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Holistic Trash Collection System Integrating Human Collaboration with Technology

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Abstract: Effective waste management is of paramount importance as it contributes significantly to environmental preservation, mitigates health hazards, and aids in the preservation of precious resources. Conversely, mishandling waste not only presents severe environmental risks but can also disrupt the balance of ecosystems and pose threats to biodiversity. The emission of carbon dioxide, methane, and greenhouse gases (GHGs) can constitute a significant factor in the progression of global warming and climate change, consequently giving rise to atmospheric pollution. This pollution, in turn, has the potential to exacerbate respiratory ailments, elevate the likelihood of cardiovascular disorders, and negatively impact overall public health. Hence, efficient management of trash is extremely crucial in any society. It requires integrating technology and innovative solutions, which can help eradicate this global issue. The internet of things (IoT) is a revolutionary communication paradigm with significant contributions to remote monitoring and control. IoT-based trash management aids remote garbage level monitoring but entails drawbacks like high installation and maintenance costs, increased electronic waste production (53 million metric tons in 2013), and substantial energy consumption for always-vigilant IoT devices. Our research endeavors to formulate a comprehensive model for an efficient and cost-effective waste collection system. It emphasizes the need for global commitment by policymakers, stakeholders, and civil society, working together to achieve a common goal. In order to mitigate the depletion of manpower, fuel resources, and time, our proposed method leverages quick response (QR) codes to enable the remote monitoring of waste bin capacity across diverse city locations. We propose to minimize the deployment of IoT devices, utilizing them only when absolutely necessary and thereby allocating their use exclusively to central garbage collection facilities. Our solution places the onus of monitoring garbage levels at the community level firmly on the shoulders of civilians, demonstrating that a critical aspect of any technology is its ability to interact and collaborate with humans. Within our framework, citizens will employ our proposed mobile application to scan QR codes affixed to waste bins, select the relevant garbage level, and transmit this data to the waste collection teams' database. Subsequently, these teams will plan for optimized garbage collection procedures, considering parameters such as garbage volume and the most efficient collection routes aimed at minimizing both time and fuel consumption.

Keywords: trash collection system; internet of things; remote garbage level monitoring; QR code-based waste collection; integrating technology in the waste collection; human collaboration; waste collection teams; optimized garbage collection procedures

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1. Introduction

In the present era, waste production has significantly increased, leading to overflowing garbage bins throughout the city. This creates unhygienic conditions, affecting the aesthetics of the surroundings and posing risks of disease transmission [1]. Wastes accumulated over long periods of time in the dump yards can be even more devastating. It can cause the contamination of land and water bodies. Harmful chemicals released from these wastes can seep into the land and adversely affect the groundwater [2]. Effective waste management can readily mitigate land and water pollution while also curbing the proliferation of diseases [3]. In urban areas, daily waste collection is a labor-intensive task with significant implications for the environment and society. This necessitates the adept management of waste truck routes, coupled with a diligent assessment of environmental, economic, and social factors [4].

A comprehensive trash collection system holds significant relevance and value in society, particularly with the growing urban populations and the accompanying rise in daily trash quantities [5,6]. This presents a significant dilemma for many nations that lack the financial means to engage sufficient manpower to tackle this problem. Hence, to address this issue, a smart and intelligent system is needed to minimize the need for manual labor while maximizing efficiency and delivering superior results. In order to develop such a system, data plays a pivotal role. Firstly, it encompasses information about the types of locations requiring garbage collection, such as residential areas, industrial sites, or marketplaces. Secondly, it includes data on the quantity of waste generated by these locations, enabling the system to target areas with greater precision. Lastly, it considers whether the waste is recyclable or non-recyclable [7].

Our innovative holistic trash collection system (HTCS) represents a paradigm shift in waste management. It amalgamates human participation with cutting-edge technology to establish a highly efficient and productive framework for trash collection, sorting, and disposal. The system leverages the versatility of quick response (QR) codes for labeling garbage bins. QR codes are two-dimensional barcodes that can be easily scanned by smartphones. They possess the capacity to store up to 7089 alphanumeric characters, making them ideal for storing various data types, such as website URLs, contact details, geographical information, and product specifications [8]. Through the integration of QR code-equipped bins and a user-friendly mobile app involving the community, our proposed system strives to enhance waste reduction, elevate recycling rates, and enhance the cleanliness and sustainability of communities. Our approach markedly diminishes the extensive dependency on IoT sensors, a prevalent practice in some of the previous research on smart bins, where these sensors were the exclusive means of collecting data related to waste levels [9]. We are not advocating for the complete removal of IoT sensors. Instead, we propose to utilize them primarily in the central garbage collection facilities, given that the number of central collection units is significantly lower compared to the extensively deployed QR-enabled garbage bins installed in the neighborhoods, ensuring a more resource-efficient approach.

The primary aim of the proposed model is to establish a more organized waste management system that minimizes the environmental impact of waste disposal and promotes responsible waste handling. Through the utilization of advanced technology for waste monitoring and tracking, the system strives to decrease landfill waste, boost recycling rates, and enhance the overall cleanliness and sustainability of communities.

Our innovative approach employs technology, including QR codes and IoT technology, alongside community participation to streamline and enhance the waste management process. In our research, we intend to make the following contributions:

- Propose an efficient waste collection system utilizing QR codes affixed to trash bins for real-time data on bin contents when scanned.
- Optimize waste management team efficiency by streamlining collection routes, resulting in time and fuel savings while ensuring that waste collection trucks do not attend to bins that are not completely filled.
- Enhance recycling through our framework by employing QR codes to identify food waste and recyclable/non-recyclable materials and then guide these materials to the designated processing facilities. This segregation guarantees that recyclable materials remain unadulterated, simplifying the recycling process, while food waste is directed for proper processing and reuse.

