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A Survey on: Smart Waste Monitoring and Tracking System

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Abstract: *The challenge modern waste management faces is how to connect technological progress with citizen participation. The literature, above all recent discussions of IoT, AI, and data analytics, suggests opportunities for advancement. However, the solutions are mostly in silos, for example, monitoring at the bin level, route optimization for waste collection, and automated sorting, which provide little in terms of a method to trace back to household accountability, leading to erratic segregation techniques and thereby reducing long-term sustainability. In this paper, I propose an integrated IoT waste-tracking and management system that extends the innovative continuum of infrastructure, household-level ID, and real-time monitoring to promote effectiveness and transparency. The project aims to achieve automation and transparency to involve citizens in a way that transcends voluntarism and engagement. It is also worth noting that the design developed a GIS-based household authentication system using RFID to monitor individual disposal events and facilitate traceability. It should be noted that there are also smart waste disposal units with multifunctional sensors that can recognize the type of waste and send it to the appropriate compartment to enable appropriate segregation and mitigate contamination. The cloud-based platform may use an embedded controller to record each disposal transaction as an entry. The interactive dashboard will be available to municipal staff to deliver compliance reporting data and take timely measures. The other innovation is the automated regulatory layer, which is modelled on the digital fine systems that enhance accountability through the imposition of specific fines due to noncompliance. By introducing citizen-level monitoring, automatic authentication, and governance along data lines, this framework helps to curb major loopholes in current innovative waste management processes. It gives a foundation on which predictive analytics, decision support based on artificial intelligence, and blockchain-driven transparency will be integrated in the future to create an urban environment that is cleaner, more efficient, and sustainable.*

Keywords*:* *waste management*

I. INTRODUCTION

As one of the city governments' most serious challenges today, effective waste management is rapidly changing. Urban population growth, industrialization, and the rise of consumer culture have generated unprecedented municipal solid waste [1]. It is estimated that millions of tons of waste are generated each day in urban areas, and this trend is expected to increase dramatically in the coming decades [2]. The growing waste problem has resulted in overflowing landfills, climate change, groundwater pollution, public health concerns, and a general decline in urban livability [3]. Traditional collection and disposal systems, which rely on manual and routine operations, struggle with the massive scale and complexity of modern waste generation [4]. Given this reality, cities must adopt innovative technology-driven approaches that establish household accountability [5].

Historically, municipal waste management strategies have prioritized collection, landfilling, and recycling over at-source segregation, arguably the most critical stage of the process [6]. Without segregation at the source, recycling, composting, and safe disposal become less efficient and resource-intensive [7]. Studies have shown that failure to separate waste into dry, wet, and hazardous streams reduces recycling efficiency and increases environmental and public health risks [8]. Campaigns and regulations promoting segregation at source have existed for years, but compliance among citizens remains low due to poor enforcement [9].

Technological innovations have attempted to address these challenges. With the emergence of the Internet of Things (IoT), Artificial Intelligence (AI), and embedded systems, we have seen the introduction of smart bins, monitoring dashboards, and optimized collection routing [10]. IoT-enabled sensors provide real-time data on fill levels and environmental conditions, which can be transmitted to municipal dashboards for timely action [11]. AI models, such as computer vision and machine learning, are being applied to classify waste, whereas GIS-based systems are improving truck routing to reduce costs and environmental impacts [12]. Despite these advances, most solutions remain siloed, focusing only on bin monitoring or logistics without incorporating citizen accountability or behavioral enforcement [13]. As a result, even the most advanced systems can fail if households do not comply with segregation norms or consistently dispose of waste [14].

Of the existing citizen identification mechanisms, barcodes, QR codes, and mobile apps are typically the most prominent; however, these implementations have inherent challenges [15]. QR and barcode technologies require manual scanning, which is labor-intensive and unsuitable for large-scale deployment [16]. Mobile applications depend heavily on citizen involvement, often leading to incomplete data and poor compliance [17]. Moreover, none of these mechanisms enforce accountability in real time; they record transactions but cannot sanction non-compliance or reward sustained participation, creating a gap between technological capability and governance enforcement [18]. Consequently, municipal authorities struggle to improve adherence to waste management directives despite the availability of monitoring tools [19].

This research project addresses these deficiencies by proposing a holistic, innovative waste management framework that integrates authentication, waste type detection, and enforcement within a single IoT–cloud ecosystem [20]. At its core is a household-level RFID tracking module, which enables automatic identification of households at the point of disposal, eliminating the need for manual scanning of barcodes or QR codes [21]. RFID technology is durable and scalable, ensuring that every collection event is reliably recorded and assigned to households, thereby establishing accountability [22].

A key innovation is the Smart Drop Box, which was designed as a supplementary disposal mechanism for households missing scheduled collections [23]. The system uses dual-lid access control: the first lid opens when an authorized RFID card is scanned, allowing waste to be input, while integrated sensors, including moisture and proximity detectors, determine whether the waste is dry, wet, or hazardous [24]. The second lid opens only if segregation is correct; otherwise, waste is rejected, and an alert is triggered. This enforces compliance at the point of disposal, transforming segregation from voluntary to mandatory [25].

In addition to local verification, the system enables real-time monitoring. Each disposal event, accepted or rejected, is logged by a Raspberry Pi controller and uploaded to a cloud database [26]. Municipal staff members can access dashboards to track participation, generate compliance reports, and identify defaulters. The framework also introduces an automated fine system modeled after e-Challan processes, where non-compliant households are penalized, notified, and temporarily restricted from municipal services until compliance is restored [27].

Additional efficiency comes from fill-level sensors embedded in bins, which provide timely notifications to prevent overflow and optimize collection scheduling [28]. Cloud analytics can then dynamically route collection trucks, reducing unnecessary trips, fuel consumption, and costs [29]. Backup power ensures system reliability even during outages, reinforcing scalability and resilience [30].

Unlike previous approaches that focused narrowly on bin monitoring, routing optimization, or AI-based classification, this study integrated multiple layers—authentication, segregation verification, real-time tracking, and automated enforcement—into a comprehensive framework [31]. The result is a transparent, enforceable, and sustainable system that directly addresses the lack of accountability mechanisms at the household level [32].

This paper contributes three key advancements: (1) household-level traceability of waste disposal via RFID for accountability [33]; (2) sensor-based verification to enforce segregation at source, reducing contamination, and improving recycling efficiency [34]; and (3) an automated fine mechanism that links compliance enforcement directly with municipal governance [35]. Collectively, these elements form a roadmap for future innovative waste management systems that are environmentally adaptive, socially enforceable, and aligned with the goals of sustainable urban development [36].

The remainder of this paper is structured as follows: Section 2 discusses existing embedded and IoT-based waste collection systems; Section 3 explores computer vision and AI-based systems; Section 4 details the methodology and proposed system architecture; Section 5 examines the outcomes and contributions; and Section 6 presents the conclusion along with future directions in predictive analytics, blockchain-based transparency, and integration into innovative city ecosystems [37].

II. GARBAGE COLLECTION SYSTEM

This garbage collection system employs RFID, IoT, and sensor automation, improving accountability and efficiency in municipal waste management [38]. Each household was assigned a unique RFID card, which was scanned at the collection point to verify the user's identity. When waste is collected door-to-door, the RFID reader unit integrated with the garbage truck stores household details, including date and time, ensuring accurate participation tracking at the disposal point [39].

