Integrated Predictive Analysis Framework for Smart Waste Management

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This paper presents a comprehensive and flexible framework for optimizing smart waste management practices. In the context of increasingly complex waste management challenges, the integration of predictive analytics offers a promising approach to enhance efficiency, sustainability, and resource allocation. The creation of a framework serves as a baseline for revolutionizing traditional waste management practices by integrating advanced technologies and data-driven strategies. A structured interviews with key stakeholders was conducted to gather insights on current practices, challenges, and laws implemented for waste management control. Simultaneously, a comprehensive literature review was performed to identify best practices and technological advancements in smart waste management, such as IoT and data analytics. Furthermore, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) tool is utilized to ensure a systematic and transparent literature review process, aiding in the selection and evaluation of relevant studies. A content analysis of 11 articles, which met the eligibility criteria, were carried out. The development of the proposed integrated predictive analysis framework involves integrating various advanced technologies commonly used in existing frameworks. This comprehensive integration of technologies was chosen to create a highly efficient and effective waste management system. By combining these technologies, the proposed framework aims to address the limitations of current systems, offering a scalable, flexible, cost-effective, and environmentally friendly solution for modern waste management challenges.
Keywords: framework, IoT, predictive analysis, smart waste management.

1. Introduction

Waste management is a fundamental challenge (Wamba et al., 2023) that societies around the globe face today. As urban populations grow and consumption patterns change, the volume of waste generated is increasing at an unprecedented rate. This surge in waste production brings forth a multitude of problems that impact public health, environmental sustainability, and economic stability (Costa et al., 2023).

The main problem in waste management is the improper waste disposal (Geetha & Rajalakshmi., 2020) which lead to inefficiency and ineffectiveness of current systems in handling the increasing volume of waste generated by modern societies. Inefficient waste collection schedules often result in overflowing bins and littered streets, creating unsanitary conditions and attracting pests, which pose significant public health risks.

Inefficient waste collection systems (Silva et al., 2023), high operational costs, inadequate recycling practices, and the improper disposal of hazardous materials are some of the critical issues that need to be addressed.

In Ota, Ogun State the region's ecosystem and public health have remained at risk due to the growing and inappropriate attitude toward waste disposal among many locals (Oluwafemi et al., 2021). Due to a lack of an appropriate and long-lasting trash collection and management system, it has encouraged an increase in environmental pollution throughout time.

According to a study, waste management is affected by the improper waste disposal and behaviour of the public (Geetha & Rajalakshmi, 2020). Furthermore, in addition to reporting on Jammu's inadequate municipal solid waste management system (Masood, & Ahmad, 2020)., the study draws attention to other pressing problems that require immediate action, such as a lack of scientific methods, equipment, public education, and law. Additionally, Significant gaps exist in understanding the specific human health risks associated with improper waste disposal (Raphela et al., 2024). many people lack sufficient knowledge about the specific health hazards that improper waste disposal can pose. This gap in awareness means that individuals might not fully grasp how improper disposal methods such as dumping waste in open areas or not following recycling protocols can lead to health problems such as infections, respiratory issues, or even long-term diseases. Addressing this disparity is essential for implementing effective waste management practices and improving public health.

Given the reliance on conventional waste management techniques that lead to ineffective municipal solid waste management collection, higher operating expenses, and marine plastic leakage, navigating the problem of solid waste management in the Philippines is essential. This problem emphasizes the necessity of switching to effective garbage collection and transportation systems. It is in line with the overarching objective of lessening the environmental effect of cities by 2030, with a focus on enhanced waste management and air quality for inclusive, secure, resilient, and sustainable urban living (Pendang 2023).

Ecosystems and human health are seriously at risk due to the modern economy's waste's growing volume and complexity. Traditional waste management systems, however, face numerous challenges such as inefficient collection schedules, high operational costs, and inadequate recycling practices (Kaza et al., 2018).

With the above-mentioned issues and problems faced by many regions, one of the most significant issues in waste management is the lack of a standardized framework for proper waste handling and disposal. A standardized framework would ensure that best practices are implemented uniformly, optimizing resource allocation, enhancing recycling rates, and minimizing the environmental impact. Such a framework is essential for establishing clear guidelines (Lotfi et al., 2022), regulatory compliance, and coordinated efforts across municipalities, ultimately contributing to more sustainable and effective waste management systems.

