World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

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Smart city approach to intelligent waste volume management

Taiwo Bakare-Abidola [1,*], Jelil Olaoye [2], Bello Hafisat Omodasola [3], Bello Abdur-Rafiu Adekunle [4], Nebechi Kate Obiora [5] and Dauda Umar Muhammad [6]

[1] *Department of Environmental Science, Georgia Southern University, Georgia, USA.*
[2] *Department of Applied Physical Science, Environmental Science Concentration, Georgia Southern University, Georgia, USA.*
[3] *Department of Geography and Environmental Management University of Ilorin, Ilorin, Kwara State, Nigeria.*
[4] *Department of Telecommunications Engineering, Federal University of Technology, Minna, Nigeria.*
[5] *Africa Center of Excellence for Sustainable Power and Energy Development, ACE- SPED, University of Nigeria, Nsukka 410001, Nigeria.*
[6] *Department of Electrical and Electronics Engineering Kebbi State University of Science and Technology Aliero, Nigeria.*

World Journal of Advanced Research and Reviews, 2025, 25(03), 854-862

Publication history: Received on 03 February 2025; revised on 10 March 2025; accepted on 12 March 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.25.3.0792

Abstract

This study introduces an innovative system designed to revolutionize waste management by integrating technologies. The proposed solution leverages the Internet of Things (IoT) to create smart waste bins equipped with sensors that monitor fill levels in real time. These sensors transmit data to an IoT-based platform, where it is processed to optimize waste collection routes and generate actionable insights for resource allocation and service improvement. Additionally, the system empowers citizens by providing real-time access to waste bin statuses through a user-friendly mobile application or web interface. A functional prototype of the smart bin, along with the waste management application, was developed and tested in a real-world scenario. The results demonstrate the system's potential to transform waste disposal practices, enhance operational efficiency, and optimize the use of economic and material resources.

Keywords: Waste Volume Optimization; Real-Time Monitoring; Route Optimization; Predictive Analytics; Sustainable Waste Management; Smart Bins

1. Introduction

Waste management has emerged as one of the most pressing challenges of the 21st century, driven by rapid urbanization, population growth, and increasing consumption patterns. According to the World Bank (2018), global waste generation is projected to increase by 70% by 2050, reaching 3.4 billion tons annually. Urban areas, which account for the majority of this waste, are particularly vulnerable to the inefficiencies of traditional waste management systems. These systems, which rely on fixed schedules and manual processes, often result in overflowing bins, irregular collection, and environmental pollution (Kaza et al., 2018). "Smart Cities" have emerged, encompassing smart grids, smart transportation, smart manufacturing, smart buildings, and more. (Taiwo et al., 2024). In smart cities, IoT sensors collect data on waste management, enabling data-driven decision-making. Additionally, IoT enhances public safety, security, and environmental monitoring. Recently, there has been a growing interest in integrating IoT technology into waste management systems.(Akintayo et al., 2024). Inefficient waste management not only exacerbates environmental degradation but also poses significant public health risks and economic burdens. For instance, improper waste disposal contributes to air and water pollution, greenhouse gas emissions, and the spread of diseases (Wilson et al., 2015). As cities continue to grow, there is an urgent need for innovative solutions to address these challenges and transition toward sustainable waste management practices. The concept of smart cities has gained traction as a transformative

* Corresponding author: Taiwo Bakare-Abidola

approach to addressing urban challenges, including waste management. Smart cities leverage advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing to create intelligent systems that optimize resource use, enhance service delivery, and improve quality of life (Anthopoulos, 2017). In the context of waste management, these technologies enable real-time monitoring, predictive analytics, and data-driven decision-making, shifting from reactive to proactive approaches. For example, IoT-enabled smart bins can monitor waste levels in real time and transmit data to centralized systems, allowing municipalities to optimize collection routes and reduce operational costs (Zanella et al., 2014). Similarly, AI algorithms can analyze historical and real-time data to predict waste generation patterns, enabling proactive resource allocation and reducing environmental impact (Rathore et al., 2016). By integrating these technologies, smart cities can transform waste management into a more efficient, sustainable, and citizen-centric process.