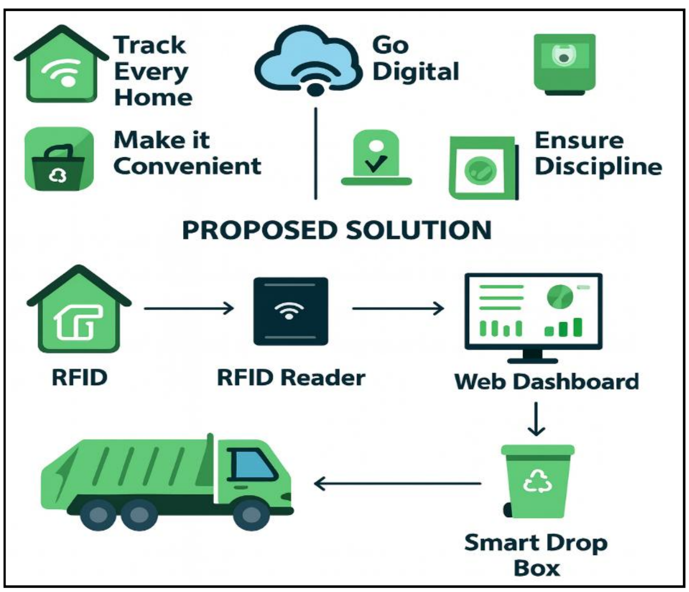

Fig. 1 Block Diagram

For households that miss regular collection days, a Smart Drop Box provides an alternative disposal option [40]. Drop Box incorporates a dual-lid mechanism to restrict access. The first lid opens only when a valid RFID card is scanned. In contrast, moisture and proximity sensors, along with classification logic, identify whether the deposited item is dry, wet, or hazardous [41]. If the waste is correctly segregated, the second lid opens and directs it to the appropriate compartment. Otherwise, the input is denied, the inner lid remains locked, and the system notifies the user with a buzzer and displays a message [42].

All disposal transactions, both accepted and rejected, are logged by a Raspberry Pi controller and uploaded to the cloud in real time [43]. Municipal staff can access this data through a dedicated application to monitor collection events, flag noncompliant households, and generate reports. When households fail to dispose of waste for a predefined period, the system automatically issues alerts and fines to enhance accountability [44].

Additionally, fill-level sensors embedded in bins monitor the capacity and send alerts as they approach their threshold [45]. This helps prevent overflow, streamline collection schedules, and reduce unnecessary trips. A stable power supply with battery backup ensures continuous operation, even during outages [46]. Integrating authentication, waste-type detection, and real-time monitoring makes this garbage collection framework a cleaner, smarter, and more transparent approach to urban sanitation [47]. The figure below shows the overall system in operation.

III. EMBEDDED-BASED GARBAGE COLLECTION SYSTEM

Abhishek et al. [1] reviewed IoT- and embedded-based innovative waste systems focused on sensor integration, real-time monitoring estimation, and automated collection. It is shown that smart bins equipped with ultrasonic, infrared, and weight sensors improve efficiency, reduce overflow, and optimize routes; however, the authors report challenges such as costs, sensor errors, and limited public engagement. The authors summarize current research gaps in standardization and adoption at scale and recommend future research on AI-based prediction of waste collection and systems powered by renewable energy sources.

Alourani et al. [2] described an intelligent waste management system (iSSWM) that incorporates IoT-enabled bins, cloud analytics, and deep learning-based classification and segregation. Smart bins upload bin data to a cloud server, which notifies the collecting agents via a mobile app. VGG-19 achieved 99.7% accuracy in classifying plastic, glass, and metal waste. Therefore, this waste management system reduces manual labor and increases efficiency; however, there is still a gap in evaluating the overall system at larger scales in the real world to assess cost-effectiveness.

Shubham Mengade et al. [3] provide a solution for Smart Trash Managers using IoT-based smart bins with ultrasonic sensors and a GPS module to monitor fill levels and send the data to a real-time central dashboard. The design includes hardware and a software dashboard for municipal officers to track the bin's status, worker attendance, and sanitation operations; when a bin is full, an automated SMS alert is sent to workers. The results and discussion conclude that the Smart Trash Manager system can accurately monitor trash fill levels, provide appropriate geolocation for bins, and improve garbage collection schedules when municipal units are informed to avoid sanitary overflow. The study demonstrates competence in evaluating waste management solutions. It outlines a system that fills a gap in the waste management process by incorporating a centralized platform that considers all personnel involved, and proposes a new, real-time, scalable solution that addresses waste monitoring and municipal waste management.

Ahmed et al. [4] propose an architecture powered by AI and IoT for municipal waste management in smart cities. The system consists of smart bins equipped with ultrasonic sensors, RFID, NodeMCU controllers, and GPS modules to monitor fill levels and send the recent fill levels to municipal offices and carrier trucks in real time via the Blynk app and Google Maps. They found that this approach minimizes collection costs, limits overflow, and increases route optimization. The authors highlight that the implementation can scale and maintain alignment with the Sustainable Development Goals. Still, they note a few gaps, including high installation costs, reliance on continuous grid power, limited use of machine learning, and limited predictive AI models for compliance and long-term sustainability.

K. Sivapriya et al. [5] present an innovative waste management system that is designed by the Internet of Things, Arduino, NodeMCU, and MIT App Inventor applications, where the work uses IoT sensors to monitor garbage bins online and in real-time as to fill level, moisture, and smoke or fire. The smart bins are conveniently open to users, and data is transmitted via Wi-Fi to a mobile application for waste management authorities. The analysis of the experimental results detailed the monitoring accuracy, the reduction of overflowing bins, and user convenience. The discussion detailed the efficiencies achieved in service operations, optimized routes, and real-time notifications to

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improve urban hygiene. The study identified several gaps in the existing research, including a predictive analytics model that leverages AI, full integration of waste segregation and recycling, and a model for large-scale deployment in a large urban area.

Sravya Sruthi et al. [6] describe an autonomous waste management system using embedded technologies to make municipal waste collection more efficient and less costly. Their approach uses RFID for user authentication, IR and proximity sensors to detect waste, an Arduino microcontroller to control the system, and a conveyor belt to automatically sort metallic, dry, and wet waste. The results show effective real-time monitoring and segregation, with data sent via a web application to municipal authorities for easier management. The authors highlight benefits such as reduced human effort, traceability via RFID tracking, and the potential to better utilize waste, including the extraction of ethanol from organic waste. The remaining challenges include scalability, reliance on power, long-term sensor durability, and the lack of advanced AI-driven analytics to improve accuracy and enable predictive waste management.

Mishra et al. [7] reviewed the bright dustbin concept as an Internet of Things-based service for sustainable waste management. Feedback on sensor integration (perimenstrual, infrared, odor, temperature), connectivity, and data analytics enables real-time monitoring and routing, making citizens active participants through mobile applications. This review highlights efficient waste collection, reduced overflow, hygiene improvements, and better recycling systems. This review suggests there is potential to achieve sustainability outcomes and that citizens are more likely to participate. However, the authors note that there are implementation challenges, including costs, connectivity, and privacy concerns, which offer future research opportunities for large-scale implementation.

Sangram C. Patil et al. [8] present a method for implementing a Smart Waste Management system for 100% door-to-door waste collection in Pune using IoT-enabled hardware and Android/web applications. The Smart Waste Management system assigns unique RFID cards to households and industries, uses ultrasonic sensors and GSM and GPS modules to monitor dustbin levels, and uploads live data to the Firebase database. Waste pickers, trucks, and drivers will follow predetermined efficient routes based on notifications sent after the dustbins are 80%. In contrast, the administration will monitor everything and generate reports through a web dashboard. The system achieved 100% door-to-door waste collection, ensured user compliance through tracking, facilitated more efficient municipal management, maintained records of users who failed to participate, generated MIS reports, and imposed fines for violators. Accordingly, this study addressed the research gap in the lack of connection among the key components of waste management (i.e., households, waste pickers, vehicles, and dumping stations). This study shows that a centralized IoT-based platform can manage an integrated waste collection system for municipal waste management, improving accountability and helping preserve environmental sustainability.

Prabhakaran et al. [9] proposed an innovative IoT-based dustbin system to address the problem of overflowing bins in urban areas. The methodology incorporates ultrasonic and infrared sensors with human detection capabilities to monitor waste levels, an Arduino UNO microcontroller, an ESP8266 Wi-Fi module, and a ThingSpeak cloud for data streaming. Other features discussed include automatic lid opening and operation, LCDs, and notifications to inform users of capacity. The method also applies Dijkstra's algorithm, which was simulated using MATLAB, to calculate the shortest path for a garbage collection vehicle from the route, improving fuel consumption and collection time. The examination confirms that the system can monitor dustbin status, provide real-time data, and reduce the distance/increase the efficiency of waste collection. The discussion chapter proposed that integrating IoT with the shortest-path algorithm improves efficiency and reduces environmental risk. The research gap was primarily limited to large-scale pilot or usability (lightweight testing). Although it acknowledged the drawback of relying on Internet connectivity, it did not integrate into municipal governance systems that would compel or enforce hygienic practices.