- Empower waste management teams with the capability to monitor the volume and composition of waste gathered from diverse locations, enhancing the transparency of the entire system. These data can serve to pinpoint areas for enhancing waste reduction and recycling endeavors and quantifying the effectiveness of waste reduction initiatives.
- Engage communities in waste management efforts by employing waste bins equipped with QR codes. We enhance community involvement by implementing rewards programs that incentivize recycling when participants provide information about recyclable and non-recyclable items.
- Lower the waste management cost with our proposed system by minimizing the utilization of IoT sensors for each bin, optimizing collection routes, and diminishing the requirement for manual waste sorting.
- Boost environmental sustainability by limiting IoT sensor use, significantly reducing e-waste and energy consumption. This lessens toxic landfill waste, lowers resource-intensive electronics production, cuts greenhouse gas emissions, and promotes a more sustainable future.

The rest of this paper is structured as follows: Section 2 reviews the literature on the role of QR technology, IoT devices, people, and data in waste management. Section 3 provides an overview of the proposed system. Section 4 introduces our framework for trash collection and discusses several factors for successfully implementing the proposed framework. Finally, Section 5 concludes the paper and discusses future work.

2. Literature Survey

This section discusses the previously published literature on waste collection and management. The previous efforts mostly discuss IoT-assisted waste collection, IoT-enabled smart bins [10,11], or the specific issues related to the waste-management cycle. Sheng et al. [12] proposed an IoT-based system utilizing deep learning models and LoRa (long-range) communication technology. Rogoff et al. [13] discussed automated waste collection systems that utilize underground vacuum pipes and automated collection vehicles for efficient and hygienic waste disposal. Glouche et al. [14,15] explored smart waste management using self-describing complex objects, where waste items are equipped with RFID tags and other sensors to enable automated identification, sorting, and disposal processes. When compared to previous efforts, our work proposes an end-to-end holistic trash collection system with all the implementation details, aspects of human collaboration with technology, and data analysis algorithms for waste collection trends.

Aparna et al. [3] discussed an IoT-assisted waste collection and management system using QR codes. This is a thoughtful and innovative study that explores the potential of using internet of things (IoT) technology and QR codes to improve waste collection and management. The authors propose a system in which waste bins are equipped with IoT devices and QR codes, allowing for the real-time monitoring of waste levels and efficient collection. The study provides a detailed description of the system's architecture and demonstrates its potential through simulation results. Using QR codes for waste classification also adds an interesting feature to the system. Overall, this study presents a promising solution for addressing the challenges of waste management, particularly in urban areas. The system's ability to provide real-time data on waste levels and efficient collection can greatly improve the effectiveness and efficiency of waste management. Additionally, integrating QR codes for waste classification enhances the system's capabilities and makes it more user-friendly. This study is a valuable resource for researchers and practitioners working in the field of waste management and IoT.

Taelman et al. [7] presented a literature review of waste management practices in European cities by analyzing current practices, identifying their strengths and weaknesses, and considering economic, environmental, and social sustainability factors. The authors also provide examples of best practices and recommendations for city planners and policymakers to improve waste management practices in their cities. Unlike our work, this paper does not provide the technical details of the proposed waste management system.

Pelonero et al. [16] proposed a data-centric approach to design an IoT-based garbage collection system that aims to incentivize citizens to recycle waste and improve their waste disposal habits. The proposed system utilizes IoT sensors and a mobile app to collect data on garbage collection and recycling rates. The collected data are then used to incentivize citizens to recycle more and reduce their waste generation. The system allows citizens to receive rewards in the form of discounts, vouchers, or loyalty points for their recycling efforts, and an incentivization mechanism can encourage citizens to recycle more and contribute to the overall sustainability of the city. The proposed system also includes features such as the real-time monitoring of waste levels, dynamic route planning, and the predictive maintenance of garbage collection trucks for efficient and cost-effective waste management. The paper highlights the importance of citizen participation and engagement in waste management and proposes a data-driven solution to improve waste management practices that has the potential to transform the traditional garbage collection service into a more data-centric and citizen-focused one.

Lee et al. [17] propose the creation of an integrated system for managing radioactive waste, incorporating a QR code-based approach with real-time monitoring capabilities. This innovative system offers a streamlined and systematic method for handling small-packaged radioactive waste, covering the entire process from generation to treatment. By doing so, it aims to reduce the volume of radioactive waste and subsequently lower disposal costs.The QR code system can store essential information, including the waste generation year, generator details, container specifications, total radioactivity levels, visual representations of contents, and physical characteristics. This system can seamlessly connect with on-site operations through the radioactive waste cycle history management system, significantly enhancing operational efficiency, minimizing the risk of human error, and bolstering reliability in radioactive waste management. Additionally, this safety-focused radioactive waste management system harnesses cutting-edge ICT technologies to enhance monitoring, tracking, and decision-making processes [18].

Wang et al. [19] proposed a municipal waste management system that utilizes deep learning-based classification and cloud computing to reduce the cost of waste classification, monitoring, and collection. The system subdivides recyclable waste into six categories and uses deep-learning convolution neural networks to achieve high accuracy in garbage classification. The envisioned system incorporates IoT devices equipped with sensors to monitor both the total waste generation and the operational status of waste containers. This data is harnessed by the waste management center for real-time decision-making, encompassing adjustments to equipment deployment, maintenance schedules, waste collection, and optimizing vehicle routing plans. MobileNetV3 has been singled out as the optimal and precise classifier for this particular system.

Vishnu et al. [20] examined various technological strategies for solid waste management within smart city contexts. The literature is classified into three key categories: RFID, WSN, and IoT-based methodologies, with IoT-based systems emerging as the most effective among them. In the realm of automating solid waste management in urban environments, LoRaWAN stands out as the preferred communication protocol. The research also pinpoints several areas where further investigation is warranted, including the design of ultra-low-power nodes, the optimization of energy harvesting techniques for self-sustaining nodes, bin-based waste segregation, and the utilization of hybrid network architectures.

The paper [21] proposes a smart waste management system called the internet of garbage bins (IoGBs), which uses IoT technology to monitor waste bin fill levels and optimize waste collection schedules, reducing operational costs and improving the sustainability of waste management.