The adoption of smart waste management systems offers numerous environmental and economic benefits. Real-time monitoring and route optimization can significantly reduce fuel consumption and greenhouse gas emissions associated with waste collection vehicles (Marshall & Farahbakhsh, 2013). For instance, a study in Amsterdam demonstrated that optimizing waste collection routes using big data analytics reduced fuel consumption by 20% (Rathore et al., 2016). Additionally, smart waste management systems can promote recycling and resource recovery, contributing to the principles of a circular economy. By providing citizens with real-time information about waste bin statuses and collection schedules, these systems can also enhance public participation and awareness, fostering a culture of sustainability (Nam & Pardo, 2011). Furthermore, the data generated by smart waste management systems can inform policy decisions and long-term urban planning, enabling cities to achieve their sustainability goals (Al Nuaimi et al., 2015). Despite the potential benefits, the implementation of smart waste management systems faces several challenges. High initial costs, particularly for IoT infrastructure and AI algorithms, are a significant barrier for many municipalities, especially in developing countries (Anthopoulos, 2017). Data privacy and security concerns also arise from the collection and analysis of large volumes of data, necessitating robust cybersecurity measures (Rathore et al., 2016). Social challenges, such as public resistance to change and lack of awareness, further hinder the adoption of smart waste management systems (Nam & Pardo, 2011). Addressing these challenges requires a collaborative approach involving governments, private sector stakeholders, and the public. Policymakers must also prioritize investments in infrastructure and technology, while fostering public awareness and engagement to ensure the successful implementation of smart waste management systems. This paper makes the following key contributions to the field of smart waste management (1) Development of a Smart Waste Bin Prototype: A novel IoT-based smart waste bin is proposed and implemented as a functional prototype. This bin is equipped with sensors to monitor waste levels in real time, enabling efficient waste collection and management. (2) Integration with IoT Middleware: The smart waste bin is seamlessly integrated with an IoT middleware platform, which processes and analyzes the collected data to optimize waste collection routes and generate actionable insights. (3) User-Centric Mobile and Web Applications: A new mobile application and its web counterpart are developed to enhance interaction between waste generators (residential users) and the waste management system. These applications provide real-time information about waste bin statuses, collection schedules, and user-specific waste management tips. The remainder of this paper is structured as follows Section 2: A review of related work on waste management, highlighting the most relevant solutions and advancements in the literature. Section 3: A detailed description of the proposed solution, including the design and implementation of the hardware (smart waste bin), software (mobile and web applications), and communication infrastructure. Section 4: An analysis of the performance and effectiveness of the proposed system, based on real-world deployment and testing of the prototype. Section 5: Conclusions drawn from the study, along with potential future research directions and improvements.

2. Review of Related Work

Traditional waste management systems have long relied on fixed schedules and manual processes, which are increasingly inadequate in addressing the growing volume and complexity of urban waste. According to Kaza et al. (2018), these systems often result in inefficiencies such as overflowing bins, irregular collection, and environmental pollution. For instance, in many developing countries, waste collection services are infrequent and unreliable, leading to the accumulation of waste in public spaces and the spread of diseases (Wilson et al., 2015). Furthermore, the lack of real-time data on waste generation and collection routes results in unnecessary fuel consumption and greenhouse gas emissions (Marshall & Farahbakhsh, 2013). These challenges highlight the urgent need for innovative approaches to waste management that can adapt to the dynamic nature of urban environments.

The integration of the Internet of Things (IoT) into waste management has emerged as a promising solution to address the inefficiencies of traditional systems. IoT-enabled devices, such as smart bins equipped with sensors, can monitor waste levels in real time and transmit data to centralized systems for analysis (Zanella et al., 2014). For example, a study by Rathore et al. (2016) demonstrated that IoT-based smart bins could reduce waste collection costs by 30% by optimizing collection routes based on real-time data. Similarly, in Barcelona, the deployment of IoT-enabled smart bins and GPS-equipped waste collection vehicles resulted in a significant reduction in operational costs and improved service efficiency (Bakici et al., 2013). These findings underscore the potential of IoT technologies to transform waste management into a more efficient and sustainable process.

