(REVIEW ARTICLE)

A review on real-time waste tracking and route optimization using cloud-based IoT systems

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Abstract

The increasing need for green urbanization has surfaced the inefficiencies of conventional waste collection infrastructure. Proposes a smart waste collection system based on IoT sensors and TOPSIS multi-criteria decision support method for route optimization with criteria such as toxicity, volume, and time duration. With multiple influencing variables compared to using one parameter, the system proposed here achieved a reduction of 14% in the overall collection distance. Likewise, it deals with the application of IoT for real-time medical waste monitoring in smart cities. It suggests an Android-based route navigation and real-time bin statistics-supported Medical Waste Collection Management (MWCM) system for ensuring waste collection truck routing. It is designed to minimize labor, cost, and environmental footprints while facilitating sustainable development goals. Drawing upon the past trend of embedding cutting-edge technologies in urban waste management, we investigate the use of Industry 4.0 and cyberphysical systems for the collection of residential waste in downtown Toronto. A mathematical model is formulated to solve routing, scheduling, and assignment problems, with optimization objectives aimed at cost-effectiveness, environmental sustainability, and public health factors. The model is tested using a binary bat algorithm and scenario analysis and has been shown to be effective in improving operational sustainability and reliability. Combined, all Papers offer varied but complementary solutions to smart waste management, highlighting the importance of IoT, decision algorithms, and smart planning in the transformation of municipal services.

Keywords: Internet of Things (IoT); Waste Management; Route Optimization; Cloud Computing; TOPSIS

1. Introduction

The purpose of this project is to target the use of Internet of Things (IoT) technology in the optimization of waste collection systems. It points out how the rapid growth in urban populations and the increase in the volumes of waste posed a challenge to conventional municipal waste collection systems, which often use inefficient fixed routes. The proposed framework integrates real-time sensor information with multi-criteria decision-making methods like TOPSIS to dynamically decide the optimal waste collection routes. Given parameters such as toxicity, capacity of the container, and fill time, the process guarantees a more efficient, responsive, and sustainable process of collecting waste in smart cities [1]. The critical requirement for effective collection of medical waste in fast-growing urban areas, particularly in the form of public health risks generated by untreated infectious waste. The authors propose a Medical Waste Collection Management (MWCM) system that uses smart bins based on the Internet of Things that offer real-time monitoring. These are linked to a cloud-based platform and navigation tools through an Android app, allowing collection trucks to travel optimally and on a need basis. The aim is to create a cleaner, safer and greener city environment while minimizing labor, fuel consumption, and operational expenses [2]. The researchers consider how increasing urbanization causes a sudden surge in the production of household waste, particularly in the highly populated downtown districts with more complex waste collection logistics. Industry 4.0 technologies are used by the study to envision the waste collection

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system as a cyberphysical system that encapsulates routing, bin assignment, and scheduling issues within a single optimization model. The Introduction emphasizes the need for adaptable and cost-effective systems that also consider environmental and health factors. It provides the groundwork for considering algorithmic solutions, like binary bat algorithms, to provide these multi-objective needs [3]. The revolution of smart city infrastructure, particularly waste management, where past practices are not sustainable anymore. It offers an end-to-end IoT-based solution for the real time monitoring of waste bins, supported by a central cloud platform and communication interfaces like GSM and LoRa. It is meant to reduce unnecessary journeys, rationalize route planning, and make municipal services more responsive. The launch highlights the manner in which combining IoT, cloud computing, and optimization algorithms can turn city waste collection into a data-driven, scalable, and eco-efficient process [4].

2. IOT technologies in waste collection

Role of IoT Sensors in Monitoring Waste Levels (Ultrasonic, Gas Sensors, RFID):

- Ultrasonic sensors are deployed in waste containers to sense their fill levels, allowing efficient and timely waste collection.[1][5]
- Gas sensors monitor noxious or toxic gases emitted from rotting waste, allowing for prioritizing toxic bin collection and increasing safety.[1][5]
- RFID sensors enable tracking and identification of the bins, improving logistics and asset management, particularly when trucks come to collect them.[3][5]

Real-Time Data Transmission and Monitoring Systems:

- Data (e.g., fill level, toxicity, and identity) from bins is transmitted in real time by IoT sensors to a central system, usually via wireless communication technologies such as Wi-Fi or GSM.[4][1][5]
- Continuous, automated monitoring at city or facility scale makes dynamic scheduling possible collections are initiated only if bins are full, preventing unnecessary trips.[4][5]