Sosunova et al. [10] systematically reviewed IoT-enabled Smart Waste Management (SWM) applications in smart cities, identifying 173 primary studies from 3,732 articles across 5 databases. This review identifies city-level SWM systems and smart garbage bin (SGB)-level systems while indicating the services provided, technologies used, and types of sensors in each application. The review signals essential issues relating to the significant role of stakeholders, including citizens, municipal authorities, and private companies. In addition, the authors emphasize the importance of information flow between various parts of the system and actor similarities. They identified opportunities to advance IoT, artificial intelligence, and data analytics to optimize waste collection, route planning, environmental monitoring, and citizen services. The review identifies research gaps and issues associated with stakeholder integration, insufficient historical waste data for decision-making, and a lack of standardization regarding SGB technologies, and it provides suggestions for future direction in plans to develop sustainable and efficient SWM systems.

Chakraborty et al. [11] proposed an innovative waste management system that uses Internet of Things (IoT), GPS, RFID, and cloud technology. The authors described a framework for innovative waste management consisting of sensor-based smart containers, GPRS-based tracking of waste management vehicles, and two mobile applications, one for citizens and one for municipal workers, complemented by an admin panel for centralized management and monitoring. The results of their framework demonstrated improved accountability, citizen engagement, and reduced incidence of overflowing or bin damage. By their own analysis, the proposed framework presented challenges in: (i) scalability beyond a few trial areas, (ii) optimized predictive modeling for decision making, and finally (iii) incorporating recycling and material reuse practices before implementation in a smart city context.

Laxmi et al. [12] described an inexpensive, innovative garbage monitoring system to help optimize waste collection and improve fuel economy. The methodology includes an Arduino UNO (ATmega328P), a GSM module, ultrasonic sensors, RFID readers, and temperature-humidity sensors to monitor the levels and conditions of the bin. The estimate is sent over a cellular network to the cloud (Adafruit.io), where municipal personnel can assess each bin's status in real time. The results show that at a low cost, the device accurately monitors garbage levels and decomposition parameters in bins, and the corresponding RFID mechanism enables accountability for garbage collectors by logging who empties the bins and when. The authors suggest that this solution increases efficiency, reduces manual labor, and avoids the health hazards associated with community decomposition monitoring. However, this study also identifies research gaps in scalability, advanced route optimization, and predictive analytics, which are essential to large-scale application of the solution in smart cities.

Kadus et al. [13] suggest a Smart Netbin, which utilizes the Internet of Things (IoT), load sensors, infra-red (IR) sensors, shredders, and Wi-Fi modules to positively influence garbage disposal through granting temporary Wi-Fi access as a reward for garbage disposal. The methodology uses an Arduino Uno to process the garbage weight from the load sensors and check whether it exceeds certain thresholds before sending the Wi-Fi access codes to the user. The results demonstrate that the system can combine cleanliness with perks for users, reducing trash overflow and making the area more hygienic. This research presents benefits for the system, including low cost, a simple design, and improved use of public participation. The research gap lies in the limited scale of real-world deployment, and there has been no testing at the scale of automatic waste segregation.

Shaik Akbar et al. [14] propose an IoT-based door-to-door system for residential and commercial waste collection. The system employs smart pushcarts with load cells and QR codes to characteristically measure each household's dry, wet, and hazardous waste. Workers scan a QR code in a mobile application to document garbage status and send that data in real time to a central server, which can be analyzed to monitor total waste collected, waste types, and workforce performance. The results demonstrated (1) a high level of transparency for waste collection by municipal solid waste workers, (2) a consistent approach with new regulations as directed in SWM 2016, and (3) the ability to generate garbage collection reports daily, weekly, and monthly. The study identified a research gap in the availability of authentic household-level waste data in India. It demonstrated that IoT-based systems for efficient and accountable waste management have the potential to significantly change residents' waste-production behaviors and the delivery of municipal services.

Gutierrez et al. [15] propose a Smart Waste Collection System that utilizes IoT-enabled trashcans, GIS, and graph optimization algorithms for urban waste logistics. They used a methodology that relies on trashcan sensors that wirelessly transmit fill levels back to a route optimization engine that uses shortest-path spanning trees, genetic algorithms, and clustering to identify an optimal collection route. They simulated the use of their system in Copenhagen using 3,046 bins, showing that dynamic collection methods minimized waste overflow and waiting time but led to

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longer routes and higher costs than the static sectorial method of route collection. Gutierrez et al.'s study highlighted efficiency gains while identifying a lack of research on the economic feasibility of implementing these systems on a larger scale and adequate data to integrate historical data or use AI-based fashioning for route recommendations.

Suchit S. Purohit et al. [16] contribute an automated solid waste collection system that utilizes RFID, GPS, GIS, and GSM to identify, track, and motivate solid waste collection and management. Each container has an RFID tag, and trucks read the tags to send real-time data regarding the container's location, the truck's weight, and collection status to the GIS. This system was tested in Ahmedabad and provided precise tracking, real-time monitoring, and data collection, along with improved routing and transparent reporting of the collected data. The authors fill a gap in the real-time automated monitoring of municipal waste.

Chowdhury et al. [17] recommended a real-time waste management system, WIWSBIS, consisting of RFID and a load cell to identify bins, weigh waste, and locate stolen bins. The approach involved a topology of passive RFID tags, load cells attached to refuse trucks, handheld PDA-based readers, and an overall system architecture with five layers for an effective data-capture and transport methodology. Specifically, the results indicated improved billing accuracy for households, enhanced tracking of missing bins, and reduced operational costs. The fieldwork referenced its practical context for further implementation in the City of Casey, Melbourne. In this case study, large-scale waste collection and bin theft were two critical issues recognized during their fieldwork. Nevertheless, gaps in the research emerged in the discussion on RFID security, standardization issues, and the potential scalability of the infrastructure across additional municipalities over the long term.

Suresh et al. [18] proposed an Internet of Things (IoT)-based innovative waste management system using ESP32 and an array of ultrasonic, DHT11, and MQ2 sensors to monitor garbage bin levels, environmental conditions (ambient temperature and humidity), and the presence of gas. The data are transmitted to ThingSpeak and Google Sheets for alerts, ensuring real-time notifications for waste collection and potentially reducing collection costs. Effectively, the study enhanced sanitation through an innovative waste management system; however, it conducted only a simulation study. Future studies may develop more advanced waste management systems (e.g., GPS/MQTT) or expand on an IoT-based simulation for practical deployment.

According to Petchrompo et al. [19], there are three steps in developing a data-driven model that leverages clustering and optimization to enhance the effectiveness and efficiency of plastic waste collection in voluntary recycling. The model was applied to the WON Project in Thailand, resulting in increased plastic collection and reduced trips per vehicle. The study identified limitations, including the absence of automation, real-time adaptiveness, and scalability to multi-vehicle fleets.

Dubey et al. [20] presented a household waste management system based on IoT and machine learning to develop a green smart society. The framework has two levels of segregation for waste tracking: household and society. It uses sensors to separate biodegradable from non-biodegradable waste, compost the biodegradable waste, and further separate the non-biodegradable waste using inductive and capacitive sensors. A KNN (K-Nearest Neighbour) model uses sensor data to detect waste types, levels, and gas concentrations, and to alert based on these findings. The findings showcase an enhancement in segregation, recycling, and sustainability. Residual gaps in research exist for large-scale deployment, municipal and governance integration, and real-time adaptability within varying urban environments.