Artificial intelligence (AI) and big data analytics have also played a critical role in advancing smart waste management systems. AI algorithms can analyze historical and real-time data to predict waste generation patterns, enabling proactive resource allocation and reducing environmental impact (Al Nuaimi et al., 2015). For instance, a study in Seoul, South Korea, used machine learning to predict daily waste generation with an accuracy of 85%, allowing for more efficient waste collection schedules (Lim et al., 2018). Big data analytics, on the other hand, integrates data from multiple sources, such as weather forecasts, population density, and waste generation trends, to provide actionable insights for waste management (Rathore et al., 2016). In Amsterdam, the use of big data analytics for route optimization reduced fuel consumption by 20% and lowered greenhouse gas emissions (Rathore et al., 2016). These advancements demonstrate the potential of AI and big data analytics to enhance the efficiency and sustainability of waste management systems. Citizen engagement is a critical component of smart waste management systems, as it encourages public participation and awareness. Mobile applications and web platforms have been developed to provide citizens with real-time information about waste bin statuses, collection schedules, and recycling tips (Nam & Pardo, 2011). For example, a study by Anthopoulos (2017) highlighted the success of a mobile application in Singapore that allowed citizens to report waste-related issues and access information about nearby recycling facilities. Similarly, in Copenhagen, a cloud-based waste management system enabled citizens to monitor waste collection activities in real time and provide feedback to municipal authorities (Anthopoulos, 2017). These initiatives demonstrate the importance of citizen engagement in fostering a culture of sustainability and improving the effectiveness of waste management systems.

Despite the promising advancements in smart waste management, several challenges and limitations remain. High initial costs, particularly for IoT infrastructure and AI algorithms, are a significant barrier for many municipalities, especially in developing countries (Anthopoulos, 2017). Data privacy and security concerns also arise from the collection and analysis of large volumes of data, necessitating robust cybersecurity measures (Rathore et al., 2016). Social challenges, such as public resistance to change and lack of awareness, further hinder the adoption of smart waste management systems (Nam & Pardo, 2011). Additionally, the rapid evolution of technology means that many existing solutions may become obsolete, requiring continuous updates and investments (Al Nuaimi et al., 2015). Addressing these challenges requires a collaborative approach involving governments, private sector stakeholders, and the public. While significant progress has been made in the development and implementation of smart waste management systems, several research gaps remain. For instance, there is a need for standardized frameworks and guidelines to facilitate the integration of IoT, AI, and big data analytics into existing waste management systems (Al Nuaimi et al., 2015). Additionally, further research is needed to explore the potential of emerging technologies, such as blockchain, for transparent and secure waste tracking (Lim et al., 2018). Future studies should also focus on the social and economic impacts of smart waste management systems, particularly in developing countries where resource constraints and infrastructure limitations are more pronounced (Wilson et al., 2015). By addressing these gaps, researchers can contribute to the development of more efficient, sustainable, and inclusive waste management systems.

2.1. Proposal of the My Waste Management Solution for Smart Cities

The current waste management systems employed in urban areas are outdated and fail to meet the evolving needs of modern municipalities. These systems rely on large fleets of collection vehicles that traverse extensive and often inefficient routes on fixed daily or weekly schedules. This approach results in unnecessary costs, wasted time, and significant environmental harm. The excessive use of fossil fuels contributes to greenhouse gas emissions, while poor waste management practices lead to soil and water contamination, further exacerbating environmental degradation. This paper introduces an innovative solution that integrates hardware, software, and communication technologies to optimize urban waste management. The proposed system aims to reduce public expenditure, minimize environmental impact, and promote active citizen participation in waste management processes. By leveraging advanced technologies, the solution seeks to create a more efficient, sustainable, and citizen-centric waste management model. The research methodology adopted in this study is based on a case study approach, involving the real-world deployment of the proposed solution. A functional prototype of the smart waste container and a waste management application, integrated through the In. IoT middleware, were developed and tested in a real-world scenario. The system's performance and effectiveness were validated through practical experimentation. The proposed solution is described in detail below.