In order to attain an effective and efficient waste management, there should be a systematic approach (Joshi et al., 2023) to implement and manage IoT-enabled solutions for waste management. Designing a framework for smart waste management involves creating a systematic integrated approach (Muhić et al., 2023) in the process of designing a model of practical application of technology to solve the problem of waste management in cities. A working, efficient and sustainable framework to manage the e-wastes of has become a crucial need in current times (Ahsan et al., 2022). In addition, large volumes of data will be produced by the sensors; managing this data using conventional methods will not be effective; in this situation, big data analytics is crucial, hence a framework based on IoT will be more scalable and efficient consisting of multiple stages to come up with an optimal garbage collection plan (Kanaga & Jacob, 2021).

To address these issues, the researcher decided to address the challenges in waste management by developing a standardized yet flexible framework for waste collection and disposal. This approach aims to create a consistent set of guidelines and procedures that can be applied universally across different regions or municipalities. By standardizing the process, the framework ensures that best practices are followed, leading to more efficient and effective waste management.

At the same time, the framework is designed to be flexible, allowing it to adapt to the specific needs and conditions of various areas. For example, urban and rural areas may have different waste generation patterns, collection schedules, and environmental concerns. The flexible nature of the framework means it can be customized to accommodate these differences while still maintaining a consistent overall structure.

This dual approach of standardization and flexibility ensures that the framework can be widely adopted, providing a reliable and adaptable solution to the complex challenges of waste collection and disposal. It aims to improve the efficiency of waste management systems, reduce environmental impact, and ensure compliance with regulations, all while being versatile enough to meet the unique demands of different communities.

2. Methodology

To gather comprehensive insights into the current waste management practices and identify areas for improvement, the researcher used qualitative data collection (Effendy et al., 2023) through structured interviews with key stakeholders, including waste management officials, and sanitation workers. Qualitative data collection involves gathering non-numeric, descriptive information to gain deep insights into concepts, opinions, and experiences. This process employs methods such as interviews, where structured, semi-structured, or unstructured formats allow researchers to explore participants' thoughts in detail. These interviews focused on understanding existing collection, segregation, and transportation methods, as well as the challenges faced in each phase.

The researcher conducted an interview with the municipal waste management office regarding the procedure of waste disposal and collection within its area, aiming to understand the current practices, challenges, and potential areas for improvement. The researcher collected detailed insights into the day-to-day operations and strategic planning of waste management systems. The interviews provided qualitative data on various aspects, including waste collection schedules, sorting methods, recycling processes, and disposal techniques. Additionally, the conversations highlighted the operational inefficiencies, financial constraints, and regulatory hurdles faced by waste management entities. With this, descriptive data is crucial for identifying gaps in the existing framework and formulating recommendations for enhancing the efficiency and sustainability of waste management practices.

On the other hand, a comprehensive literature review (Shah et al., 2023; Shah et al., 2021) was conducted to identify existing smart waste management frameworks. A comprehensive literature review is a critical and thorough evaluation of existing research and scholarly publications on a specific topic. Its purpose is to synthesize the current state of knowledge, identify gaps in the literature, and provide a foundation for new research. This review included case studies and reports from reputable sources, focusing on technologies such as IoT, data analytics, and machine learning. The findings provided a foundational understanding of current best practices and highlighted gaps that the proposed framework aims to address.

Defining the research topic was the first step conducted by the researcher to establish the objective of the review by identifying the specific area of the study. A search for relevant literature was made identifying academic database and sources and develop a list of keywords and search terms related to the topic.

Initially, three databases (Google Scholar, MDPI and Science Direct) were chosen for their open access and advanced search capabilities. These databases offer simple filters that enhance the precision of searches. After selecting the databases, search queries was determined to ensure a thorough and relevant selection of sources. The process begins by identifying the key concepts related to the research question, such as "smart waste management", "waste management framework", and “framework”. Researchers then formulate search terms and include synonyms and related concepts to broaden the search, ensuring all relevant literature is captured. Boolean operators are crucial in this process: using AND to combine different concepts narrows the search. For instance, searching for "smart waste management AND framework" ensures both terms are present. Additional filters was also applied to narrow the selection like custom range when it comes to publication year. Applying these strategies across relevant databases and search engines helps in gathering a comprehensive set of studies, leading to a well-rounded literature review.