Haque et al. [21] proposed an IoT-based waste collection system that uses smart bins equipped with real-time monitoring and optimized navigation. These smart bins are outfitted with various sensors, including ultrasonic, infrared, and BME680, to detect the fill level, humidity, temperature, and volatile organic compound (VOC) levels, and send this data via an ESP8266 module to the cloud. The web page dashboard for real-time monitoring enabled alerts and status updates for smart bins and provided optimized navigation for their waste collection routine using the Google API. The results showed a 30.76% reduction in distance traveled compared to a business-as-usual waste collection routine, resulting in lower fuel consumption and labor costs. However, because it requires WiFi access and the edge nodes are battery-powered, the technological implications for scalability and long-term energy sustainability warrant further investigation. Further, the research gap between low-power communication and sustainable power sources should be addressed.

Alsayaydeh et al. [22] developed an innovative IoT waste management system by integrating multiple sensors, cloud analytics, and GPS-assisted routing. They conducted field tests that showed a fill-level accuracy of 85% and a 20% reduction in truck route mileage, improving efficiency and reducing CO_2 emissions. However, there were limitations due to Wi-Fi packet loss, sensor drift, and scaling issues.

Abdullah et al. [23] introduced an IoT-based smart bin with GPS and GPRS sensors, optimized using GA, to manage waste collection processes in Mecca efficiently. Their results indicated enhanced route efficiency and reduced costs, but their study illustrated the gap between not deploying their solution at scale and managing food waste during peak seasons.

Jouhara et al. [24] review waste management methods used in the home for biological and physicochemical treatment to reduce billable waste volume, the resulting need for transport, and, ultimately, to produce energy from waste. In their article, the authors highlighted biological and physicochemical methods for waste treatment as opportunities to enhance sustainable, efficient household waste management. Additionally, the challenges posed by harmful emissions, the complexity of the steps involved, and the need for prescriptive user involvement were flagged. The authors also illustrated that, despite the potential for biological and physicochemical waste treatment, there remains a gap in the use of domestically relevant solutions for scaling, costing, and environmentally safe waste management in the home.

Afolalu et al. [25] described a smart waste bin that uses automation to enhance solid waste management. The waste bin consists of an Arduino microcontroller, ultrasonic sensors, an MQ-2 gas sensor, a servo motor, an LCD Display, and a GSM module. The smart waste bin automatically detects users coming into view, opens the lid, measures its fill level, and sends a text message to the user when it reaches half full (50%) or full (100%), or when foul gases are detected. Validations were successfully performed, and it was confirmed that the smart waste bin worked reliably when detecting users, opening their lids, and sending messages. Subsequently, improved waste-collection efficiency was achieved through reduced manual management of the smart waste bin. The authors note that future improvements could include adding a buzzer sound alert and increasing battery capacity to allow the same smart bin to work longer.

Suvarnamma et al. [26] developed SmartBin, an innovative waste bin system that combines waste segregation, tracking, and IoT-based monitoring and reporting to manage waste effectively. The SmartBin uses inductive and capacitive sensors to classify waste into metallic, plastic, and glass. SmartBin uses RFID and GPS/GPRS modules to enable waste bin tracking by location, weight, and household. The waste classification data are sent and transmitted to a remote server for storage and analysis. In contrast, the tracking, location, and weight data are used for route planning based on properly classified waste that can be recycled. They conducted tests that showed effective differentiation of disposable waste and effective real-time monitoring and triggering notifications once the SmartBin was full (70%). Suvarnamma and Pradeepkiran outlined future scope for biogas production, route optimization, and robotic waste collection, making SmartBin a scalable approach for waste management in smart cities.

Zoumpoulis et al. [27] systematically reviewed 79 studies on smart bins to explore their potential for sustainable urban waste management. The paper highlighted that most studies involved IoT-enabled fill-level monitoring and perception technologies (e.g., ultrasonic, gas, and vision-based sensors). Although many studies have reported efficient real-time tracking and routing optimization through prototypes and case studies, only a few have explicitly reported automated waste segregation. The review acknowledged a general lack of consistency and standardization among the mechanization methodologies reported in the literature, while most studies reported low-to-medium (TRL) levels of technology readiness. The authors concluded that gaps exist in maturing cost-effective, standardized smart bins that fully complement circular economy models by integrating material separation.

Rai et al. [28] proposed a Smart Dustbin system that leverages IoT devices to track and monitor waste in real time, thereby improving the efficiency of local collection notifications. The system utilizes ultrasonic and passive infrared sensors connected to an ESP32 microcontroller. It provides visualization of waste levels in a web-based dashboard/mapping system via Wi-Fi or GSM. The Smart Dustbin provided features such as fill-level monitoring, SMS alerts, mapping, and reduced labor (monitoring) by automating the process, ensuring timely rubbish collection. While their tests showed a usable system that works reliably, concerns of network dependency, signal-to-noise sensor fluctuations, and other factors presented minor challenges. Ultimately, their research demonstrates a cost-effective, scalable model that can be installed in any smart city; however, greater inclusion of predictive analytics and network routing would help make the waste-disposal process more sustainable.

Manik et al. [29] introduced the Smart Waste Management System (SWMS), which provides a framework for addressing waste issues arising from urbanization in Nusantara, Indonesia's new capital. The SWMS utilizes IoT and ICT technologies and deploys multiple sensors to monitor, categorize, and track waste in real time. Waste pickup is triggered when the bin's fill rate exceeds a defined threshold, which directs the GPS-enabled vehicle to its exact location. This is achieved via a central system accessed through web or mobile applications. This framework was intended to improve operational efficiency while aligning with the city’s goal of creating an innovative and sustainable urban area. The authors recommend integrating ICT and IoT for clean, sustainable urban environments. Success in Nusantara can serve as a pilot for other cities to implement sustainable waste management systems.

Shyamala S.C. et al. [30] propose an innovative waste management model that utilizes ultrasonic and moisture sensors connected to an ATmega328P microcontroller to monitor bin fill levels, wet waste, and spillage. The system transmits data detected from the sensors to a waste management center (WMC) through GSM/GPRS. The results show accurate detection of the bin status, wet/dryness of the waste, and garbage on roads, all of which assist the municipal solid waste agency in reducing the associated collection costs while maintaining sanitary conditions. The limitations noted by the researchers included that, instead of adapting the model to a centralized server, notifications are sent to a phone number; only overall fill levels are monitored; and there is no GPS-based route optimization, which may always leave room for improvement to make it more scalable and efficient.

Suprava Ranjan Laha et al. [31] present an innovative LoRa-based waste management system that uses ultrasonic sensors and an Arduino UNO to monitor bin levels, locations, and collection routes using the Floyd-Warshall algorithm. These include real-time monitoring, decreased operational costs, and minimized environmental effects. Compared with GSM- or Wi-Fi-based designs, it offers low power, long range, and easy scalability. However, problems remain with future deployment on a larger scale and total integration with renewable energy.

Norfadzlia Mohd Yusof et al. [32] have developed an innovative waste bin system that uses renewable solar power, Arduino sensors, and Wi-Fi for IoT. The methodology demonstrates how the innovative bin binning system tracks the fill levels of each bin, uploads data to a cloud-based central server, sends alerts to collectors via SMS, and provides a web application for bin status and locations. The results showed increased collection efficiency, cost reductions, real-time monitoring, and tracking. The discussion covers Wi-Fi limitations, limited lid-opening detection and location, and the proposed GPS and additional locomotive sensors. The gaps in research areas include tracking customer complaints and tremendous improvements in full automation.

Menaka Pushpa Arthur et al. [33] compare innovative dustbin systems with IoT and deep learning techniques in their collective efforts to manage urban waste. Their empirical study surveyed sensors, AI, and IoT devices to measure fill level and optimize the physical collection system. The results demonstrated reduced labor time, prevention of overflow, and enhanced hygiene. Challenges discussed in the study include the difficulty of real-time integration and deployment at a significant scale. The research gap proposed includes dynamic assessment, scalability, and the use of AI to facilitate autonomous waste management.

Nagesh Bagnwa Mapari et al. [34] propose an innovative IoT-based waste management system that uses sensors, Arduino, GPS, and GSM to monitor bin levels. Alerts were provided at 75% and 90% fill for the bins so that city administrators could collect them promptly. The results showed reductions in the number of overflow events in the garbage bins and in delays. The study shows potential efficiency gains but highlights gaps in large-scale deployment feasibility and issues with garbage collection vehicle routing.