Smart cities are being introduced globally, with examples in cities like Mangaluru [22,23], Seoul [24], Greater Noida [25], and Kerala [26] where innovative QR code-based systems have been successfully implemented for household waste collection. In this system, primary waste collection vehicles, responsible for collecting refuse from door to door, employ QR code scanning technology placed at household entrances during the collection process. Subsequently, the gathered refuse is transferred to secondary collection vehicles, which then transport it to designated disposal sites. Furthermore, beyond waste management, the QR codes installed at residences can serve as versatile tools, facilitating various public services, including the payment of utility bills, property taxes, and telephone bills, among others.

Panainte-Lehadus et al. [27] have presented a case study conducted in a specific locality to evaluate the efficiency of different household waste collection methods and statistics about the community involved in the waste collection. The authors used a combination of data analysis, surveys, and interviews to collect and analyze data on waste generation, collection, and disposal. The results showed that the current waste collection system in the locality was inefficient, with high contamination levels and illegal dumping. The data analysis also presented that community characteristics such as education level, locality, age, and gender have a substantial effect on the household waste collection mechanism. The authors recommend several improvements, such as the implementation of separate collection for organic waste, the use of recycling bins, and education and awareness campaigns to promote sustainable waste management practices. The study provides valuable insights into the challenges and opportunities of household waste collection, highlighting the importance of effective waste management strategies in promoting sustainable development. The analysis of this study holds considerable significance, as it reveals that community involvement is very important for an effective household trash collection system.

Some trash collection systems have high development and maintenance costs. The authors in [28] present a new approach to trash collection that involves an automated system that can move around autonomously, detect trash, and collect it. The system consists of a mobile base, a manipulator arm, and a set of sensors, including a camera and a lidar. The paper describes the design and construction of the system and evaluates its performance in simulated and real-world environments. The results demonstrate the feasibility and effectiveness of the proposed approach, which can potentially improve the efficiency and sustainability of trash collection.

Vishnu et al. [29] proposed a waste management system using IoT devices to track waste levels in public and residential bins. The proposed system measures the level of unfilled bins using an ultrasonic sensor, which calculates the ground distance from the bin's surface to get the capacity. It is also used to send location, store data for statistics measurements, and send all of the processed data to the central monitoring station, which give stats about the level of bins. Further, the decision on waste collection will be made based on the bin level.

Table 1 provides a concise overview of the various studies in the field of trash management, shedding light on the diversity of approaches used to tackle the different tasks associated with trash collection systems. QR codes have been used in different contexts in previous studies. For example, QR codes have been used for tracking domestic waste segregation [30] or wastebank sorting [31].

Prior studies have primarily focused on the integration of technology and IoT in various aspects of waste management, including garbage collection, waste segregation, and recycling. In contrast, our holistic approach not only leverages technology but also fosters community participation, resulting in elevated recycling rates, cost reductions, and the implementation of more sustainable waste management practices. Furthermore, the utilization of QR codes enhances community engagement in waste management and provides real-time data for informed decision-making.

Table 1. A brief tabular outline of the related works with the proposed trash management tasks.

Used Techniques	Trash Management Tasks					
	QR Code	RFID	IoT Sensors	Data Collection	Route Planing	Bin Overflow Control
Zhang et al. [32]			✓	✓	✓	✓
Hannan et al. [33]		✓	✓	✓	✓	✓
Anjum et al. [34]		✓	✓		✓	✓
Anjum et al. [35]			✓	✓	✓	✓
Nguyen et al. [36]			✓	✓	✓	✓
Metagar et al. [37]		✓	✓			✓
Pardini et al. [38]			✓			✓
Jagannathan et al. [30]	✓		✓			
Aleyadeh and Taha [39]			✓	✓	✓	✓
Wandee et al. [40]	✓		✓	✓		
Sosunova and Porras [41]		✓	✓	✓	✓	✓
Widaningsih and Suheri [31]	✓			✓		

3. Proposed QR-Based Systems: An Overview

Our system employs a fusion of bins featuring QR codes, central sensor technology, and a mobile app for community waste tracking and monitoring. Users will categorize the type of waste within their homes using the mobile app. Bins are equipped with a QR code that must be scanned by the user to specify the amount of waste they are disposing of. The data are then transmitted to a central database. The mobile app allows users to track their waste and recycling habits, set reminders for trash pick-up days, and access information about local waste management services. The app also includes a rewards program that incentivizes users to recycle and reduce their waste. The bins at the central garbage collection facility are equipped with sensors that detect the volume of waste being dumped and transmit the data to a central database via the IoT. The sensors in these smart bins are also used to track their location and facilitate maintenance and repair by the administration.

By combining technology and community engagement, our approach presents a holistic waste management solution. It harnesses machine learning and artificial intelligence algorithms to analyze and predict waste generation patterns, enabling the optimization of collection schedules and routes. This optimization yields benefits for both the waste collection agency and the community, enhancing efficiency and lowering costs. Furthermore, our system promotes community-driven waste management initiatives, including the establishment of composting and recycling facilities, as well as the implementation of recycling and composting incentives to encourage resident involvement. In summary, our proposed approach integrates technology and community participation to develop a more sustainable and cost-effective waste management system.

Table 2 analyzes various aspects related to trash management using a QR code-based system and an IoT device-based system, outlining the pros and cons associated with each aspect. The table provides a comparison of monitoring methods, cost considerations, environmental impacts, human participation, and approaches for monitoring garbage levels. By assessing these diverse aspects, our proposed approach makes well-informed decisions regarding the most appropriate method, taking into account factors like cost, environmental impact, human involvement, and monitoring techniques.

Table 2. A comparison of the pros and cons of a QR code-based system vs. an IoT device-based system.

Aspect	Quick Response (QR) Code-Based System	Internet of Things (IoT) Device-Based System
Cost	Economical, minimal upfront investment	Potentially high installation and maintenance costs for IoT devices
Environmental Impact	Low electronic waste production	Contribution to electronic waste through IoT Devices
Human Involvement	Citizen participation in scanning QR codes	Reliance on IoT devices for monitoring
Garbage Level	QR codes scanned by citizens for garbage level reporting	IoT devices installed in garbage bins for remote monitoring

In the following section, we discuss each entity of the proposed system in detail.