2.2. IoT Architecture Reference Model for the Waste Management System

To ensure standardization and interoperability in IoT-based waste management systems, a reference architecture model is essential. Such a model enables seamless connectivity between IoT devices, often referred to as "objects," and addresses challenges related to scalability, interoperability, reliability, and quality of service. numerous IoT reference architectures and models have been proposed by various research groups and organizations. However, the lack of a unified framework often leads to conflicting ideas and complicates the standardization process.

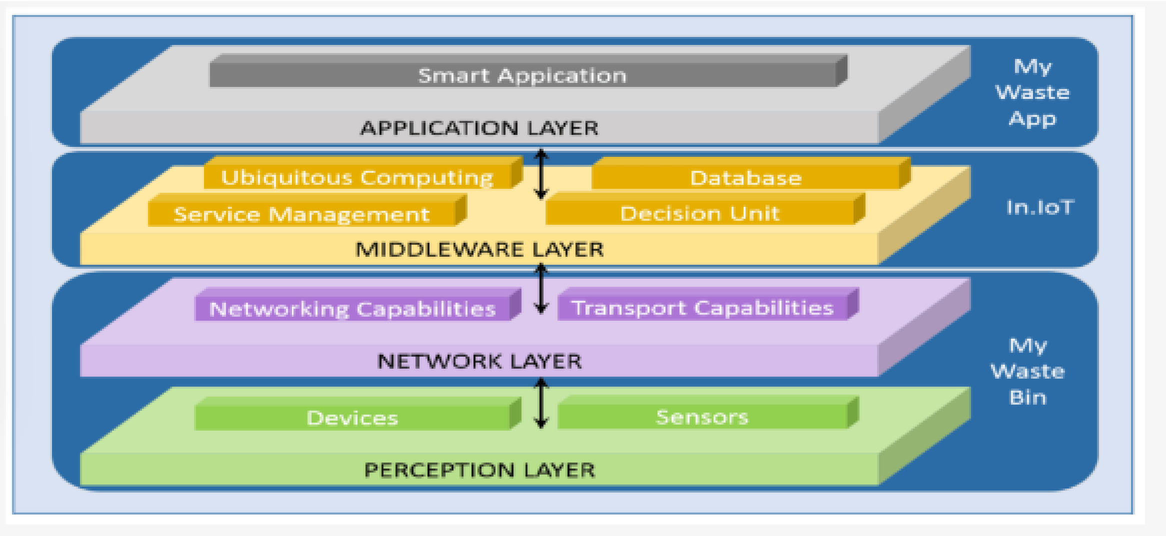

Figure 1 Architecture for the waste management System

Many IoT architecture models are designed based on specific needs or structured around fundamental layers. A common approach involves a three-layer architecture consisting of the application layer, network layer, and perception layer.

2.3. Layered IoT Architecture for Waste Management

The IoT architecture is structured into distinct layers, each serving a specific function within the system. These layers are designed to work in harmony, ensuring efficient data collection, transmission, processing, and user interaction.

2.3.1. Perception Layer

The perception layer, analogous to the physical layer in the Open Systems Interconnection (OSI) model, operates at the hardware level. Its primary role is to gather physical data, process it, and transmit it securely to higher layers. This layer utilizes specialized sensors to detect and measure parameters such as weight, temperature, humidity, and other environmental factors. Additionally, it collects identification data from objects using technologies like QR codes and RFID tags.

2.3.2. Network Layer

The network layer is responsible for transmitting the data collected by the perception layer to the upper layers, where processing occurs. It employs various communication protocols, including ZigBee, Z-Wave, GSM, UMTS, Wi-Fi, Infrared, and 6LoWPAN. Beyond data transmission, this layer also handles cloud computing and data management processes, ensuring seamless connectivity and efficient data flow.

2.3.3. Middleware Layer

The middleware layer acts as a software intermediary that enables communication between IoT components that would otherwise be incompatible. It functions as an interpreter, facilitating interaction between the application and perception layers. This layer plays a critical role in ensuring effective communication and supports the development of new IoT technologies by providing concurrency and interoperability.