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IV. COMPUTER VISION-BASED GARBAGE COLLECTION SYSTEMS

Dr. Dharmpal Singh et al. [35] (GarbageGo) describe a practical mobile app ecosystem "GarbageGo" that integrates citizen reporting (an image upload), YOLO/TensorFlow image classification, real-time GPS truck tracking (Haversine formula), predictive analytics, and gamified rewards to minimize uncollected street waste; the approach is an architecture + prototype design (mobile app + cloud backend + ML model) with workflow description and simulation/analytical evaluation of components (classification, routing, notification); the results and discussion posit improved responsiveness with the potential to reduce collection delay, and greater citizen engagement through incentives, but acknowledge that the system is still untested at city scale, faces issues with hazardous/e-waste classification and traffic-aware routing; the research gaps are apparent: untested real-world deployment data, limited training data for complicated/hazardous waste classes, traffic-aware route optimization, and rigorous privacy/usability testing.

Wenbo Liu et al. [36] introduce a Convolutional Neural Network (CNN) based intelligent garbage classification and recycling system that automates feature learning to increase accuracy and throughput compared to all traditional methods; there were a set of tasks completed for the methodology, including dataset acquisition/annotation (camera + web imagery), designing a specific CNN (with convolutions, pooling, fully connected layers), GPU-based training, and comparative experiments against more classic approaches; findings reported extremely high classification accuracy (reported around ~94% to 99% accuracy across study), improved classification time, and overall improved system throughput when compared to classic/manual-feature methods; in the discussion section, the authors claim that deep networks extract meaningful features massively and create a means of automated systems for sorting/recycling pipelines; noted research gaps include need for reliance on typed of stated dataset quality and diverse datasets (more larger and diverse and real-world datasets are needed), robustness to light/occlusion conditions, and evaluation based on full pipelines (imaging → material sorting → recycling outcomes).

Alsabt et al. [37] studied AI and ML for optimizing waste management, aiming to improve economic efficiency and reduce environmental impacts. Using the World Bank's *What a Waste* dataset, the authors applied preprocessing techniques, such as data cleaning and feature selection. ML models include regression for forecasting, classification algorithms such as SVM, RF, and XGBoost, and linear programming for optimization. The results showed 85% accuracy in predicting waste generation, outperforming Johnson et al. (2020) at 70%. The classification highlighted recycling and waste-to-energy as viable strategies, although recycling was less effective in low-income regions. Optimization improved the operational efficiency by 15%. This study discusses ML's transformative role in proactive policymaking and sustainability planning. However, issues of data quality and completeness remain barriers. This research identifies gaps in standardized global datasets. Future work suggests integrating IoT and blockchain with ML to enhance global waste management solutions.

David B. Olawade et al. [38] offers a wide-ranging overview of how artificial intelligence (AI) may reshape waste management with respect to collection, sorting, recycling, and monitoring, and integrating AI with IoT and other policy frameworks; the methodology in this work is a systematic literature search in Scopus and Google Scholar (papers 2021-2023), followed by thematic synthesis of the 71 papers selected for review; results coined around AI techniques (regression, SVM, decision trees, ANN, deep learning), applications (smart bins, route optimization, image-based sorting, predictive analytics), and common barriers (data quality, privacy, cost, ethics); the discussion highlights practical integration opportunities (AI+IoT+robotics), calls attention to collaborative frameworks, and the need for more policy attention in regard to ethics and data governance; the research gap identified is the distribution of data quality (or lack of), no standardized datasets, limited real-world deployments in low-resourced contexts, limited work looking at privacy/cost tradeoffs and longitudinal assessments.

Devika Kannan et al. [39] introduce SWM4.0, a framework that maps these technologies to the waste-management aims on four pillars of waste management (smart people, smart cities, smart businesses, smart factories); the approach is a systematic literature review (SLR) - with a formal SCOPUS search and a multi-step screening (617 → 391 papers) and expert validation to distill themes and an integrated framework; results included a taxonomy of I4.0 tools by waste type and process (collection, transport, recycling, disposal) and illustrations of concentrations in research (collection and municipal waste are leading); a SWM4.0 integrated framework; the discussion notes that most research focuses on IoT and collections, e.g., gaseous/liquid/hazardous wastes, and e-waste, have not been well-studied; the research gap clearly stated is the paucity of I4.0 studies specifically on e-waste, gaseous/liquid/hazardous waste, limited cross-domain integration (few studies integrated people/business/cities/factory), and empirical validation, with the need to do so at scale.

Ahmed et al. [40] introduced an IoT-based Intelligent Waste Management System (IWMS) for smart cities, which includes energy-efficient smart bins, efficient sensor data management, and sustainable, efficient waste collection routes. They used an AHA-based three-phase method: AHA-LEACH for energy-efficient bin clustering that accounts for bin energy consumption, AHA-KNN for imputing missing data, and MOAHA for multi-objective routing of the collection truck. Using MATLAB, they demonstrated a 34% reduction in energy consumption for the bin, increased data reliability, and improved route options compared with existing routes. Overall, they demonstrate the effectiveness of combining bio-inspired algorithms with IoT technologies for real-time waste management. Although they identified substantial gaps in energy- and scenario-based approaches that consider energy sustainability, data completion, and routing optimization, challenges remain in addressing large urban-scale networks and in making adjustments to adapt to contingency urban conditions.

Fang et al. [41] reviewed the impact of artificial intelligence (AI) in waste management for smart cities that incorporate AI systems, which are expected AI enhance efficiency and sustainability. This study reviewed AI in smart bins, waste-sorting robots, private prediction modeling, recycling, and waste-to-energy systems. Their findings suggest that AI can reduce transportation distance by 36.8%, transportation costs by 13.35%, and time by 28.22%, and improve waste classification accuracy by up to 99.95%. In their discussion, the researchers emphasized the importance of AI systems for logistics, improving sorting efficiency, and support for renewable energy resources from waste, but pointed out that there are some limitations to widespread adoption, notably, costs, lack of customized models specific to business needs, an absence of real-world datasets to build on, and the "black box" problem associated with AI. Gaps in the literature lie in the development of customized AI frameworks, the integration of IoT and big data concepts for real-time monitoring, and the design of hybrid models to enhance community adaptability. Overall, the review concludes that AI can be further developed to enhance waste management systems; however, barriers remain to its practical implementation to promote sustainability.

Haruna Abdu et al. [42] presented a focused survey of deep-learning approaches to waste detection and classification, compiling and analyzing many DL models and benchmark datasets for trash detection across environments; the methodology is an exhaustive literature survey across IEEE Xplore, ScienceDirect, Scopus, ACM, and manual reference mining, with organization into model types (classification, detection), datasets (20+ benchmark sets), and a strengths/limitations analysis; the results organize the state-of-the-art (CNNs and object detectors dominate), document dataset characteristics and gaps (imbalanced, environment-specific), and list typical DL pipelines and metrics; the discussion highlights problems with occlusion, lighting, domain shift, and dataset scarcity for some waste types; the research gap emphasized is the need for standardized, large, multi-environment benchmark datasets, domain adaptation methods, and more work on multi-object detection in cluttered real-world scenes.

Majchrowska et al. [43] proposed a deep learning-based framework for automatic waste detection and classification. They introduced two unified datasets: detect-waste to localize different domestic wastes and classify-waste to categorize waste into seven types of household waste, which sought to address prior dataset inconsistencies. They used a two-stage approach: EfficientDet-D2 for detection and EfficientNet-B2 for classification, and semi-supervised learning via pseudo-labeling. They conducted experiments on over 28,000 detection images and 21,000 classification images, achieving detection precision of up to 70% and classification accuracy of up to 75%. The experiments showed good performance in classifying recyclable waste types, but challenges with the unknown and non-recyclable categories were largely due to data imbalance. They emphasized the value of unified benchmarks and discussed their applications in household sorting, monitoring categorizations in cities, and underwater waste detection. Research gaps lie in improving small-object detection, improving training datasets to reduce imbalance, and extending models to account for industrial waste and facilitate real-time deployment.