After executing the search query, the process of reviewing records involves several several steps to determine their relevance to the research topic. Initially, researcher conduct a preliminary screening by examining the titles and abstracts of the retrieved studies. Then, any duplicate entries were removed to ensure the accuracy and uniqueness of the collected data. This initial filter helps in quickly identifying studies that are potentially relevant to the research topic. The next step involves a more in-depth evaluation of the full texts of selected studies. Researcher assess whether the studies address the core aspects of the research topic and meet specific inclusion criteria, such as methodological rigor and alignment with the review's focus. This detailed review includes examining the study's objectives, methods, results, and conclusions to ensure that they provide valuable insights and evidence pertinent to the topic. By systematically reviewing and synthesizing the records, researchers can effectively determine their relevance and contribution to the comprehensive literature review.

Afterward, a screen and selection literature were made to establish a criterion for inclusion and exclusion of studies by basing the search terms of relevance and publication date. Data gathered from screening was organize and extracted using excel to establish a standardized form. PRISMA (Wirani et al., 2024) was also used, which stands for Preferred Reporting Items for Systematic Reviews and Meta-Analyses, is a set of guidelines designed to improve the transparency and quality of systematic reviews and meta-analyses. The PRISMA statement includes a checklist of essential items that should be reported in these types of reviews, covering aspects like the rationale for the review, search methods, data extraction, and synthesis. The goal is to ensure that systematic reviews are conducted and reported in a way that is clear, comprehensive, and reproducible, making it easier for readers to assess the validity and relevance of the findings. These related studies were now analyzed and synthesize to group similar findings to identify patterns, trends and gaps. Finally, the researcher writes a summary of the findings of the comprehensive literature review.

To develop the integrated framework, a systems modelling approach (Pinha & Sagawa., 2020) was made. It is a structured approach to understanding, analyzing, and simulating the behavior of complex systems. It involves creating abstract representations of real-world systems to study their components, interactions, and dynamics.

The following are the steps conducted by the researcher to design the framework. First, a problem definition was made as mentioned previously on the conduct of comprehensive literature review to clearly define the scope of the research. Next, a conceptual model was developed to outline the system’s component and their interactions through abstract representation using diagrams that will aid in understanding the structure of the system.

Following the conceptualization, a data collection was conducted to gather all relevant information needed to build and validate the model. Identifying the similarities, differences and relevance of the existing literature to be integrated into the proposed framework. This can be done using the step in the comprehensive literature review by conducting search on databases and sources such as studies on existing literature. With the necessary data on hand, the model construction phase begins. During this phase, the conceptual model was translated into a formal representation using physical constructs, a representation of a real-world system to visualize, analyze and test the physical aspects and interaction within a system.

The proposed integrated framework will be validated and verified along with the actual physical system after its development to ensure its accuracy and consistency. Along with this is the simulation and analysis to study the systems behavior. Insights gained from the simulation will be applied. The findings and recommendations derived from the model are put into practice, and the model is continuously refined based on new data and feedback. This iterative process ensures that the model remains relevant and accurate, allowing for ongoing improvements and optimizations of the system being studied.

3. Results and Discussion

Based on the information collected during the interview, the city and municipalities of La Union undertake collection within their respective town centers and peri-urban centers, with an average of two to three times a week collection schedule. Collection system is door-to-door and curbside collection, or a combination of both.

Aside from that, all the LGU's do not have transfer stations since most of them have their own waste disposal facilities within their jurisdiction. Since all of the component LGU's have installed material recovery facilities (MRF), sanitary landfilled including septic vault for infectious and healthcare waste, concrete vaults for toxic and hazardous waste.

The LGU has also conducted an Information and Education Campaign, distribution of pamphlets, meetings and training and implemented municipal ordinances regulating the practice of proper waste management within its area.