Cloud Computing and Data Analytics Integration:

- Cloud-based systems enable real-time dashboards, visualization, and advanced analytics to optimize routes, resources, and plan collection effectively.[4]
- Predictive models (e.g., ARIMA/statistical algorithms) can predict when bins will be full so that proactive collection is done before overflow.[5]

Machine Learning for Waste Classification and Sorting:

- Machine learning algorithms (such as GAN, YOLO) analyze sensor or camera input to automatically recognize and classify waste, significantly enhancing accuracy in separating recyclables or toxic waste.[4]
- Smart classification of this type makes it possible to automatically sort e-waste from general or organic waste and streamline recycling processes.[4]
- There is less manual sorting involved; use of resources is enhanced, and toxic waste can be rapidly identified and targeted.[5]

3. Route optimization algorithms and techniques

- Multi-Criteria Decision Analysis (TOPSIS) for Route Optimization

    - TOPSIS technique is applied to select the most efficient waste collection routes taking into account various criteria like bin fill level, toxicity, overdue time since last collection, and route distance. All these are given weightage and computed to select routes for preferential collection that covers critical collection and also cuts down travel distance. As an example, bins with high toxicity and overdue times are prioritized during optimization.[1]

- The image above depicts the use of a ranking algorithm, probably TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), in identifying the best waste collection route. The diagram depicts a network with nodes, which are various locations, and segments between them, each with a score. The fundamental idea of the algorithm is to calculate and compare various routes according to their total TOPSIS scores. Every stretch

between two nodes possesses a unique TOPSIS score, which indicates its desirability according to some predetermined parameters (e.g., distance, road quality, traffic density, etc.). In order to determine the most optimal path between a beginning (node 1) and end (node 7), the ratings of all segments of a prospective path are added up. One route is noted in red in the fig:1 nodes are 1->9->6->7. The TOPSIS ratings for the segments along this route are 0.495 (1-9), 0.41 (9-6), and 0.524 (6-7). When all these scores are summed up, the path gets a cumulative TOPSIS total of 1.429. The text describing the accompanying image, however, gives a score of 3.447. This would indicate that the example path given in the text could be other than the one that has been highlighted, or that only part of the computation is given from the diagram by the scores presented. A greater cumulative TOPSIS value for a route indicates that it is a better choice for waste collection since it is performing better against the parameters under consideration. By putting all possible routes' cumulative scores into comparison, the algorithm determines the best path that provides the optimal balance between the different factors. This well-structured process ensures that the choice of the waste collection route is data-informed and optimized for effectiveness and efficiency: [1]
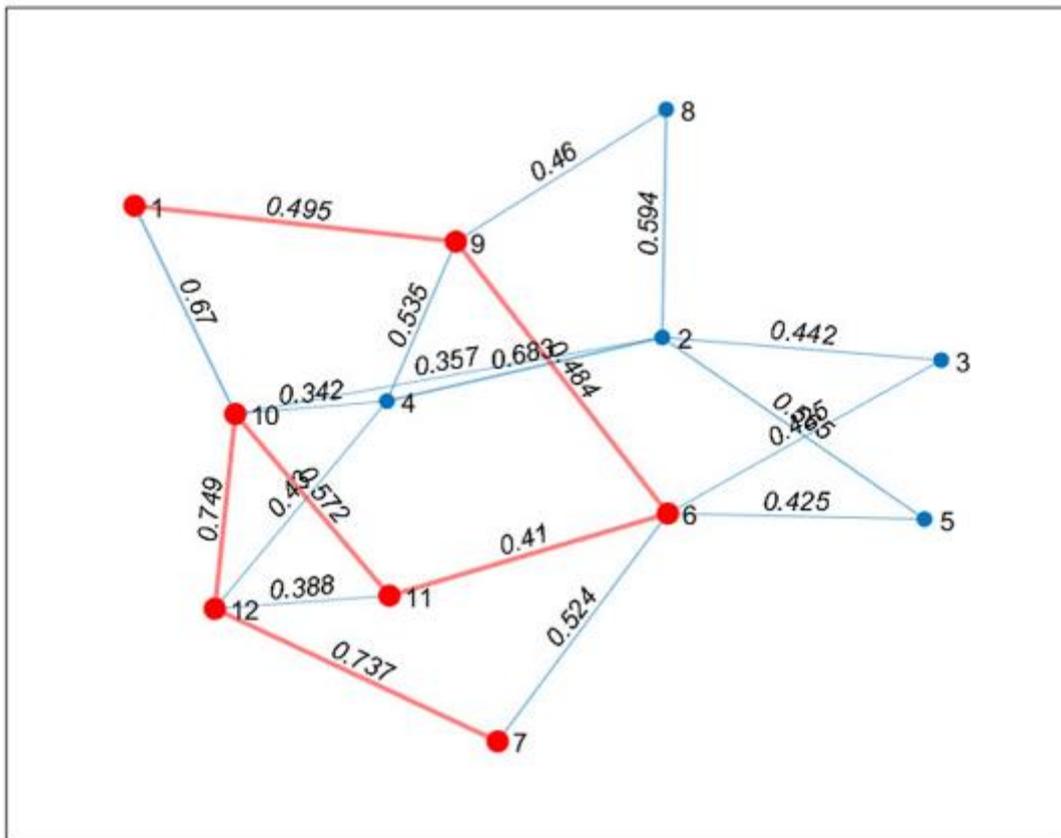