Geethamani et al. [44] shared a web-based Garbage Management System to address waste overflow, unhygienic settings, and inadequate traditional garbage collection systems in high-density areas. This approach involves building a webpage with multiple dashboards for five user categories: admin, people, drivers, buyers, and distributors. The admin can assign tasks, determine if the bins are full, manage orders, and track progress; people can complain, request bins or drivers; drivers are responsible for going for garbage with a guided route; distributors are responsible for the delivery of the garbage to buyers; and buyers can view and acquire the garbage available. The findings show that this system can reduce human effort and time, improve communication among all parties, and provide greater tracking capabilities for managing the garbage collection process. The authors suggest that it is important to first connect people digitally to the workforce. The result is a more efficient use of resources and reuse of waste, linking buyers with recycled materials, organic waste, or e-waste. The authors suggest there are still gaps in the research, particularly the lack of IoT-based real-time monitoring, limited validation of large-scale implementation, further development of an integrated/combined real-time approach, and the need for optimization models to improve efficiency and scale up the waste allocation process in the future.

Varalakshmi P. et al. [45] introduced an AI-based framework for waste classification and detection that leverages computer vision and deep learning. The methodology proposed preprocessing techniques, including image enhancement, normalization, and feature extraction, applied to pretrained CNN architectures (ResNet, VGG, and MobileNet). To classify the imaged waste, transfer learning was employed using optimization algorithms such as SGD and ADAM, and YOLO was identified as a specific area of exploration for real-time waste debt classification. The results demonstrated high accuracy in recognizing a variety of waste types, including plastic, glass, paper, metal, and organic waste. They discussed how automating waste segregation would reduce manual effort, reduce errors, and increase recycling capacity. The authors also outlined some research gaps, including scalability of the system for large datasets, capability to handle video streams in real time, and integration with autonomous or IoT-enabled platforms for waste management. This study makes a substantial contribution to the literature by including YOLO as a tool to address the speed and accuracy of waste classification tasks.

Mohammed M. et al. [46] present a real-time intelligent garbage monitoring and collection system utilizing YOLOv5 and YOLOv8 deep learning models for sustainable waste management. The methodology used a Raspberry Pi equipped with sensors and cameras to observe bins and classify garbage into main categories (e.g., full containers, garbage bags, waste outside the bin, wet trash), then subdivide the categories using a two-stage classification. YOLOv5 is used for lightweight detection of small objects on low-power hardware platforms, whereas YOLOv8 is used to classify bin subclasses more accurately. The discussion postulates that the proposed system addresses trash overflow and miscommunication with governing authorities, and reduces computational costs while performing real-time waste segregation. The research has limitations in its datasets, which are not diverse enough, and challenges in environmental conditions, hardware scalability, and in implementing the research to ensure it's part of a larger urban infrastructure. This research is original because it combines IoT and deep learning for garbage monitoring, which is efficient, cost-effective, and accurate, and it furthers newer work ranging from predictive modeling to robotic garbage collection.

K. Mallikarjuna Raju et al. [47] detail a Smart Garbage Monitoring System through an IoT (Internet of Things) approach that aims to optimize waste collection and mitigate environmental risks associated with ineffective traditional methods. In the methodology, they used Arduino UNO microcontrollers, ultrasonic sensors for bin-level identification, GSM modules for wireless communication, and GPS trackers for mapping bin locations. The system continuously monitored garbage levels and, when it reached the preset threshold, sent immediate collection messages to the authorities. It demonstrated timely collection, as the pilot study collected data in real time, accurately detected bin fill levels, followed the best collection route, limited overflow, and minimized unnecessary collection trips. The authors conclude with supporting discussions of regularities in improved operational efficiency, fuel efficiency, pollution reduction, and sustainability in smart city-regulated waste management. This paper identifies research gaps in large-scale deployments, integration with cloud-based analytics, environmental constraints in ubiquitous refuse collection, and scalability for urban environments. The authors contributed to the field by demonstrating a cost-effective IoT solution, including a sensor-based approach for more proactive waste management. Future research could consider AI-based predictive models or robotic or autonomous collection systems.

Dr. Usha S. M. et al. [48] introduced a computer vision and IoT-based garbage detection and collection system using robotic automation within the Raspberry Pi environment. The methodology incorporated a Raspberry Pi with a Pi camera, image detection and classification with OpenCV and TensorFlow, and a robotic arm for trash collection/placement into onboard bins. Ultrasonic and level sensors were used to monitor bin capacity, and notifications were provided when bins were full. YOLO-based detection was used to improve the object detection speed. The results showed that real-time trash detection was successful in controlled environments, while robotic pickup was accurate, minimizing the need for manual collections. However, the limitations of this research include reliance on a controlled environment, limited generalizability of the datasets, increased computational expense, and the need for future work to deploy outdoors under different weather or lighting conditions. The research gap surrounds the trade-off between scalability, robustness in dynamic environments, and integration with large-scale smart waste infrastructure. As part of the research contributions, this study demonstrated the possibility of implementing autonomous vision-based garbage collection systems. The authors also suggested that future work should focus on improving AI accuracy and efficient mobility, and also consider cloud integration for deployment at an urban scale.

In their work, Sahil Yadav et al. [49] described an AI-based, real-time waste separation system that uses computer vision and deep learning to automate waste classification. They used the YOLOv8 object detection model, configured to run on edge devices, along with OpenCV preprocessing and a scalable MongoDB database. The procedure used a hybrid dataset comprising TrashNet, TACO, and their own custom images. This trained model could classify waste into four categories: biodegradable, non-biodegradable, recyclable, and hazardous. The average precision (mAP) mean was 95% for IoU 0.5, with a delay of less than 2 s. These results confirm the system's effectiveness in a real-world environment. Their discussion highlighted the system's modular and scalable nature and its applicability to smart cities. They employed low-cost open-source software and edge device hardware. Their research gaps were separating waste that was occluded/on top of other waste, assessing the degree to which lighting changed, and evaluating the system's adaptability in highly dynamic outdoor environments. The contribution of this study was to demonstrate the feasibility of deploying a YOLOv8-based, real-time waste classification system in real-world settings, while presenting opportunities for future work, including IoT-enabled smart bins, anticipated robotic sorting, and multimodal data to improve robustness and autonomy.

Garg et al. [50] described a Smart Waste Management System (SWMS) that uses Python-based object detection to automate waste sorting. The project methodology consisted of collecting data from TrashNet and real-world images, annotating them, augmenting them, and training YOLOv5 and CNN models using TensorFlow and OpenCV. The SWMS architecture includes modules for image collection, object detection, and real-time classification. The modules are backed by GPUs, which provide rapid processing. The results showed excellent performance, with a precision of 92%, a recall of 88%, and an F1-score of 90%. The authors' cited research opportunities include transfer learning, balancing dataset heterogeneity, leveraging larger databases, and improving SWMS adaptability across regions. In conclusion, Garg et al. argued for moving IoT, blockchain for tracking, AR for sorting, and continuous model updates for scalability/expense reductions. Garg et al. 's work demonstrates that AI-based object detection has changed the paradigm for how we view the waste management problem, enabling an environmentally sustainable, efficient approach.

Kavade et al. [51] developed an Automated Waste Segregation System Applied Using OpenCV and image processing for real-time waste sorting. This proposed solution involves an ESP32-CAM to capture images, YOLOv5 to detect the waste category, and an Arduino to control actuators and servo motors for segregation into predefined bins. The design implemented Python, IoT, and machine learning to capture an image, classify it, and send a command to trigger disposal. This system provides results indicating its ability to classify waste material into biodegradable, plastic, and metal with impressive accuracy, capturing lumps and rounded, deformed objects, and sometimes even detecting elements reflected off the objects' shiny or translucent surfaces. The discussion section describes the design's flexibility, enabling deployment across a variety of applications, including household and public outdoor bins. Next, an exciting possibility is environmental benefits, including reducing landfill waste and facilitating composting of biodegradable waste. Remarks on implementation indicate that hardware and software can be optimized to create a scalable, sustainable device for automated multi-category waste disposal. However, misclassification owing to luster or transparency remains a challenge. Gaps in the research case suggested that more complex datasets are needed, and robustness needs to be improved in complex environments. Overall, this work presents a technically feasible, environmentally friendly, and scalable solution for automated multicategory waste segregation.