4. Holistic Trash Collection System Architecture

A sustainable society must handle its waste effectively. Given the rising daily waste volume, developing a more effective and sustainable garbage collection and disposal strategy is imperative. This idea offers a comprehensive waste disposal system that uses QR code technology. Figure 1 shows the overall flow of information in our proposed holistic trash collection system.

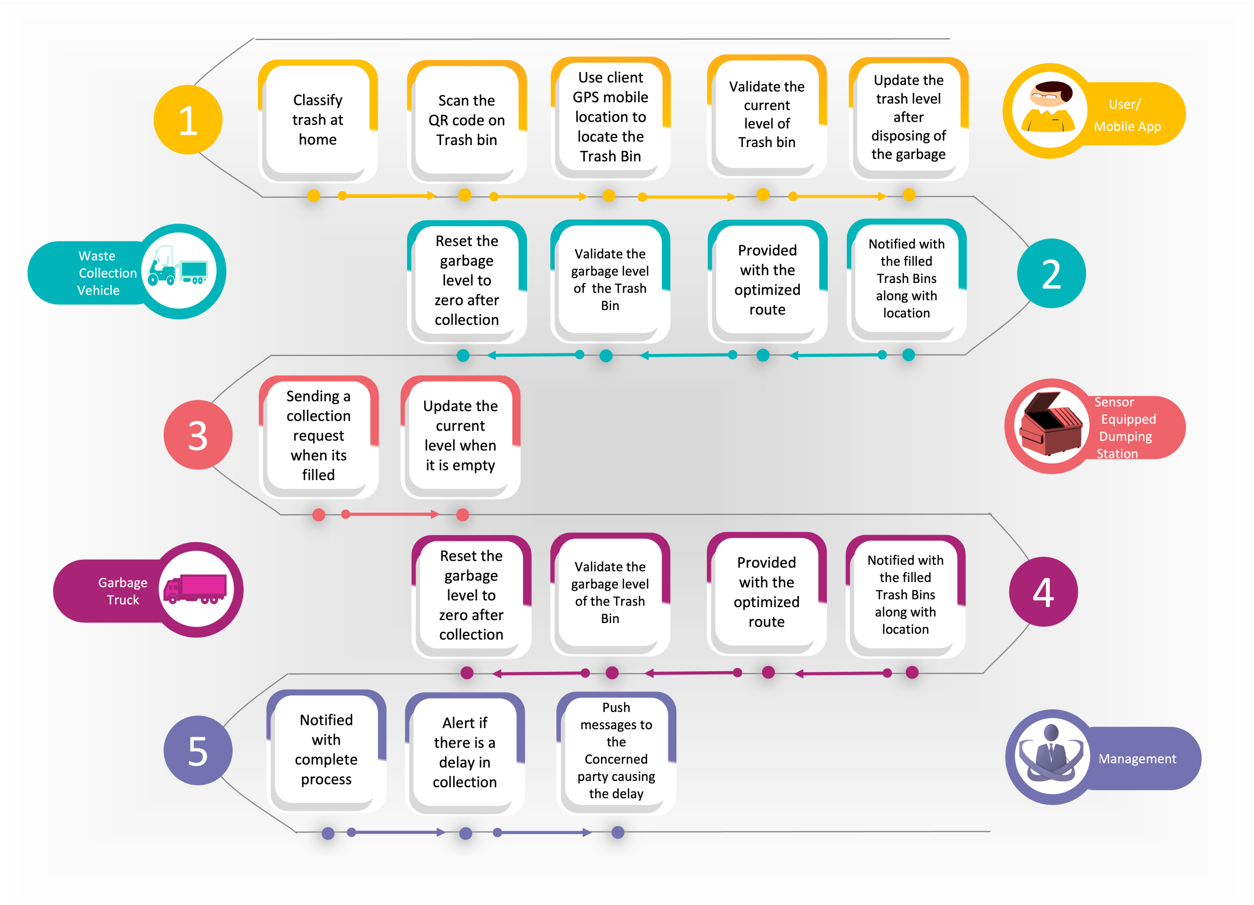

Figure 1. Flowchart of proposed holistic trash collection system.

4.1. System Components

The system will comprise six main entities, i.e., (1) Mobile App, (2) QR-based Trash Bin, (3) Sensors at Central Location, (4) Cloud-Based Analytics, (5) Waste Collection Teams, and (6) Rewards. Figure 2 illustrates the system components and the role of each system entity in terms of the information stored and processed within them.

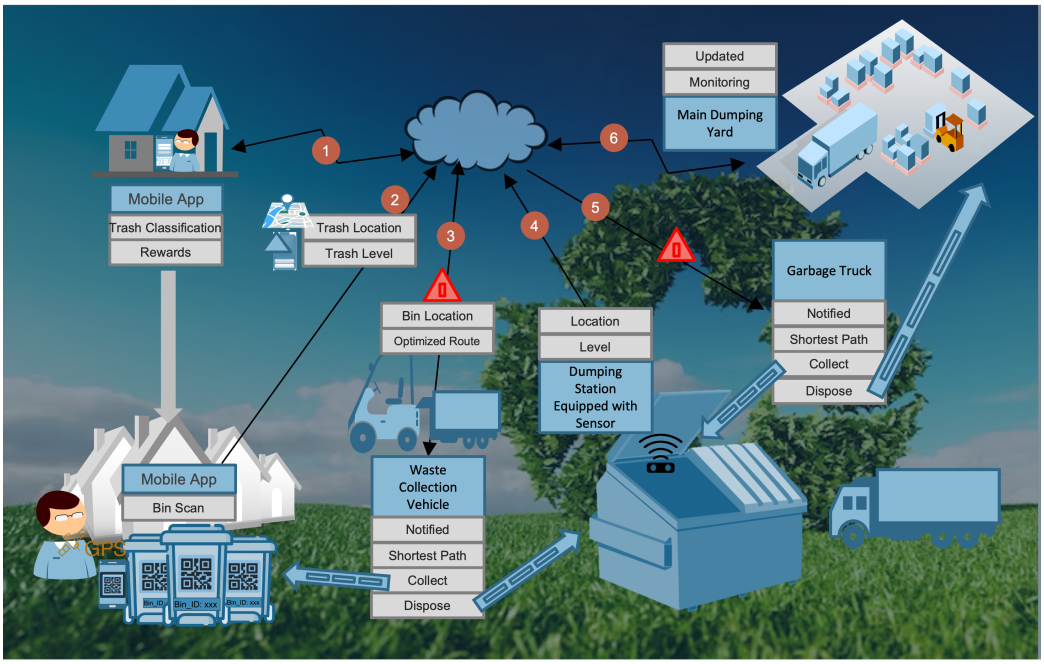

Figure 2. System Components.