Figure 1 Working of simulation that start from node 1 and ending node 7

- Heuristic and Metaheuristic Approaches (Bat Algorithm, Genetic Algorithms, Particle Swarm Optimization)

    o Heuristic and metaheuristic methods such as the Bat Algorithm, Genetic Algorithms, and Particle Swarm Optimization are utilized to solve the intricate NP-hard waste management problems of vehicle routing and scheduling. The algorithms dynamically adapt routes according to real-time sensor data and operational limits, making them efficient, energy-conscious, and emission-reducing. The Bat Algorithm, in particular, uses cyber-physical feedback to synchronize collection and processing capacity, reducing the environmental effect [3].

- Knapsack-Based Techniques for Vehicle Loading Optimization

    o The 0/1 Knapsack Algorithm is used to maximize waste collection truck loading. Bins are loaded into trucks based on factors like toxicity, volume, and priority, with the goal of maximizing high-priority (for example, highly toxic) waste collection subject to truck capacity limits. The method makes smart

choices about which bins to load onto each trip, leading to remarkable improvements in hazardous waste collection and operational efficiency.[5]

- Dynamic Routing vs. Fixed Routing Methods

  o Dynamic routing takes advantage of real-time IoT sensor information (e.g., bin fill levels or toxicity) to update and change collection routes continuously, in contrast to fixed routing that adheres to set schedules irrespective of real-time bin conditions. Dynamic approaches allow trucks to bypass empty or low-priority bins, avoid unnecessary travel, and react quickly to new conditions, improving efficiency and lowering environmental footprint.[2]

- Smart Bins: Sensors (ultrasonic, gas, etc.) are installed in waste bins to measure fill level, temperature, humidity, and possibly toxicity. Sensors allow bin status to be automatically measured and reported in real time.