Md. Wahidur Rahman et al. [52] present an intelligent waste management system that utilizes deep learning and IoT for real-time interaction and monitoring of waste classification. The methodology uses a Convolutional Neural Network (CNN) and a specifically fine-tuned ResNet-34 model to classify waste into digestible and indigestible categories. In addition, a smart trash bin was developed with IoT-enabled sensors, ultrasonic load measurement sensors, and Bluetooth connectivity to support cloud monitoring and short- and long-range data transfer via an Android application. The results show a classification rate of 95.31% and a System Usability Scale (SUS) rating of 86%. This validated the effectiveness of the proposed system in a household scenario. In the discussion section, it is noted that although CNN-based classification improves sorting accuracy, dataset quirks, the appearance of waste material, and the limited number of sensors used for waste categorization pose issues. An identified research gap is the need for larger, more variable datasets and additional sensors (e.g., IR and gas sensors) to improve the model's robustness and classification accuracy. Overall, this work demonstrates that deep learning with IoT provides a scalable framework for the smart management of real-time waste, but requires further optimization for large-scale deployments.

Dedania et al. [53] presented an IoT-enabled AI waste classification system that contributes to smart waste management. A CNN model using MobileNetV2 served as the basis for the methodology. The CNN model was trained on a total of 14,000 images (the images comprised recyclable and non-recyclable images). The model was deployed on a Raspberry Pi 4 with TensorFlow Lite. The results demonstrated low-latency classification of approximately 120 ms per frame and rapid actuation in 0.5 seconds. The discussion was centered on the solution's scalability, cost-effectiveness, and compatibility with the smart city infrastructure. They also discussed the advantages of edge deployment, particularly reduced reliance on the cloud, lower latency, and improved privacy. However, challenges remain, such as misfires due to timing issues and performance degradation under library conditions. The research gap discussed concerns future work that enhances the product's robustness, introduces new waste categories, and reduces timing and actuation errors. Overall, this investigation can be viewed as a low-cost, real-time, and scalable AI-enabled IoT solution for automated waste segregation.

Lavanya et al. [54] propose an IoT-based system for optimizing garbage pickup routes using computer vision for urban waste management. Their methodology uses a Detectron to detect bin or dumpster overflow, an ultrasonic sensor with a Raspberry Pi 5 for real-time monitoring, and heuristic algorithms (GA and ACO) for route optimization. Their system features a web dashboard built with Flask to display bin status and optimized collection routes. Key discussion points include concurrent two-layered sensing with sensors and vision, which enhances result reliability across many environments, as well as the successful use of heuristic algorithms to minimize waste collection costs, time, and greenhouse gas emissions on a large scale. Lastly, a useful web dashboard acts as a communication bridge between automation and human decision-making in their system. Their research does have some notable gaps: waste type classification was added. Still, a GPS-enabled vehicle-tracking architecture was not used, and there was no validation using a comparable large-scale waste pickup deployment. In summary, the authors have introduced a scalable, environmentally conscious model towards sustainable waste management for future cities.

Lakshmi M. [55] discusses a systematic review of smart waste management systems leveraged by Artificial Intelligence (AI) and Computer Vision. This review breaks down the methods and applications of smart waste management systems, including AI and Computer Vision, such as CNN-based methods like You Only Look Once

(YOLO) and Faster R-CNN, reinforcement learning for sorting via robots, and IoT systems across smart routes. Case studies evaluated South Korea, Amsterdam, the USA, Barcelona, and India, and found that waste recycling improved, reducing costs to maintain urban environmental cleanliness. AI bin-and-robot sorting demonstrated effective real-time operations. The discussion outlines several ethical dimensions of waste systems, including privacy, job loss, and environmental justice. Technical issues in waste management include the model's generalizability, affordability, and infrastructure readiness. The authors emphasized the use of predictive analytics to improve efficiency. Research gaps include regional scaling and citizen engagement. A framework to govern data policy is lacking. The author's future work towards solutions presents a federated learning, circular economy model approach to citizen participation.

Ali et al. [56] proposed a Deep Learning and IoT-based system for automatic waste segregation. The methodology integrates ultrasonic sensors, conveyor belts, and servomotors with convolutional neural networks (CNNs), such as VGG16 and MobileNetV2, trained on 27,998 images from Kaggle. The system classifies waste into recyclable, organic, and toxic types with an overall accuracy of 95%. The results demonstrated effective segregation, reduced manual labour input, and improved hygiene. Transfer learning and hardware–software integration enable real-time waste disposal. Automation provides superior reliability to manual disposal. Nonetheless, scalability and cost are significant barriers to its widespread adoption. Additionally, the segregation system relies heavily on the quality of the datasets. Research gaps should also address the limited capacity to adapt to various types of waste and infrastructure-related issues. Future work will suggest expanding the datasets and reducing the costs of extended-axis deployment.

Sivakumar et al. [57] detailed a smart IoT-based solid waste management system using computer vision techniques and deep learning. The authors' methodology utilized CNN with ResNet V2 transfer learning to classify biodegradable and non-biodegradable waste. The hardware, which included a Raspberry Pi, sensors, and a Jetson Nano, was used to capture and process real-time images. The initial dataset was pre-processed by rescaling, perturbing (augmenting), and batch normalization to improve accuracy. The authors achieved 94.44% accuracy and 9.26% loss, beating the ANN, SVM, KNN, and DT classifiers. The ANOVA and MCC statistical tests demonstrated the superiority of the model. In the discussion section, the authors reported that their work was statistically highly efficient at the household/source-of-waste problem level, but not as effective at a mixed waste dumping yard site. Automation with hybrid pooling layers directly contributes to the stability of their model. The research gap focused on scalability, which can be an issue with unstructured waste at municipal dumps; therefore, only a robotic segregation automation with adaptive learning was proposed for practical purposes, intended for larger waste volumes.

Kayalvizhi et al. [58] presented a smart waste management and waste segregation system using IoT, machine learning, and an Android app. The methodology includes IoT-enabled bins (ultrasonic sensors), cloud-based machine learning algorithms for waste prediction, route optimization, and an app for monitoring. The experimental results indicate an efficient waste segregation system, reduced waste management costs, increased recycling rates, and improved public health/well. This discussion highlights scalability, automation, and public involvement through mobile phone integration. However, the gaps in research center on high infrastructure costs, increased reliance on network connectivity, and limited adaptation to rural/low-resource settings. The paper suggests adding future elements of emerging technology, such as smart home bins that utilize blockchain.

Son V. T. Dao et al. [59] introduced an AI-based approach for sustainable waste management through Machine Learning and Deep Learning. This methodology fuses bibliometric and scientometric analysis with MobileNetV3 for feature extraction, Harris Hawk Optimization for feature selection, and ML algorithms, namely Decision Tree, Logistic Regression, and Random Forest. The results showed improved classification accuracy, operational efficiency, and real-time decision-making in waste management tasks, including segregation and transportation. The discussion explores AI's impact on automation, scalability, and lowering the environmental impact. Research gaps include limited dataset diversity, large-scale implementation challenges, and a lack of viable deployment frameworks. This paper proposes that future directions will be defined by improved datasets, optimized hybrid models, and real-world applications.

Gayathri Rajakumaran et al. [60] present a smart waste segregation system based on image classification and multi-object detection using convolutional neural networks (CNNs) - ResNet50 and YOLOv3, respectively. The waste segregation system uses drones equipped with Global Positioning System (GPS) and Global System for Mobile Communications (GSM) to pinpoint waste locations and notify the relevant parties, improving efficiency and minimizing labor requirements. This automated waste segregation system is faster, cleaner, and more environmentally sustainable than traditional landfill scenario planning and studies. However, it may not currently handle complex categories such as e-waste or medical waste; thus, there is a need for additional classifications and datasets, as well as frameworks that can scale to urban populations.

