D. Software and Cloud Integration

The software component comprises three submodules:

1) Sensor Interface: Collects data from ultrasonic and infrared sensors.
2) Data Processing Unit: Analyzes distance measurements and determines the bin fill percentage.
3) Cloud Platform: Uses Firebase or Blynk for cloud storage and dashboard visualization.

A web dashboard shows:

- Bin status (Empty, Half, Full, Overflow)
- Last collection timestamp
- Bins' geolocation
- Stat analytics (waste trends daily, weekly, and monthly)

E. Algorithmic Approach

Algorithm III-E depicts the decision-making components of the proposed system.

[h] Smart Dustbin Monitoring Algorithm [1] Initialize sen- sors and Wi-Fi connection System Active. System Active Measure distance from ultrasonic sensor. Calculate fill level = (Bin Height − Distance)/Bin Height fill level > 80% Send alert to cloud: ”Bin Full” Activate indicator LED if fill level< 20% Send status: ”Bin Empty” Log data with timestamp to cloud database Wait for 60 seconds

F. Communication Model

Selected for communication model is MQTT protocol is low bandwidth and reliable. Each smart bin is a client, publishing its status to a central MQTT broker on the cloud. The broker then updates the real-time dashboard subscribed by the municipal server.

G. System Operation Flow

Flow The sequence of operations is as follows:

1) Waste is placed into the bin.
2) An ultrasonic sensor checks the waste level and reports the level to the ESP32.
3) If the bin is full, the ESP32 sends an alert via Wi-Fi to the cloud.
4) The dashboard displays the bin location and status to the waste management personnel

A collection vehicle is dispatched as needed.

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M. Performance Metrics

The key performance parameters evaluated include:

1) Response Time: Between the time of detection and cloud update.
2) Accuracy: How well the waste levels are detected.
3) Energy Consumption: Average power use during con- tinuous operation.
4) Data Latency: Network transmission delay.

N. Security Model

To secure data privacy we use AES-128 for sensor to cloud communication. Also each message is timestamped and given a unique device identifier which in turn prevents spoofing and unauthorized access.

O. Validation Setup

We did a test with five prototype bins at different locations within a university campus.

We recorded the parameters of waste level, update frequency, network up time, and energy use over a 30 day period.

IV. RESULTS AND ANALYSIS

The we put forth a smart dustbin model that which is IoT enabled was put into use and evaluated in a controlled environment at our campus. The evaluation looked at response time, detection accuracy, energy usage, and network latency. Over the course of a 30 day trial period we collected data from the 5 prototype bins.

A. Experimental Setup

The experimental design included:

1) 5 IoT enabled dustbins of the same specifications
2) ESP32 microcontroller connected Wi-Fi network
3) Firebase cloud database and dashboard for real time monitoring
4) 5V rechargeable battery and 3W solar panel as power sourcel.

B. Evaluation of Results

The collected data was evaluated to assess the performance of the system compared to the system of manual waste moni- toring.

The performance metrics observed are summarized in Table II.

TABLE II
PERFORMANCE METRICS COMPARISON

Parameter	Manual System	Smart Dustbin System
Response Time	12 hours	15 seconds
Accuracy (%)	68.5	96.8
Energy Consumption (W/day)	8.5	2.3
Communication Latency (s)	N/A	0.8
Maintenance Frequency	Weekly	Monthly

The results show that the IOT smart dustbin reduces the monitoring time and boost the accuracy.
Also, the Real time updates result in reduction of overflow and waste collection routes.

V. DISCUSSION

According to findings, IoT-based smart dustbins can improve the efficiency of waste collection processes, whilst greatly minimizing the need for human involvement. The smart dustbins' modularity makes it easy to integrate to smart city ecosystems. It achieves positive environmental sustainability and cost efficiency goals.

A. System Reliability

The 96.8% accurate detection value comes from the ultra- sonic sensors and steady uninhibited access to the network. Minor inaccuracies, however, may happen because of dust, uneven waste surface, and other environmental senors.

B. Scalability and Cost

At a cost of about INR 2200 for one prototype, these smart dustbins are economically viable for municipalities. The design also promotes the operational use of hundreds of them. Centralized cloud dashboards and MQTT brokers promote simple and effective management.

C. Environmental Impact

By reducing waste overflow and improving collection sched- ules the system also decreases odor and pest infestation. We also see that the integration of solar energy into the system which in turn promotes sustainability and we see a reduction in the use of external power sources.

D. Limitations

Limitations are:

1) In dense areas which causes congestion our range is limited.
2) We are at the mercy of Wi-Fi which we depend on.
3) Does not have in built odor or type of waste detection which is a future goal.