Conversely, using a comprehensive literature review along with PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses), the following results are as follows:

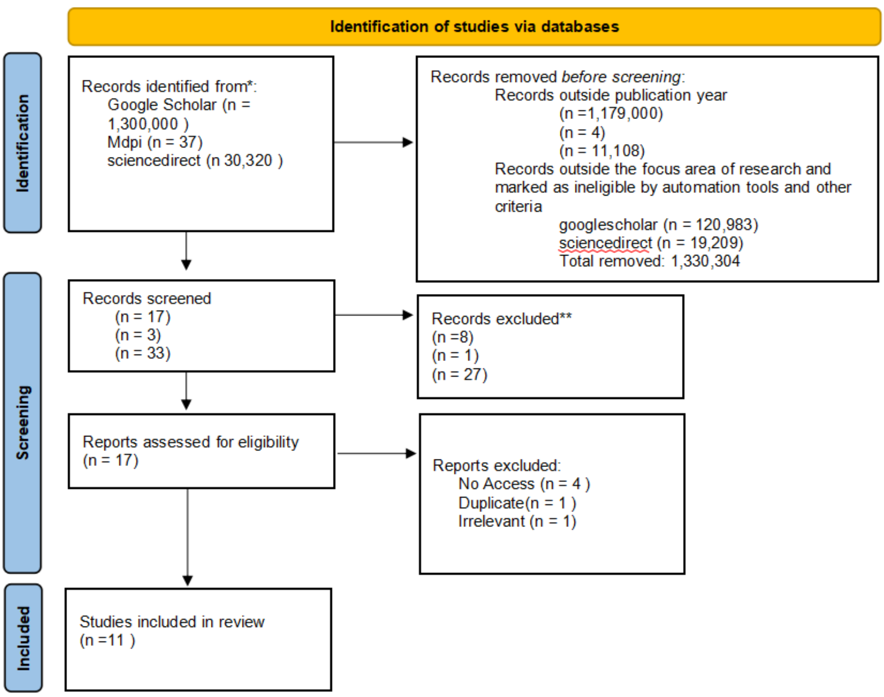

Figure 1. PRISMA for systematic review

It is evident on the figure illustrating the search output of the comprehensive literature review from the three databases, the review process involved a comprehensive screening of records. The figure clearly shows the number of records included and excluded at each stage, providing a detailed overview of the selection process. This visualization helps to understand the methodology and rigor of the literature review, ensuring transparency and clarity in the data extraction and analysis phases.

The figure not only shows how many studies were included and excluded at each stage but also highlights reasons for exclusion where applicable. This transparency helps to demonstrate the thoroughness of the review process, ensuring that each step of the review is systematically documented, and the selection process is clearly outlined.

Table 1. Selected (11) literature for review

Existing Framework	Objective
A novel framework for waste management in smart city transformation with industry 4.0 technologies (Kumar, 2024)	Develop a roadmap for industry 4.0 technologies relevant to managing waste in smart cities. Proposes a novel framework for analyzing the deployment enablers of Industry 4.0 technologies, implementation barriers, current best practices, and opportunities for digital technologies (EBPO) for smart city transformation.
IoT based smart waste management system in aspect of COVID-19 (Saha & Chaki, 2023)	Smart Bin Deployment. Discusses the architecture of the proposed framework and explains efficient data connection between waste bins and distant servers to achieve QoS in data transfer. Dynamic waste collection procedure and identifies the optimal path between the smart bins and the waste collectors.
Towards a framework for the adoption of smart urban waste management system: A case study of the federal capital territory, Abuja (Hala et al., 2023)	Improve the Abuja waste management system using smart waste management system
Design of waste management system using ensemble neural networks (Geetha et al., 2022)	Introduce a novel method for waste detection and classification to address the challenges of waste management.
Smart waste management 4.0: The transition from a systematic review to an integrated framework (Kannan et al., 2024)	Existing solutions supporting SWM4.0 are extracted to develop a framework for exploring the use of I4.0 technologies.
A smart framework for municipal solid waste collection management: A case study in Greater Cairo Region (Alobky et al., 2023)	Aims at providing optimized collection systems to accommodate various housing levels and considering the available resources.
Framework of Smart and Integrated Household Waste Management System: A Systematic Literature Review Using PRISMA (Wirani et al., 2024)	Links with other integrated dimensions and identifies the types of household waste management processes based on the Integrated Sustainable Waste Management (ISWM) framework, dimensions that support smart household waste management system, and the stakeholders involved.