4. IOT-assisted waste collection system architectures

- System Parts (Bins, Trucks, Centralized Cloud Platform)
  o Smart Bins: Sensors (ultrasonic, gas, etc.) are installed in waste bins to measure fill level, temperature, humidity, and possibly toxicity. Sensors allow bin status to be automatically measured and reported in real time.[4][5]
  o Vehicles: Waste collection vehicles tend to be GPS-enabled and networked, meaning routes and status are trackable, optimizable, and dynamically updatable.[5][2]
  o Centralized Cloud Platform: All sensor and vehicle data gathered is routed through a cloud platform, the system's" brain." It collects, stores, and processes all inputs to enable sophisticated decision-making and coordination.[4][5]
- Data Flow Model (Sensors → Cloud → Decision Making → Vehicle Dispatch))
  o Step 1: Sensing: Sensors collect information regarding bin fill level, waste type, toxicity, and surroundings. Information is sent through wireless protocols (Wi-Fi, GSM, etc.) in real time.[4][5]
  o Step 2: Cloud Data Aggregation: Sensor data streams to a cloud database, where it is collected, visualized, and analyzed. Advanced analytics and predictive models (such as ARIMA or ML algorithms) can predict best pickup times and detect urgent conditions.[4]
  o Step 3: Automated Decision-Making: Aggregated data is used by the system to automatically rank bins by priority (e.g., full/overflowing, hazardous, or longest-out bins).[5]
  o Step 4: Vehicle Dispatch: Dynamic collection routes are determined and sent to the vehicle fleet to reduce travel, fuel, and cost, and service critical bins first.[2][5]
- Integration of GPS and Mobile Applications for Driver Navigation
  o GPS Routing: The vehicles are equipped with GPS trackers and mapping systems, where management is able to allocate particular bins and zones to each route, monitor progress, and make real-time adjustments.[2][5]
  o Mobile Driver Apps: Drivers have routes and bin pickup instructions delivered through specific Android or web applications. Capabilities may be real-time navigation, bin-fill alerts, reporting of completed pickups, and live update support if routes need adjustments due to unforeseen circumstances.[2]
  o Feedback Loop: Drivers are able to offer status reports, mark problems, or give feedback input, which is fed back to the central system for ongoing optimization.[5][2]x
- Real-Time Monitoring and Notification Systems
  o Central Dashboards: Waste operators and municipal managers track every bin and truck in real time through cloud-based dashboards, which graphically represent fill levels, route completion, and alerts.[4][5]
  o Notification Systems: Automated notifications are sent when bins are full, hazardous, or are inoperable, or if a booked collection is missed. Notifications can be sent to both drivers (to re-route as required) and administrators (for maintenance or escalation).[2][4]
  o User Involvement: Certain systems can alert citizens/residents to collection schedules or prompt improved disposal practices.[4]

- Working of Waste Collection

Figure 2 The Waste Collection Cloud and its connections with the cyber-physical waste collection system including customers, garbage trucks, waste management sites and customer support

The picture and accompanying description relate to two kinds of waste collection systems: physical and conventional.

- **Conventional Waste Collection: In** the traditional approach, collection is done based on a scheduled plan. Collection routes are fixed and don't vary with bin-fullness. This can result in inefficiencies since the trucks could pick bins that are not full or fail to pick bins that are full. The passage mentions a low utilization of collection trucks as among the disadvantages of this system.
- **Cyber-Physical Waste Collection:** The cyber-physical system is a new, data-centric concept. It employs Industry 4.0 technologies like sensors, wireless communication devices, and RFID tags to track the waste quantity in each trash can. This data is gathered and processed in a central "Waste Collection Cloud." Architecture

The figure, titled "Figure 2," depicts the architecture of the system. It has a number of components integrated together:

- Customers' residence: Garbage cans have RFID tags installed that probably talk to sensors. Customers can also communicate with the system through PC or mobile phone.
- Waste Collection Cloud: The core part. It has a database, algorithms and apps, and an access point. It employs data to predict garbage quantity, optimize and schedule collection routes, and coordinate logistics. The cloud also includes a web page for customer service.
- Garbage truck depot: Collection vehicles are outfitted with GPS and RFID technology. Drivers utilize handheld devices to receive their optimized routes.
- Waste disposal facilities: These facilities, such as sorting centers, recycling plants, incineration, and composting stations, are also within the system. The cloud manages their capacity and operations.

The principal advantage of this cyber-physical system is that it makes possible dynamic scheduling of routes from knowledge of the current fill level of bins. This enhances performance and efficiency in waste collection, making for improved resource utilization and a more responsive service. It converts waste collection from fixed to adaptive, and from rigid to smart.[3]

5. Advanced smart waste management systems in urban environments

5.1. Overview of IoT-Facilitated Waste Management Frameworks and Architectures

Intelligent waste management systems combine the use of IoT technology to track, analyze, and optimize waste collection. Systems use sensor-enabled bins, cloud connectivity, and data analysis platforms to offer real-time information on waste levels, supporting dynamic routing and operational effectiveness [11]. Architectural layers generally involve the perception (sensor) layer, the network (communications) layer, data processing in the cloud, and monitoring and management applications. [6]

5.2. Integration of Smart Sensors: Ultrasonic, Gas, RFID, and Time-of-Flight Technologies for Real-Time Monitoring

Sensors embedded in waste bins detect fill levels and hazardous conditions. Ultrasonic sensors measure garbage volume, gas sensors detect toxicity and hazards, RFID tags identify bin location and type, while Time-of-Flight (ToF) sensors provide precise volume measurements using light reflection. These measurements are communicated promptly to central monitoring systems, allowing timely collection and preventing overflows.[4][6]