Gopalkrishna V. Gaonkar et al. [61] conducted a comparative assessment of solid waste management across countries using secondary data on waste composition, generation, and disposal techniques. The study found that paper accounted for the largest share of waste in both the USA (35%) and India (41%), and that disposal techniques differed, with the USA and the UK relying mainly on landfilling. At the same time, recycling was the dominant technique in Germany. The findings indicated that among urban cities, Mumbai produced the highest amount of solid waste (6550 tons/day), whereas Ahmedabad produced the least (2350 tons/day). The research gap is the need for an integrated waste management system that considers both technology and social behaviour, addressing scalability, energy efficiency, and sustainability into the future.

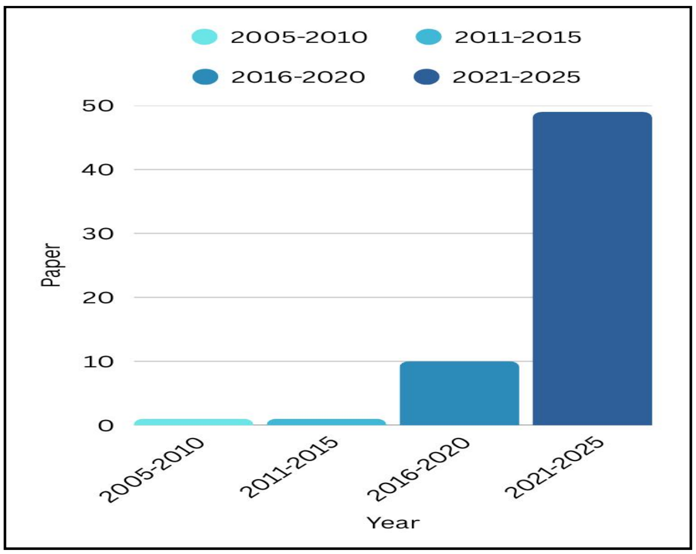

Fig 2. Research Trend Over the Years

Figure 2 presents the pattern of investigation in smart waste management systems from 2005 to 2025. It clearly demonstrates that the number of published papers has increased sharply, especially in the period 2021-2025, with close to 50 papers published, compared with fewer than 15 in all previous timeframes. Such growth indicates increasing global interest in IoT, AI, and smart-city applications in waste management, especially amid rapid urbanization, the demand for sustainability, and technological advances. The trend also indicates how the field has advanced from a small kernel of exploration in 2005-2015 to an emerging research hotspot from 2020 onward.

V. DISCUSSION

The reviewed literature highlights a variety of technological advancements within waste management, including IoT-based monitoring systems with embedded hardware, AI-based sorting, and route planning. The use of IoT smart bins with ultrasonic, infrared, and weight sensors to monitor fill levels, prevent overflow, and trigger real-time event-driven notifications is commonplace. Monitoring systems demonstrated improved operational efficiency and reduced reliance on personnel resources. Other technologies have relied on machine learning and deep learning methods, including CNNs, YOLO, and TensorFlow Lite, to improve the accuracy of waste sorting, automation, and logistical planning. Various applications of Location Intelligence and GIS-based optimization models to integrate dynamic truck routing and improve efficiency, rather than traditional static scheduling, have been employed. Overall, the literature shows that innovative waste management is a well-developed field, with clear evidence of sensor-based monitoring, automation, and data-driven decision-making in practice.

These advancements inform the proposed system, which provides RFID-based tracking of household waste at the waste institute during capture, with no manual input required. The Smart Drop Box module holds households accountable for non-compliance if they fail to use the drop box for 4 calendar weeks, requiring waste collection within a 24-hour window. In addition to waste-type detection (dry, wet, hazardous), compartmentalizing waste deposits, and notifications of waste fill levels, the drop-box promotes separation and non-compliance. An automatic fine mechanism, akin to e-Challan mechanisms, provides a layer of regulatory accountability by removing waste management from a system designed for voluntary compliance to one of accountable compliance and regulation. Cloud connectivity and web-based dashboards provide transparency into household use, allowing municipal staff to monitor compliance, generate historical reports, and receive real-time compliance notifications.

By consolidating accountability, automation, segregation verification, and enforcement through a unified IoT–cloud structure, this project moves beyond current bin monitoring, route optimization, or waste classification strategies to create an enforcement structure for household-level engagement, while also laying the groundwork for future AI-driven predictive analytics on disposal behaviors and non-compliance patterns that will assist with assure informed planning for urban sanitary management policies. Ultimately, this ensures long-term employer transparency, accountability, and governance as they engage with urban waste management.

Research Gap

The most prevalent systems are either bin-centric or logistic-centric. They primarily developed systems that focus exclusively on preventing bin overflow, optimizing routing, or reducing contamination, with little attention directed towards household accountability. [48] [49]

Most barcode/QR code–based approaches aiming to link households to bins encounter barriers that stem from manual scanning, damage to code/labels, and scalability concerns in densely populated cities. [50]

Without systems for compliance and enforcement, households cannot be expected to participate consistently or be accountable. [51]

In current AI and sensor-based classification systems, the expectation or assumption is that there is prior segregation; however, these systems do not offer verification of segregation or enforcement at the household level. [52]

Legal enforcement around segregation is inconsistent, compromising the success of recycling systems at the municipal level. [53]

Very few studies leverage predictive analytics or other sophisticated AI models to monitor processes, predict citizen behavior, or plan waste management initiatives. [54] [55]

Cloud platforms are primarily used for data storage and visualization, although there are limited capabilities for real-time enforcement, municipal system interoperability, or automated fines. [56] [57]

VI. CONCLUSION & FUTURE SCOPE

This research examined various innovative waste management systems employing IoT, embedded technology, and AI-based techniques to improve collection, monitoring, and segregation efficiency. Despite these advancements, most solutions are still limited to bin-based monitoring and routing optimization and/or lack an essential component of citizen accountability/compliance. Systems using QR codes, barcodes, or mobile applications provide citizen engagement but are problematic for scalability, require a high workforce, and lack automation. Similarly, embedded sensor-based systems provide acceptable usage status information on bins. However, they are still limited by their inability to enforce segregation or penalize users who refuse to comply, ultimately inhibiting the projects' long-term viability. The restrictive limits of their integration into municipal governance mean they are underutilized and unlikely to have any real-world impact.

However, in this proposed system, the traditional bin-centric framework will be changed to one in which we are accountable to citizens. Every waste disposal is tracked via RFID, with household segregation evidence linked to each household. The Smart Drop Box enhances compliance by not only tracking whether waste is placed in the boxes and whether it is dry, wet, or hazardous, but also locking access to the bins when they are full and sending alerts to the municipality. It is important to note that applying an automated, delicate process, following e-Challan systems, addresses the policy failure to govern by developing a set of fines and incentives to replace discretionary enforcement. Collectively, these modules provide a comprehensive, technology-enabled, legally enforceable systems model that identifies where existing systems fail and offers the opportunity to transform municipal solid waste management (MSWM) into a more transparent, cleaner, and more intelligent system.

Although the proposed framework significantly advances the literature, considerable opportunities for further advancement remain. A vital avenue is to incorporate artificial intelligence and predictive analytics further to forecast waste generation patterns, identify non-compliance patterns, and enable dynamic optimization of collection schedules. The system can also be enhanced with computer vision and deep learning methods to support independent and reliable sorting verification, contamination detection, and quality assessment of recyclable materials. Another potential improvement, blockchain, could facilitate trust between municipal authorities and citizens by providing immutable records of waste-disposal behavior, fines, and property-owner compliance.

In terms of deployment, future research should focus on scalability and interoperability across large urban centers with multiple infrastructure capabilities. This requires low-power Internet of Things (IoT) devices, standardized communication protocols, and cost-effective sensors. A fine system can connect with broader smart city ecosystems by integrating innovative platforms that address water management, energy consumption, and traffic issues within a more unified urban governance framework. Finally, there is potential to explore citizen engagement options, such as reward-based gamification or tax rebates, to encourage continued compliance with our innovative fine system. These future directions underscore the potential to transform waste management systems in smart cities through IoT, Artificial Intelligence (AI), blockchain, and citizen-centered design, creating the next generation of sustainable, transparent, and automated systems.

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