2.3.4. Application Layer

While the application layer does not directly contribute to the IoT architecture's construction, it is where user-facing services are developed. This layer interprets and presents the collected data to users, making it accessible and actionable. It serves as the interface between the system and its end-users, enabling them to interact with and benefit from the IoT infrastructure.

2.4. Architecture of the My Waste Management System

The proposed system features a practical solution where waste compartments are continuously monitored by sensors. These sensors provide real-time data on the fill levels of each compartment, which is then transmitted to a central processing unit. This data enables authorities to identify priority collection areas, optimize collection routes, and generate statistical insights for efficient resource allocation. The system's primary focus, however, is to empower citizens by providing them with real-time information about nearby waste bins.

Through a web or mobile application, users can check the fill levels of waste compartments near their homes. If the nearest bin is full, the system directs users to the next available disposal point and provides an estimated collection time for the full bin. This feature allows users to decide whether to dispose of their waste at a slightly farther location or wait until the nearest bin is emptied.

The My Waste Management system is divided into three main components,

- Smart Bin: Equipped with sensors to monitor fill levels and transmit data.
- IoT Middleware: Integrates and processes data from the smart bins.
- User Application: Provides citizens with real-time information and disposal options via a web or mobile interface.

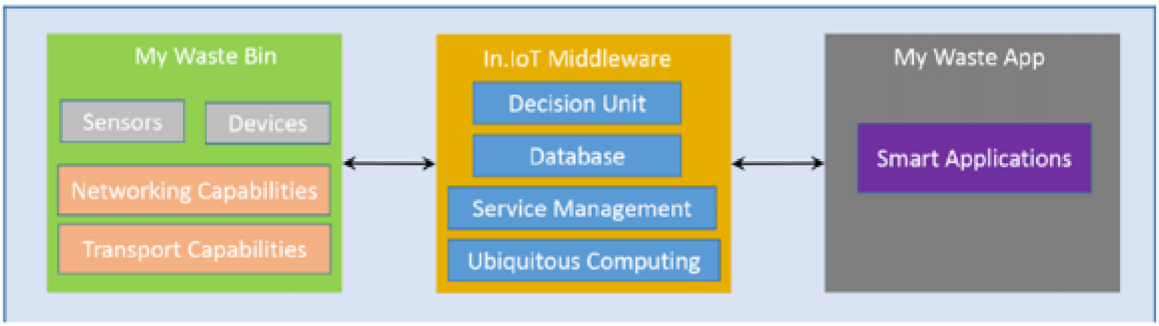

Figure 2 System Architecture

System Overview: Hardware, Software, and Communication Technologies

The proposed system integrates hardware, software, and communication technologies to optimize urban waste management. Below, we describe the components of the system and demonstrate how it can be effectively utilized to enhance waste management in cities.

2.5. My Waste Bin

The smart waste bin consists of a container with a lid, equipped with various sensors to monitor waste levels. The HC-SR04 ultrasonic sensor measures the fill level of the compartment, preventing overflow and excessive waste accumulation. A load cell module, coupled with an HX711 driver, measures the weight of the waste, providing additional data for residues with low volume but significant mass. The system also includes a DHT11 temperature and humidity sensor to monitor environmental conditions, offering users relevant information about the bin's surroundings.

Figure 3 Waste Bin Prototype

To enable location tracking, a Neo-6M GPS module is integrated into the bin, providing geographic coordinates that help users locate the nearest available bin. Communication between the bin and the middleware is facilitated by a SIM900 GSM/GPRS module, which uses 2G cellular technology. This choice was made due to its widespread infrastructure, low operational costs, and reliable coverage, even in areas with limited signal strength. The system's central processing unit is an Arduino board, chosen for its simplicity and suitability for IoT applications. Power is supplied by a rechargeable battery connected to a photovoltaic solar panel, ensuring continuous operation.