We will explain these entities as follows:

4.1.1. Mobile App

The mobile application will facilitate waste disposal by scanning the QR code on the trash bin. Figure 3 shows the comprehensive flow of the mobile app. The application will present the user with a menu that includes options for trash classification, bin scanning, checking awarded rewards, and contacting the authorities in case of any system-related issues, as depicted in Figure 3A. Within the trash classification screen, users have the choice to categorize the waste they intend to dispose of according to its type, including options such as paper, plastic, glass, or food waste, as exemplified in Figure 3B. Once the user has finished classifying the garbage at home, the next step is to scan the QR code affixed to the bin located outside their home for waste disposal, as depicted in Figure 3C. Subsequently, the user is prompted to select the current bin level, allowing them to actively engage in the community's collective efforts for effective waste management facilitated by our proposed holistic trash collection system (HTCS), as illustrated in Figure 3D. The mobile application will serve as a user-friendly guide, aiding individuals in the process of waste classification within their homes and its subsequent placement into the bin. This ensures the software we develop caters to users across diverse age groups. The mobile app will encompass a wide array of functions, including educating users on waste classification with the assistance of a robust AI facility. This feature will encourage users to employ their smartphone cameras for identifying and classifying waste items within their homes. Additionally, consumers have the capability to report issues related to garbage bins, such as overflow or damage, using the "Contact Us" feature within the same application. In order to further aid users in the event that their nearest bin is full, the application will furnish real-time data regarding the fill levels of the nearest alternative bins. App users will receive notifications and messages pertaining to waste collection within their proximity, owing to the application's integration with the cloud-based analytics system. Furthermore, the app will offer information to users regarding the nearest landfill, recycling facility, or waste pickup location.

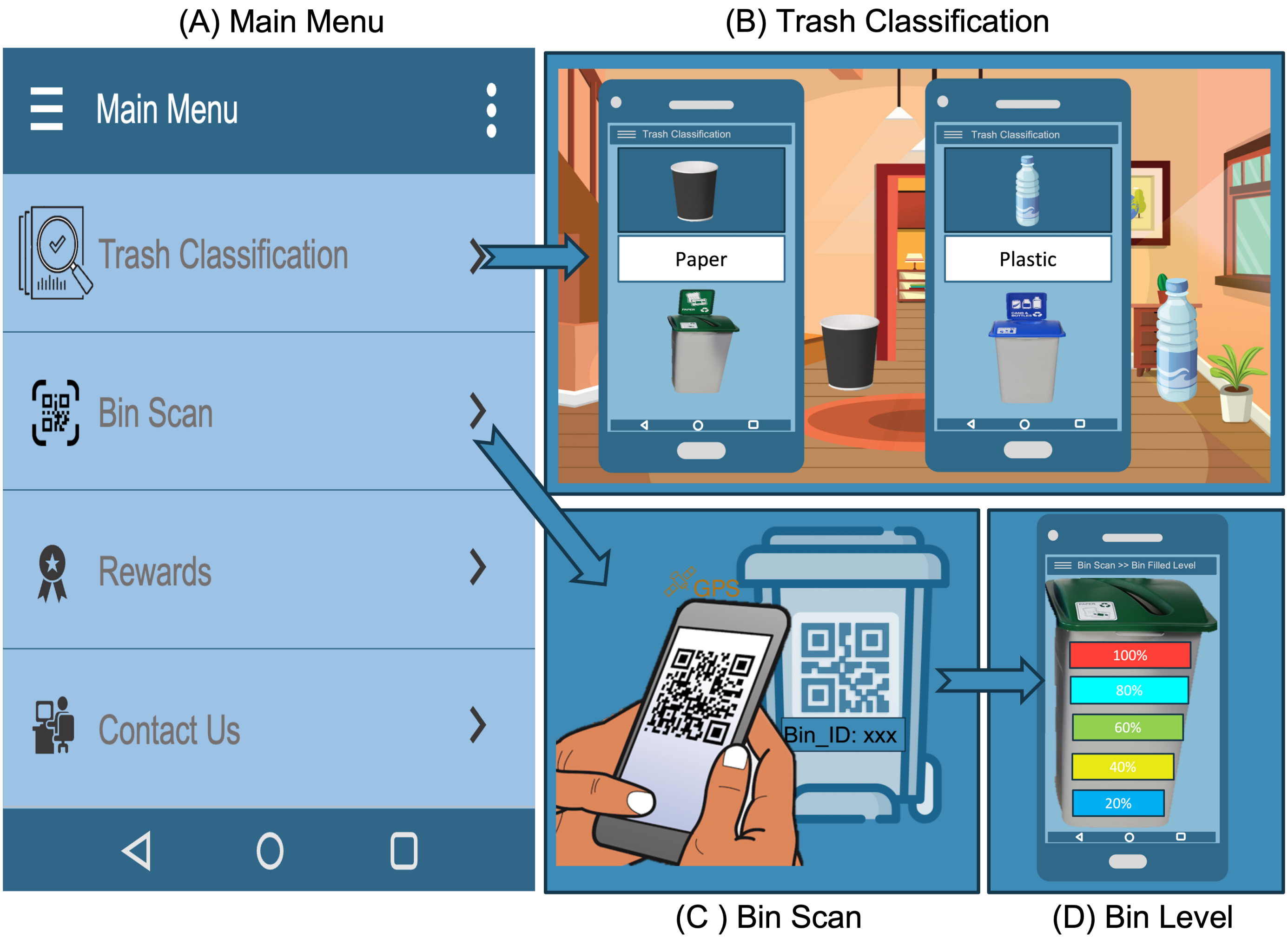

Figure 3. The flow of the Mobile App.