A Digital Transformation Framework for Smart Municipalities (Van Der Hoogen et al., 2024)	Investigate the role of digital technologies in improving urban processes, focusing on Smart City dimensions for municipalities, namely smart governance, environment, living, and technology.
Urban Facility Management Improving Livability through Smart Public Spaces in Smart Sustainable Cities (Abdelkarim et al., 2023)	Adopt intelligent technologies applied in public spaces to facilitate livability through urban facility management (UFM) involvement in improving livability.
Smart City Transformation: An Analysis of Dhaka and Its Challenges and Opportunities (Karmaker et al., 2023)	Proposes a sustainable smart city transportation framework and management technique, outlining future research directions.
A Review of Future Household Waste Management for Sustainable Environment in Malaysian Cities (Cheng et al., 2022)	Aims to integrate future-proofing framework that focuses on smart waste tracking, a gamified awareness education, and strict policies to control waste management are the way forward for the future of smart cities household waste management

Table 1 presents a comprehensive overview of the selected literature for review, focusing on various existing frameworks related to waste management. Each entry in the table outlines the framework discussed in the corresponding study, along with its specific objectives. By summarizing these frameworks and their goals, the table provides a clear understanding of the current approaches and methodologies used in the field.

The objective of including this table is to highlight the different strategies and technologies employed by previous research efforts to address challenges in waste management. This might include frameworks that utilize technologies like IoT, machine learning, and big data analytics, each aiming to optimize aspects such as waste collection, segregation, recycling, or overall system efficiency.

Moreover, the table allows for an easy comparison between the various frameworks, helping to identify common themes, strengths, and potential gaps in the existing literature. This comparison is crucial for setting the context of the current research, which seeks to build upon or differentiate itself from these existing solutions. By clearly outlining the objectives of each framework, the table also helps to clarify how the proposed research will contribute to advancing the field and addressing any unresolved challenges.

After thoroughly reviewing the existing literature, table 2 presents the similarities and differences of each study. This table presents a comprehensive view of how various technologies and components are used in smart waste management frameworks, highlighting both commonalities and distinct characteristics.

Table 2. Comparison of Existing Framework

Aspect	Similarities	Differences
Artificial Intelligence	Commonly used for predictive analytics and optimizing waste management processes.	Variations in AI models and algorithms used (e.g., neural networks, decision trees, support vector machines).
IoT	Frequently employed for real-time monitoring and data collection.	Different types of IoT devices and sensors used based on specific needs (e.g., volume sensors, GPS trackers).

Sensors	Integral for detecting waste levels and types.	Sensor technologies (e.g., ultrasonic, infrared, RFID) with varying accuracy and costs.
Machine Learning	Utilized for waste classification and predictive maintenance.	Differences in training data quality and feature engineering approaches
Smart Truck	Equipped with GPS and IoT for efficient routing and waste collection	Variability in automation levels, from semi-automated to fully autonomous trucks.
Routing	Optimized using AI and machine learning for efficiency.	Differences in routing algorithms and real-time traffic data integration
Waste Segregation	Automated systems for sorting waste into categories.	Varying levels of accuracy and speed depending on the technology and processes used.
Waste Detection	Employs sensors and AI for identifying waste types and levels.	Differences in detection accuracy and the range of detectable materials.
Network Technology	Essential for connecting devices and transmitting data.	Various network technologies employed, such as Wi-Fi, LPWAN, 5G, and Bluetooth, depending on the requirements.
Big Data Analytics	Analyzes large volumes of data to identify patterns and trends.	Variations in data processing frameworks and tools used (e.g., Hadoop, Spark).

After carefully evaluating the existing literature, a comprehensive framework will be created. This framework will be based on the insights and findings from the reviewed studies, ensuring it incorporates the most relevant and up-to-date information. The evaluation process will involve critically analyzing the methodologies, results, and conclusions of the existing research to identify key themes and gaps.