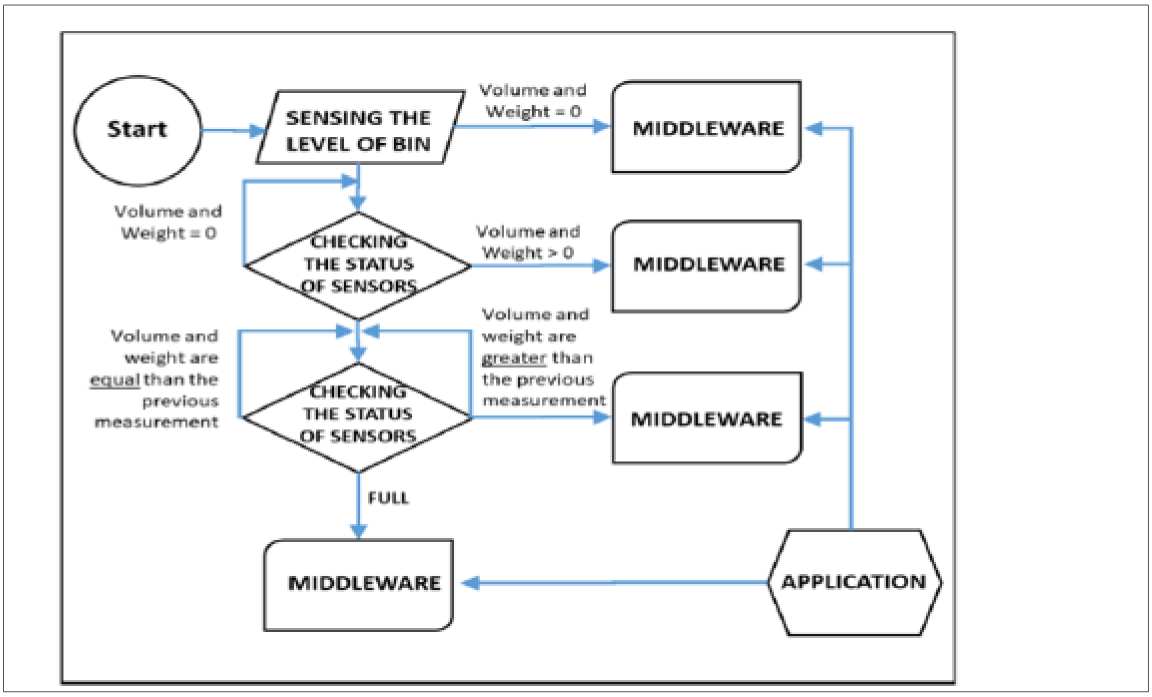

Figure 4 Wastebin Flow chart

When initialized, the bin transmits its GPS coordinates, along with sensor data (weight, volume, temperature, and humidity), to the middleware. The system periodically updates this information, allowing users to monitor bin status in real time. Once a bin reaches full capacity, the system notifies users and directs them to the nearest available bin.

2.6. IoT Middleware Integration

Middleware serves as a bridge between IoT devices and applications, enabling seamless communication and data management. In this system, the In IoT middleware is used to store and process data from the smart bins. It provides real-time updates on bin status and location, accessible via a web interface.

2.7. My Waste App

The My Waste App is a hybrid mobile application developed using the Ionic framework, compatible with both Android and iOS platforms. It allows users to check the status of nearby waste bins, receive disposal recommendations, and view collection schedules. The app is designed with user-friendly features, such as the ability to register favorite bins and receive notifications about their status. Users can also access the system via a web browser, which provides additional functionality for waste collection agencies to optimize routes and manage bin data. The app's development prioritized user needs, business requirements, and environmental goals. It aims to promote responsible waste disposal, reduce collection costs, and minimize traffic congestion caused by waste collection vehicles.