4.1.2. QR-Based Trash Bin

The QR-based trash bins will be crafted to be reliable, efficient, and simple to operate. The trash bin will include a QR code that can be read by a mobile device running our mobile app, as shown in Figure 4.

Figure 4. QR-based Trash Bin.

QR codes will serve as tools for monitoring trash bin usage and fill levels. When users scan the QR code using the mobile app, they can inspect the current trash level and verify the accuracy of the information provided by the previous user. Additionally, as a fail-safe measure in case the QR code is damaged, each bin comes equipped with a unique ID number already stored in the collection team's database. This ID number serves as an additional means of identification, enabling users to access and modify the bin's information, even if the QR code is unreadable or compromised. Users can adjust the recorded garbage fill level information if they find discrepancies with the previously saved data. Furthermore, the application allows users to update the garbage level after disposing of their waste.

Utilizing the QR code for monitoring trash bin fill levels can significantly enhance route management in several ways. For instance, it enables the provision of real-time updates on those bins in need of immediate attention, facilitating the optimization of collection routes and bolstering waste management efficiency. By directing collection trucks to locations where they are most needed, this approach reduces travel time and minimizes fuel consumption. Moreover, monitoring trash bin fill levels serves as a preventive measure against garbage overflow. When bins reach capacity, individuals tend to leave their waste around the bins, which adversely impacts the environment and contributes to littering. Therefore, this comprehensive and immediate trash collection system has the potential to enhance waste management efficiency, leading to a cleaner and more sustainable environment.

QR-Coded Bin Route Optimization Algorithm

For route optimization, Algorithm 1 takes a set of QR-coded bins and a set of routes as the input, outputting an optimized route based on the shortest distance and weight of each route. It first calculates the total distance and weight of each route and then sorts the routes in increasing order of distance. It sets the initial route to be the shortest route, and then iteratively adds bins to the route if the distance and weight constraints are met. Finally, it returns the optimized route.

Algorithm 1 QR-Coded Bin Route Optimization Algorithm

Input: A set of QR-coded bins B, a set of routes R
Output: An optimized route r^*
foreach *route* $r \in R$ **do**
    Calculate the total distance d_r of route r; Calculate the total weight w_r of route r;
end
Sort the routes in increasing order of d_r; Set the initial route $r^* = R_1$;
while *there exists a route* r *that has not been added to* r^* **do**
    foreach *bin* $b \in B$ **do**
        if *bin* b *is not in* r^* **then**
            Calculate the distance d_{new} from the end of r^* to b; Calculate the weight w_{new} of r^* plus b; **if** $d_{new} \leq$ *maximum route distance and* $w_{new} \leq$ *maximum route weight* **then**
                Add bin b to the end of r^*;
            end
        end
    end
end
return *Optimized route* r^*;

Unreadable QR Code Resolution Algorithm

In order to address issues related to the QR codes affixed to the bins, Algorithm 2 concentrates on rectifying the problems stemming from unreadable or unscannable QR codes. It systematically attempts to read each QR code, and if any issues are detected, it prompts the user for the bin's ID and any details of the encountered problems. The algorithm then assesses whether the problem is recurring or unique. If the problem is found to be recurring, the specific bin may be removed from the list. However, if the problem is identified as unique, it will be added to the list of problematic bins requiring manual inspection or retagging.

Algorithm 2 Unreadable QR Code Resolution Algorithm

```
Input: A set of QR-coded bins B
Output: A list of problematic QR codes P
foreach bin b ∈ B do
    Scan the QR code on bin b; if QR code is readable then
        Record bin ID and its associated data;
    else
        Add bin ID to the list of problematic QR codes P;
    end
end
foreach problematic QR code p ∈ P do
    if problematic QR code p is a repeat then
        Remove bin associated with p from set of bins B;
    end
    else if problematic QR code p is unique then
        Assign bin to a temporary location for manual inspection and re-tagging;
    end
end
```

In instances where a bin cannot be identified due to a damaged QR code, we have contingency measures in place. One approach involves the manual entry of the bin's unique ID number using the mobile app, which still retains information regarding the bin's location and fill level. Additionally, the bin's GPS co-ordinates can be accessed via the mobile app for identification in such scenarios. Hence, while the QR code plays a pivotal role in the proposed process, alternative methods exist for locating and monitoring the fill levels of the trash bins if the code is absent or unreadable. Irrespective of the method used for bin identification, it is imperative to establish a system for real-time data collection on bin fill levels.

4.1.3. Sensors at Central Garbage Collection Facility

Sensors will exclusively be installed within those trash bins located at the central garbage collection center, serving the sole purpose of gauging garbage levels. These sensors will leverage IoT technology to promptly transmit data to the cloud. They are expected to exhibit a prolonged operational lifespan, resilience to environmental factors, and minimal maintenance requisites. The sensors will employ either infrared or ultrasonic technologies for ascertaining the fill levels of the bins. Infrared sensors, in particular, harness infrared light—electromagnetic radiation with a wavelength exceeding that of visible light—to detect and quantify the bin's fill level. These sensors function by emitting infrared light into the trash bin and subsequently measuring the intensity of reflected light. As the trash accumulates, the reflected light diminishes, facilitating the sensor's determination of the fill level. Ultrasonic sensors, on the other hand, use high-frequency sound waves to detect and measure the fill level of the trash bin. These sensors work by emitting high-frequency sound waves into the trash bin and measuring the time it takes for the sound waves to bounce back. As the trash level rises, the time it takes for the sound waves to bounce back increases, allowing the sensor to determine the fill level.

These sensors will transmit observed data to the cloud-based analytics system to predict bin fill levels. Upon detecting that a container is either full or in need of attention, the sensors will promptly alert the garbage collection staff in real time, ensuring efficient communication without unnecessary repetition. Both infrared and ultrasonic sensors are widely employed in applications necessitating non-contact detection and measurement of physical attributes, including fill-level assessment in trash bins, distance measurement, and object detection, among others. The selection of sensor technology is contingent upon multiple factors, including cost considerations, performance prerequisites, and prevailing environmental conditions. Consequently, we have the flexibility to employ both sensor types in our application based on the specific requirements and conditions of the implementation.