5.3. Cloud and Edge Computing Architectures for Data Aggregation and Analytics

Collected sensor data is transmitted to cloud platforms where it is stored, processed, and analyzed. Edge computing devices near the sensors filter and preprocess data to enhance responsiveness and reduce transmission load.[9] Advanced analytics such as predictive models (e.g., ARIMA) forecast fill levels, while AI models assist in classification and decision-making. This architecture supports scalable, real-time management of waste collection in urban settings.[6]

5.4. Incentive-Based Models and Public Engagement

To improve citizen participation, some systems integrate incentive mechanisms rewarding residents for proper waste disposal, using IoT-enabled smart bins that track user contributions. [7] Such models encourage sorting and recycling behaviors, reduce littering, and support circular economic principles by transforming waste into resources. These approaches also help raise public awareness and foster sustainable urban environments.[11]

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6. Optimization techniques for waste collection and routing

6.1. Multi-Criteria Decision-Making (TOPSIS) for Route Choice Based on Toxicity, Volume, and Timing

The TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) algorithm is used to optimize routes of waste collection by considering multiple criteria at once, such as toxicity of the waste, bin volume, time elapsed since previous collection, and distance between bins. This multi-criteria method ensures that routes focus on bins with urgent needs first and reduce travel distance and increase efficiency of operations. TOPSIS-based routing results in a balanced route with attention to key waste collection and reduction of travel costs, as indicated by simulations.[1]

6.2. Heuristic and Metaheuristic Algorithms (Bat Algorithm, Genetic Algorithms) for Dynamic Routing

Metaheuristic techniques such as the Bat Algorithm and Genetic Algorithms are used to tackle complex vehicle routing problems in real time. The Improved Bat Optimization method dynamically adjusts routes for medical waste pickup according to fill levels and urgency, reducing travel distance and fuel usage. These heuristic methods efficiently handle NP-hard routing situations and support real-time IoT sensor data, enabling flexible and efficient route planning.[2]

6.3. Knapsack-Based Vehicle Loading Optimization with Priority on Toxic Waste

The knapsack optimization method is used to optimally load waste collection trucks by choosing bins that maximize the collection of high-priority toxic waste subject to truck capacity limitations. The technique maximizes hazardous or toxic waste handling with the consequence of up to 47% increase in collecting critical waste over standard approaches and decreasing the number of trips. The addition of IoT sensor feedback on toxicity and fill levels enables this efficient loading policy.[5]

6.4. Dynamic vs. Fixed Routing Strategies and Time Window Introduction

Dynamic routing algorithms change routes in real-time according to sensor information like bin fill levels and toxicity readings, enabling trucks to bypass low-priority or empty bins and receive priority bins quickly. This is in contrast to fixed routing techniques that stick to pre-planned schedules independent of actual bin conditions. Time windows incorporating them guarantee collection within permissible periods, making the best use of labor and vehicles with a target to ensure service levels, as in urban container cluster collections.[3]

6.5. Prize-Collecting and Integrated Route Planning Policies for Operational Efficiency

An integrated selection and routing (ISR) policy approximates urgency or "prize" values for waste bin groups to optimize service efficiency. It models the routing issue as a prize-collecting vehicle routing problem with time windows and driver breaks, seeking to minimize distance traveled while serving priority-filled bins. Metaheuristic techniques

effectively solve the problem, generating feasible cost reductions (up to 40% route length reduction) and lower fleet sizes without compromising service levels in realistic municipal applications.[12]

7. AI and machine learning in waste classification and management

7.1. Waste classification with the help of convolutional neural networks (CNN), YOLO, and GAN models

Artificial intelligence-based vision models such as CNN and YOLO allow real-time and automatic recognition and identification of waste types to support the sorting and recycling process.[9] Generative Adversarial Networks (GAN) support improving training data sets and enhancing recognition accuracy for sophisticated types of waste. These models integrated into systems provide high classification accuracy and operational efficiency, which is essential for intelligent waste management.[2]

7.2. Automation of e-waste sorting for reuse and material recovery, such as pyrolysis for biofuel and solar battery manufacturing

Automated sorters use IoT and AI to sort e-waste into plastics and metals effectively. Plastics are subjected to pyrolysis to yield biofuel and biochar, and the metals are recycled to become materials like solar batteries. That convergence of sophisticated processing supports circular economy values, achieving maximum resource extraction and minimizing the environmental footprint.[4]