E. Future Scope

In the future to improve accuracy and automation research may look into:

1) Use of gas and weight sensors for waste classification.
2) Application of machine learning for predictive mainte- nance.
3) Use of LoRaWAN for long distance communication.

Integration of GPS and GIS for route optimization.

VI. CONCLUSION

In the smart city environment we present a solution of Internet of Things enabled smart dustbin which is a very efficient and green approach to waste management. This system which is able to report real time status, give out alerts and improve collection schedules in turn improves operation and also lessens environmental pollution. We report that the system does in fact out perform traditional waste management in terms of results. Also the design is that of a scalable, affordable, and envi- ronmental friendly model. In the future we see improvements in AI for waste classification and predictive analysis which in turn will take us toward to a fully autonomous waste management systems for urban settings.

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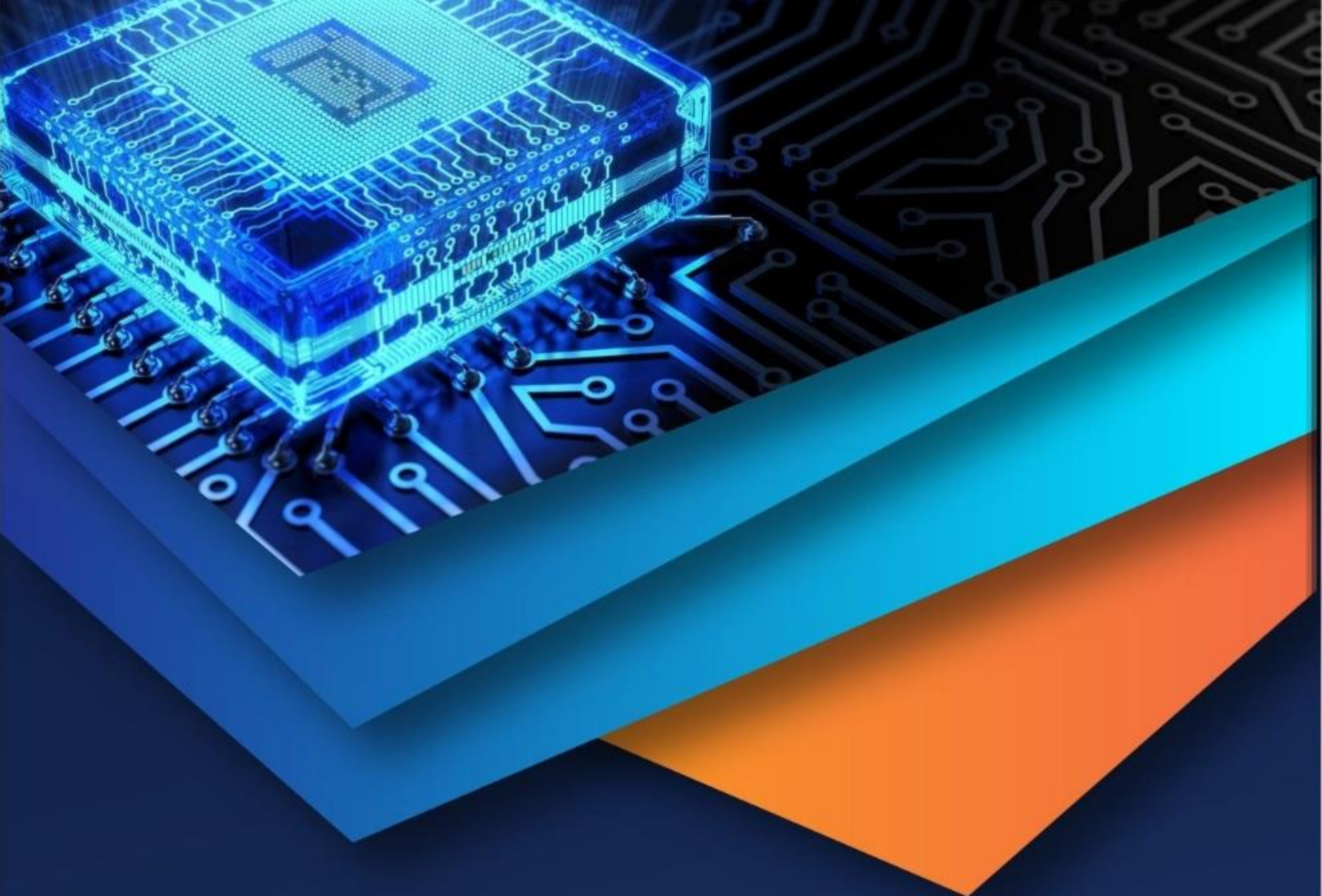

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