4.1.4. Cloud-Based Analytics

The optimization of garbage collection routes will be facilitated by the cloud-based analytics system, which utilizes data sourced from users through the mobile app and the sensors situated at the central garbage collection facility, as shown in Figure 5. Furthermore, leveraging the historical data on trash levels for each bin maintained by the cloud-based systems, the system will employ machine learning techniques to predict future waste levels in these bins and offer optimized collection route recommendations. Additionally, the system will factor in variables such as traffic conditions, road closures, and potential obstructions that could affect the collection path. It will also encompass attributes like scalability, dependability, and security. Ensuring data security, particularly safeguarding the physical integrity of IoT sensors and employing robust encryption methods, is crucial [42,43]. The system will be hosted on a cloud platform, such as Microsoft Azure or Amazon Web Services, and will continually enhance the garbage collection and management process through the utilization of real-time data.

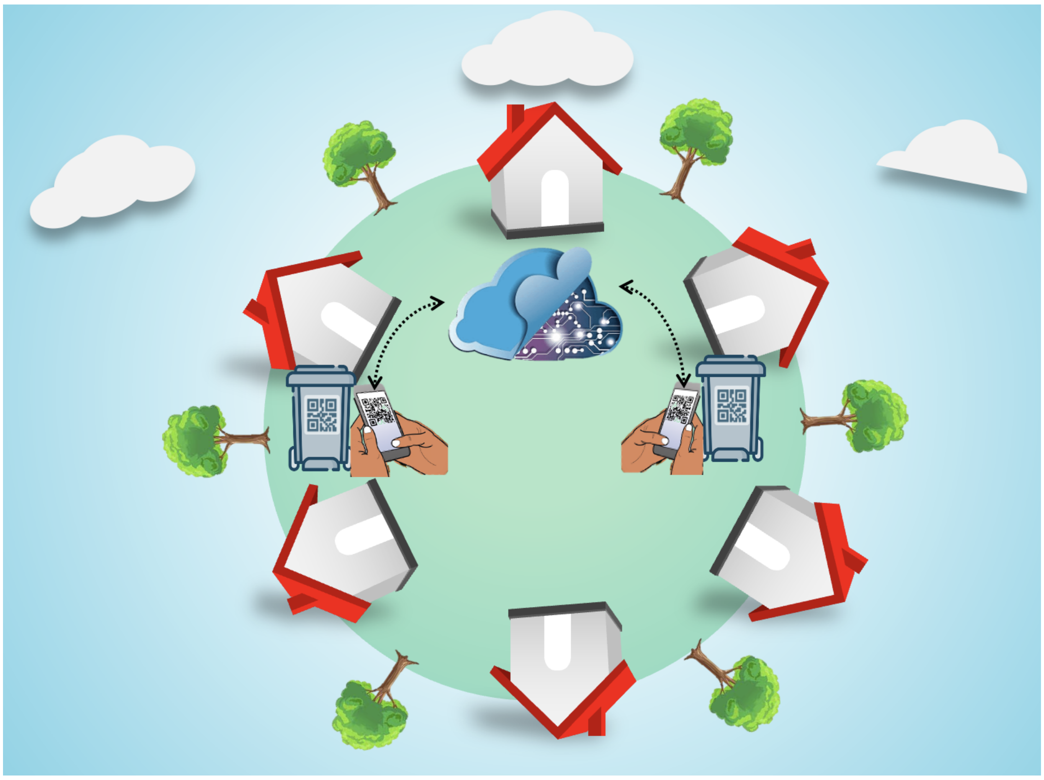

Figure 5. Cloud-based data analytics using app data.

Figure 6 illustrates the route optimization algorithm employed within our proposed system. When the waste bins reach their capacity threshold, users are required to scan the QR code, transmitting the fill level data to the cloud for subsequent bin emptying. In scenarios where multiple bins necessitate servicing concurrently, the cloud-based analytics system performs calculations to determine the most efficient route, considering factors such as minimizing distance and avoiding traffic congestion. Subsequently, this optimized route is relayed to the small garbage truck responsible for collecting waste from the bins and depositing it at the central waste disposal facility.

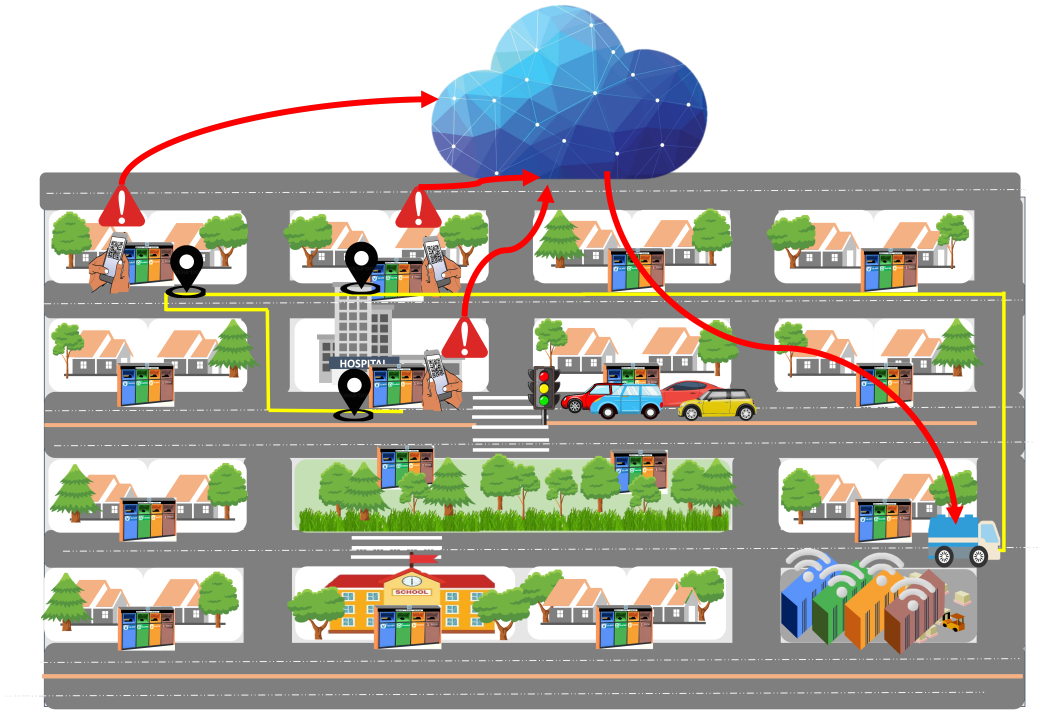

Figure 6. Illustration of route optimization using QR-based trash bin and cloud-based analytics.