7.3. Integration of computer vision and robotics for handling and sorting

Robotics with computer vision sort and pick different waste types automatically, enhancing worker safety and throughput. Image recognition by AI increases accuracy in sorting and accelerates processing at waste treatment plants. Robotics, combined with AI, solves the problems of sorting manually, providing scalable and clean waste management.[15]

7.4. Forecasting volume of waste with predictive analytics using ARIMA models and time series analysis

Time series predictive models like ARIMA leverage past sensor data to forecast patterns of waste accumulation and fill levels in bins. This predictability helps plan for proactive waste collection scheduling, minimize overflows, streamline routes, and decrease operational expenses.[8]

7.5. Difficulties with model stability, quality of data, and real-world implementations

Real-world deployment of AI solutions is challenged with challenges such as heterogeneous quality of data, environmental variations on sensor and camera behavior, small, labeled datasets, and privacy. Implementing assured robustness and scalability demands hybrid solutions of AI, sensor fusion, and fault-tolerant system design that are capable of handling real-world complexities.[9]

8. Environmental and economic impact assessments

8.1. Reductions in fuel consumption and greenhouse gas emissions via optimized waste collection routes

IoT-driven optimized routing provides waste collection trucks with the shortest and most efficient routes, reducing overall travel distance and idle time. It results in reduced fuel consumption and greenhouse gas emissions, while at the same time supporting climate change mitigation and reducing urban air pollution. Efficient route optimization also reduces wear and tear on vehicles, enabling more sustainable waste management practices.[10]

8.2. Enhancement of recycling rates and sustainable resource utilization through data-driven approaches

Information gathered using IoT sensors on waste containers facilitates accurate identification of trash contents and fullness. This makes it possible to efficiently collect recyclables and improve sorting mechanisms, both of which enhance recycling rates and resource recovery. By using analytics and intelligent scheduling, sustainable use of materials is promoted, landfill dependency lessened, and the circular economy model facilitated in municipal waste management.[7]

8.3. Cost-benefit analyses of IoT deployment, considering equipment costs and operational savings

While the initial installation cost of rolling out IoT infrastructure includes prices of sensors, communications technologies, and cloud platforms, operational costs are usually offset by savings. Savings are realized through

decreased labor requirements, improved vehicle routes, fewer trips, and longer equipment life. Research indicates that the cost savings achieved through IoT-facilitated processes enhance the medium- and long-term economic feasibility and sustainability of waste collection systems.[5]

8.4. Contributions to public health and urban sustainability, including during mass gatherings (e.g., Hajj)

Advanced waste management systems with real-time monitoring and dynamic response enhance the prevention of waste overflows and related health risks in high-density environments, such as Hajj religious events. These systems enhance sanitation, mitigate vector-borne illnesses, and help support wider goals of urban sustainability by being able to manage waste surges and provide sanitary conditions.[11]

8.5. Alignment with circular economy principles and sustainable urban development goals

IoT-powered waste management inherently supports circular economy principles by making efficient segregation, recovery, and recycling of wastes possible. The practices save resources, minimize environmental pollution, and promote sustainable material flows.[10] Consistency with international sustainable urban development objectives enables waste systems to not only add to environmental protection but also economic resilience and social well-being.[7]

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9. Challenges, security, and future directions in smart waste management

9.1. Data privacy, security risks, and IoT system vulnerabilities in waste management

• Smart waste systems are subject to multi-layered attacks: sensor spoofing and tampering, wireless link DoS (LoRaWAN, ZigBee, Wi-Fi, GSM), cloud/storage compromise, and actuator abuse; a comprehensive model suggests the use of strong encryption, authentication, physical device hardening, and privacy-preserving data management to address STRIDE-class dangers (spoofing, tampering, repudiation, information disclosure, DoS, privilege escalation).[12]

• City-scale prize-collecting routing delivers operational success but places in focus operational-side vulnerabilities (route data leakage, driver tracing, overflow/incident logs) that require access control, audit trails, and low data retention on municipal platforms.[1]