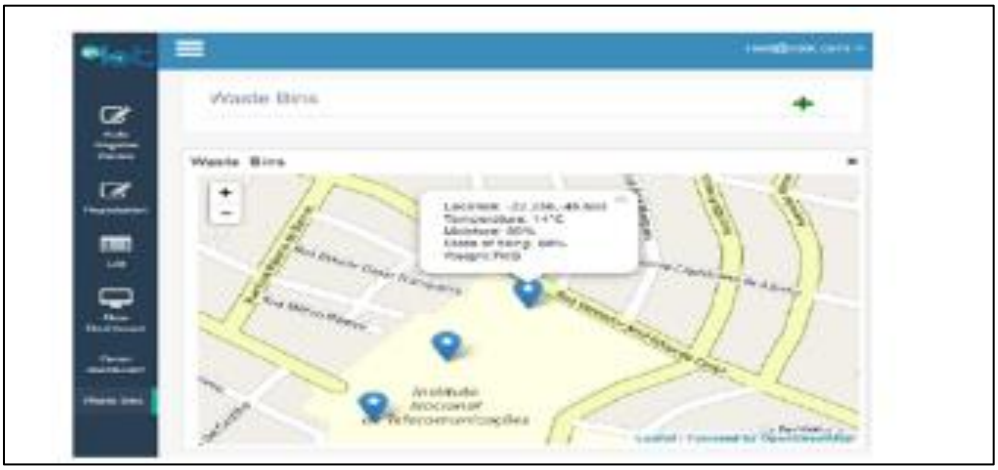

Figure 5 Middle ware platform showing the location of smart bins

3. System Evaluation, Demonstration, and Validation

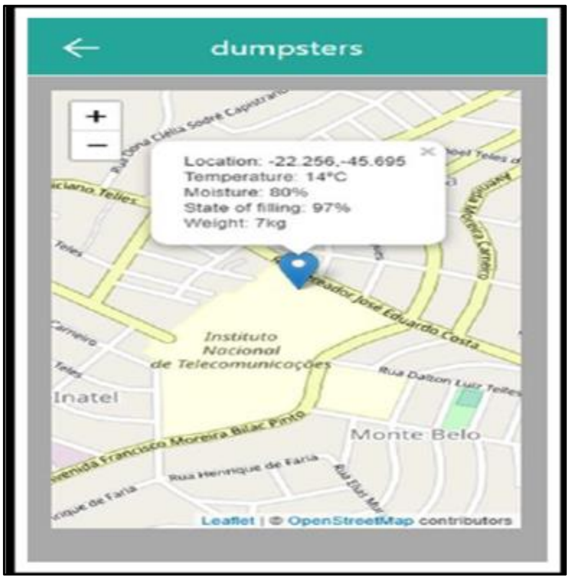

Figure 6 My waste App

The performance evaluation of the My Waste Management system was conducted through real-world experiments to validate its functionality and feasibility. The My Waste Bin prototype, integrated with the In.IoT middleware, was tested for geolocation accuracy, waste monitoring, and energy efficiency. In the first experiment, the bin's location was successfully identified and displayed on the My Waste App, allowing users to trace a route to it. The second experiment involved adding varying amounts and types of waste to the bin, with the system accurately tracking fill levels from 37% to 97% of the bin's capacity. The third experiment tested the bin's solar-powered energy system over eight weeks, confirming its ability to operate continuously without losing power, though future improvements could include battery level visualization. Overall, the experiments demonstrated the system's effectiveness in collecting and transmitting waste data, as well as its seamless interaction with end-users through the app, validating its potential to optimize waste management.

Figure 7 Route Presented by my waste App

4. Conclusions

The 21st century has seen a significant shift toward urbanization, with the United Nations predicting that nearly 70% of the global population will reside in urban areas by 2050. This rapid urban growth raises concerns about sustainability, as cities often expand without adequate planning. To address these challenges, the concept of smart cities has gained traction worldwide. This paper contributes to this effort by proposing an IoT-based, real-time waste management system designed to enhance urban living conditions from a citizen-centric perspective. The system leverages sensor and communication technologies to collect waste data from smart bins and transmit it to an online platform, enabling residents to monitor bin availability and optimize waste disposal. The development of a functional smart bin prototype, along with a mobile application and web platform, demonstrated the system's potential to transform waste management practices. Case study experiments confirmed that the system can improve how people handle waste while optimizing the use of economic and material resources. For future work, the application could be enhanced with additional features to improve user interaction and integrate route optimization algorithms for waste collection vehicles, reducing operational costs. Furthermore, a detailed analysis of the system's investment and operational expenses would provide valuable insights for scalability and implementation in diverse urban settings.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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