The development of the proposed integrated predictive analysis framework involves integrating various advanced technologies commonly used in existing frameworks. These include AI and machine learning for predictive analytics and waste classification, IoT devices and sensors for real-time monitoring and data collection, and smart trucks equipped with GPS for efficient routing and waste collection.

Additionally, the framework incorporates automated waste segregation systems, advanced waste detection technologies, robust network technologies for seamless connectivity, decision support systems for data-driven decision-making, big data analytics for identifying patterns and trends, mobile applications for user interface and management, and a central server for centralized data storage and processing.

This comprehensive integration of technologies was chosen to create a highly efficient and effective waste management system. AI and machine learning provide the ability to optimize processes and predict maintenance needs, significantly enhancing operational efficiency. IoT devices and sensors enable real-time monitoring, ensuring timely waste collection and preventing overflow. Smart trucks and optimized routing algorithms reduce fuel consumption and operational costs.

Automated segregation and advanced detection technologies increase the accuracy and speed of waste processing. Robust network technologies ensure reliable data transmission, while decision support systems and big data analytics offer valuable insights for continuous improvement.

Mobile applications enhance user engagement and management, and a central server ensures secure and centralized data management. By combining these technologies, the proposed framework aims to address the limitations of current systems, offering a scalable, flexible, cost-effective, and environmentally friendly solution for modern waste management challenges.

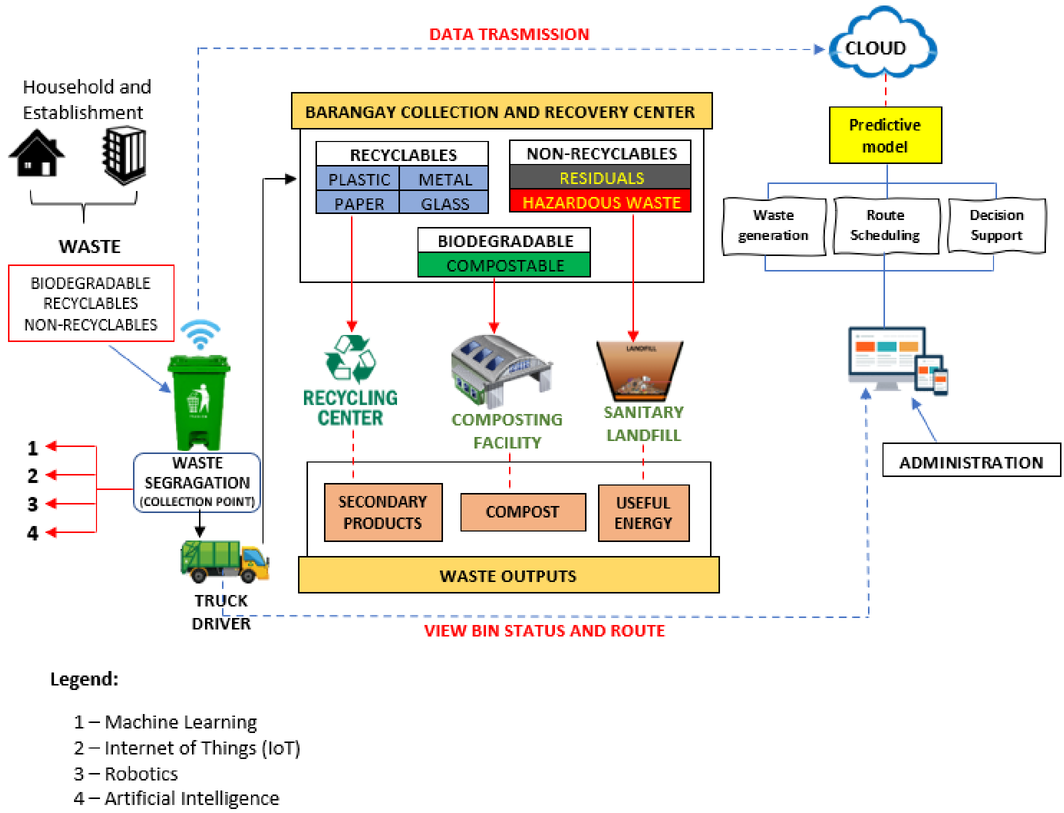

Figure 2. The proposed integrative predictive analysis framework

The process of smart waste management begins with IoT sensors deployed in waste bins and containers throughout urban areas, continuously collecting real-time data on fill levels, temperature, and other relevant parameters. This data is transmitted wirelessly to a central server or cloud platform using cellular networks, Wi-Fi, or other wireless communication protocols, ensuring up-to-date information.