9.2. Scalability, interoperability, and technological integration challenges across heterogeneous IoT devices

- Systematic reviews identify fragmentation across sensing (ultrasonic, gas, vision, weight), networks (LPWAN/Wi-Fi/cellular), and platforms, with little standardization—posing obstacles to scaling deployments, cross-vendor integration, and maintainability; hybrid IoT+AI+cloud stacks require shared data models and APIs to minimize siloed rollouts.[9]
- Real-world city deployments combining selection-and-routing with time windows demonstrate that scaling to thousands of clusters necessitates durable data pipelines and modular designs in order not to suffer from performance and interoperability bottlenecks between sub-systems (sensors, planning engines, dispatch apps).[1]

9.3. Emerging technologies: blockchain, 5G, AI enhancement, and autonomous vehicle integration

- For clinical waste, enhanced bat-optimization with cloud/Android dispatch illustrates how AI metaheuristics can both optimize fuel/emissions and time windows; in the future, low-latency 5G uplinks can enable real-time bin states, video, and vehicle telemetry, while blockchain can provide auditability and traceability for regulated streams of waste and multi-actor chains-of-custody.[15]
- Integration with perception/AI-driven routing and autonomous/assistive collection (robotics, ADAS) can minimize overflow and staff risk in crowded events (e.g., mass gatherings) when incorporated with cloud operations and smart-bin gas/ultrasonic sensing.[2]

9.4. Long-term sustainability: maintenance, sensor reliability, and energy efficiency considerations

- Incentive-driven, circular economy systems with multi-tier IoT bins (RFID, load, level, moisture) need lifecycle planning: battery life, solar charging, rugged enclosures, and field calibration to ensure low OPEX; scheduled maintenance schedules and spares stocks are essential for consistent service levels.[7]
- Case studies (Johannesburg, Pakistan SWIMS) highlight robust bin hardware (steel enclosures), gateway availability, and energy-conscious edge designs to ensure data continuity and avoid fleet over-servicing, aligning maintenance with ROI objectives.[6]

9.5. Policy frameworks, community engagement, and incentives for wider adoption

- Hub-based trading of sorted materials and point-based user incentives in private–public models can promote behavioral change and enhance collection quality; policy assistance (standards, data protection, e-waste regulation, market mecha nisms) promotes adoption and circular impacts.[7]
- Citizen education, mobile applications, and open performance dashboards (fill levels, route KPIs) municipal programs enhance engagement and trust, while procurement frameworks can incorporate security, interoperability, and sustainability requirements into smart waste tenders.[7]

10. Conclusion

The synthesis of findings from all sixteen studies makes a strong argument for the revolutionary potential of IoT-powered, AI assisted, and optimization-driven waste management systems in urban, industrial, and event-related settings. Across geographies from Mumbai's Malad zone and Groningen to Makkah, Johannesburg, and pilot deployments in Asia and Europe the data consistently point to substantial operational efficiency gains, environmental benefits, and cost reductions when moving from static, schedule-based waste collection to real-time, sensor-informed, and algorithmically optimized logistics.

10.1. Operational Efficiency Gains

- The most direct benefit reported is the reduction in vehicle usage and total route distances. In Groningen, an Integrated Selection and Routing (ISR) policy reduced route lengths by over 40% and allowed a 25% reduction in fleet size without service degradation.
- The Trash Tech deployment in Mumbai's Malad zone achieved a 20% cut in trucks deployed, with substantial fuel savings. A TOPSIS-based multi-criteria routing algorithm in delivered a 14% cut in travel distance, taking into account toxicity, volume, and elapsed time since last emptying. Knapsack-based optimization enhanced toxic waste pickup prioritization by 47% over traditional rules.
- Such optimization is made possible by real-time bin fill-level sensing by ultrasonic or ToF sensors and networked communication (Wi-Fi, LoRaWAN, GSM), charging decision-support algorithms for dynamic daily or even intra-daily route planning.

10.2. Environmental Benefits

Reduces distance travel and vehicle trips provide proportionally reduced fuel consumption and greenhouse gas emissions:

- Posted a 10% reduction in fuel consumption and the corresponding reduction in CO_2 emission through optimization of the route powered by IoT + analytics. connected a 20% truck reduction to significant reductions in city-level carbon footprint.
- Sensor-based detection of hazardous gases (methane, ammonia, hydrogen sulphide) directly addressed fire risk and air quality concerns, with the added public health focus not typically found in traditional systems.
- Included dangerous gas emission warnings, enhancing worker protection and safeguarding the environment against high density events such as the Hajj.