At the waste segregation facility, incoming waste is sorted into categories like recyclables, compostable, and non-recyclables, often aided by AI-driven sorting machines. The integrated data from IoT sensors helps optimize this process.

Predictive analytics on the central server process the data to forecast future waste generation patterns, enabling optimized collection schedules that prevent overflow and reduce operational costs. These schedules inform dynamic routing plans for waste collection trucks, designed to minimize travel distance and time, with real-time adjustments based on new sensor data.

Administrators oversee the system through a centralized dashboard that offers real-time data, decision support tools, and public engagement features, such as mobile applications for residents to report issues. This integrated approach enhances operational efficiency, reduces environmental impact, and fosters community involvement in waste management.

The primary difference of this research is the integration of predictive analysis into the waste management process. Predictive analysis involves using data, statistical algorithms, and machine learning techniques to identify patterns and make informed predictions about future events or behaviors. In the context of waste management, the integration of predictive analysis means leveraging historical data and real-time information to anticipate waste generation trends, optimize collection schedules, and enhance overall system efficiency.

By incorporating predictive analysis, the research aims to move beyond traditional reactive waste management practices, where waste is collected based on fixed schedules or when bins are full. Instead, the framework will enable proactive decision-making, allowing waste management systems to anticipate when and where waste will accumulate, allocate resources more effectively, and prevent issues like overflows or missed collections.

This integration also has the potential to reduce operational costs, minimize environmental impact, and improve service quality by ensuring that waste collection is timely and efficient. Ultimately, the research seeks to create a smarter, more sustainable approach to waste management, where data-driven insights guide every aspect of the process.

4. Conclusion

One major step in resolving the complexity and inefficiencies of conventional waste management systems is the adoption of a real-time predictive analysis framework for smart waste management. This framework can minimize operating expenses, increase recycling rates, and optimize waste collection routes by utilizing cutting-edge technologies like IoT, machine learning, and data analytics.

The use of a comprehensive literature review combined with PRISMA provides a thorough, transparent, and systematic approach to synthesizing research evidence. This methodology ensures that all relevant studies are considered, that the review process is free from bias, and that the conclusions drawn are reliable and actionable. For developing frameworks in complex fields such as smart waste management, this approach offers a solid foundation for creating effective, evidence-based solutions.

The developed integrated predictive analysis framework for smart waste management marks a significant leap forward in optimizing waste collection processes and minimizing environmental impact. However, there are several avenues for future work to enhance its capabilities and broaden its applicability. One potential area of research is the integration of more advanced machine learning and artificial intelligence algorithms to improve the precision of waste generation predictions. Exploring deep learning techniques could provide better handling of complex patterns and large datasets. Additionally, testing the scalability of the framework in diverse geographical locations and urban settings is crucial. Adapting the framework to different infrastructures and waste management practices worldwide will ensure its effectiveness across various contexts.

Further development is needed to enhance IoT sensor integration, including deploying next-generation sensors with improved accuracy, durability, and cost-effectiveness. Investigating the inclusion of additional environmental parameters, such as air quality and temperature, could refine waste decomposition rate predictions and collection schedules. Enhancing real-time decision support systems with user-friendly interfaces, real-time data visualization, and automated decision-making processes can significantly improve operational efficiency.

Incorporating public participation and feedback mechanisms into the framework could increase its effectiveness. Future research could explore methods to involve community members in reporting waste-related issues and providing feedback on waste management services via mobile applications and other platforms. Additionally, assessing the long-term economic and environmental impacts of implementing the framework, including cost savings, reductions in carbon emissions, and improvements in public health outcomes, will be critical.

Finally, integrating the waste management framework with other smart city initiatives, such as smart energy grids, water management systems, and traffic management, could lead to more comprehensive urban sustainability solutions. By addressing these areas, future research can build upon the current framework to create more efficient, adaptable, and sustainable smart waste management systems.

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