10.3. Cost Benefits Savings achieved through fuel, labor, and postponed capital expense:

- Documented 12–15% savings on operational costs from route optimization alone and fewer empty-bin calls.
- Calculated payback in less than a year on IoT hardware from reduced contactless routing and toxicity triage. Systematic review reported 12–78% cost range savings based on deployment scale and integration depth.
- Notably, cost savings scale disproportionately as systems incorporate predictive analytics (e.g., ARIMA time-series fill prediction in) to actively prevent overflows and optimize fleet utilization.

10.4. Waste Diversion & Recycling Impact Some systems extended beyond collection efficiency to enhance recycling and resource recovery

- increased by 15% more recyclables collected by utilizing analytics to pick out and route to recycling-rich zones.
- Integrated materials classification (GAN/CNN) and pyrolysis for plastic-to-biofuel upgrading, along with metal recovery for use in solar battery production — an example of IoT as an enabler for circular economy cycles.

- 's SWIMS framework encouraged participation from households through a points and rewards scheme, driving up proper disposal rates.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Ali B, Javed MA, Alharbi AA, Alotaibi S, Alkhathami M. Internet of things-assisted vehicle route optimization for municipal solid waste collection. Appl Sci. 2023;14(1):287.

[2] Rakesh U, Ramya V, Murugan VS. Classification, collection, and notification of medical waste using IoT based smart dust bins. Ing Syst Inf. 2023;28(1).

[3] Bányai T, Tamás P, Illés B, Stankevičiūtė Ž, Bányai Á. Optimization of municipal waste collection routing: impact of Industry 4.0 technologies on environmental awareness and sustainability. Int J Environ Res Public Health. 2019;16(4):634.

[4] Farjana M, Fahad AB, Alam SE, Islam MM. An IoT- and cloud-based e-waste management system for resource reclamation with a data-driven decision-making process. IoT. 2023;4(3):202-20.

[5] Khan S, Ali B, Alharbi AA, Alotaibi S, Alkhathami M. Efficient IoT-assisted waste collection for urban smart cities. Sensors. 2024;24(10):3167.

[6] Komane BL, Mathonsi TE. Design of a smart waste management system for the city of Johannesburg. arXiv [Preprint]. 2023 [cited 2025 Sep 10]. Available from: https://arxiv.org/abs/2303.14436

[7] Irfana E, Chaudharya MM, Rasoola W. IoT-based smart waste management system (SWIMS). [Preprint]. n.d.

[8] Pires LM, Figueiredo J, Martins R, Martins J. IoT-enabled real-time monitoring of urban garbage levels using time-of-flight sensing technology. Sensors. 2025;25(7):2152.

[9] Alaoui MLT, Belhiah M, Ziti S. IoT-enabled waste management in smart cities: a systematic literature review. [Preprint]. n.d.

[10] Kuzhin MF, Joshi A, Mittal V, Khatkar M, Guven U. Optimizing waste management through IoT and analytics: a case study using the waste management optimization test. BIO Web Conf. 2024;86:01090.

[11] Qurashi RSA, Almnjomi MM, Alghamdi TL, Almalki AH, Alharthi SS, Alharthi AS, Thafar MA. Smart waste management system for Makkah city using artificial intelligence and Internet of Things. arXiv [Preprint]. 2025 [cited 2025 Sep 10]. Available from: https://arxiv.org/abs/2505.19040

[12] Wouda NA, Aerts-Veenstra M, van Foreest N. An integrated selection and routing policy for urban waste collection. arXiv [Preprint]. 2024 [cited 2025 Sep 10]. Available from: https://arxiv.org/abs/2409.13386

[13] Sivapriya K, Mohanapriya N, Sneha P, Subhashini S, Haripriya S, Siamala SRJ. Waste management by smart bin and app system using IoT. Int J Eng Res Technol. 2024;13(10).

[14] Mehta H, Deriya V, Sankhe D, Kanani P, Pandya G, Shelke V. Smart bins, smarter cities: IoT-driven waste collection with real-time sensing and methane mapping. Math Model Eng Probl. 2025;12(6).

[15] R U, V R, Murugan VS. Route optimization to manage the medical waste in real-time. Int J Intell Syst Appl Eng. 2023;12(2s):671-7. Available from: https://ijisae.org/index.php/IJISAE/article/view/3689

[16] Alshaikh R, Abdelfatah A. Optimization techniques in municipal solid waste management: a systematic review. Sustainability. 2024;16(15):6585.