4.1.5. Waste Collection Teams

The waste collection team will assume responsibility for gathering garbage from the designated trash bins. Equipped with mobile devices, each team member will have the holistic waste collection system's mobile app installed. This integration will empower mobile phones to receive instantaneous notifications generated by the cloud-based analytics system. They will receive real-time updates regarding the fill levels of the bins, allowing them to optimize their collection routes, thereby reducing both collection time and costs. In order to confirm the completion of a collection task, the teams will utilize their mobile devices to scan the QR codes affixed to the garbage bins. Furthermore, the team will reset the garbage level indicator to zero once the contents have been successfully collected from a specific bin. In order to proficiently operate the technology, the garbage collection team will undergo comprehensive training.

4.1.6. Rewards

Our system incorporates a reward mechanism designed to incentivize user engagement. In order to fund these incentives, we plan to establish strategic partnerships with various organizations, offering them access to recyclable materials sourced from the collected waste and through advertisements displayed within our app. These rewards could be distributed to users in the form of vouchers or additional calling minutes. Additionally, users may receive increased rewards based on the validation of their provided information by other users, thus encouraging active participation and the sharing of reliable data.

4.2. Benefits of Using QR-Based Waste Management Systems

A practical, environmentally responsible, and user-friendly garbage collection and disposal method is provided by the holistic trash collecting system that is being developed employing QR code technology. It may completely alter how we handle garbage, creating a cleaner, more sustainable world. Waste will be managed effectively and sustainably by adopting the recommended approach, which includes sensors, a mobile app, cloud-based analytics, and garbage collection teams. Moreover, the system will offer alarms and real-time monitoring, allowing prompt and practical garbage collection.

4.2.1. Efficient Waste Collection

By harnessing QR code-based trash bins that provide real-time updates on garbage fill levels, waste collection personnel can meticulously strategize their routes, minimizing the need to travel to bins that don't require emptying. This approach not only boosts operational efficiency but also yields substantial cost reductions while drastically reducing the carbon footprint generated by collection trucks.

4.2.2. Sustainability

Through at-home garbage classification and dedicated sections within the bins for various waste types, our system ensures that the appropriate waste is deposited in the correct container. This eliminates the burden of sorting recyclable and non-recyclable materials at recycling facilities, reducing contamination. Segregation of food waste in separate containers allows the proper sorting and collection of food waste for effective food waste handling. Furthermore, real-time monitoring of garbage fill levels reduces the necessity for frequent collections of partially filled bins, resulting in fuel savings and reduced emissions. These measures collectively contribute to the establishment of a more sustainable waste management system.

4.2.3. Recycling and Food Waste Treatment for a Circular Economy

In our proposed holistic waste management system, there is a diversity of waste streams, including recyclable and non-recyclable materials. Recyclable materials, such as plastics, paper, glass, and metals, present opportunities for resource recovery and sustainable practices, emphasizing the importance of efficient sorting and recycling processes. In parallel, non-recyclable materials, such as styrofoam, ceramics, and composite materials, necessitate proper disposal methods to mitigate environmental impacts. Recyclable waste should be separated at the source, collected, and sent to recycling facilities, while non-recyclable waste should be disposed of in a landfill or incinerated using environmentally responsible methods. HTCS allows recyclable waste to be separated at the source, collected, and sent to recycling facilities, while non-recyclable waste is disposed of in a landfill or incinerated using environmentally responsible methods, considering the importance of a circular economy [44].

Food waste is characterized by its unique composition, including biodegradable materials, chemicals, and organic matter, making it a critical component of the overall waste stream. The impact of food waste on the environment, greenhouse gas emissions, and resource depletion is undeniable [45]. Our proposed HTCS enables more sustainable disposal methods and reduces contamination in landfills by separating food waste from other types of waste at the source (e.g., households and businesses) using dedicated food waste containers within bins for at-home garbage classification.

Once food waste has been collected by a garbage truck, our system allows several ways to deal with it, depending on the local waste management practices and infrastructure.

Landfill Disposal: In many areas, food waste is still sent to landfills along with other trash. However, this is often considered the least sustainable option as it contributes to methane gas emissions and takes up valuable landfill space [46].

Waste-to-Energy (WTE) Facilities: Some communities have waste-to-energy facilities that burn food waste and other organic materials to generate electricity or heat. This can help reduce the environmental impact of food waste disposal while producing energy.

Composting: Food waste can be composted to create nutrient-rich soil amendments. Depending on the scale, this can be done at home in small compost bins or through larger municipal or commercial composting facilities. The resulting compost can be used in agriculture and landscaping [47].

Anaerobic Digestion: Anaerobic digestion is a biological process that breaks down organic waste, including food waste, in the absence of oxygen. It produces biogas, which can be used for energy production, and digestate, a nutrient-rich material that can be used as a soil conditioner.

Industrial Processing: Some food waste, especially from commercial or industrial sources, may undergo specialized processing to extract valuable components or convert them into products like animal feed, biofuels, or chemicals.

Animal Feed: In some cases, food waste can be processed and used as animal feed, provided it meets safety and regulatory requirements. This approach helps reduce waste while providing a source of nutrition for animals [48].

Food Waste Reduction: As a long-term strategy, reducing food waste at the source is the most effective way to minimize the need for food waste disposal. Encourage food producers, businesses, and consumers to adopt practices that reduce food waste generation.

Bioconversion: Emerging technologies, such as black soldier fly larvae or other insects, can be used to convert food waste into protein-rich insect biomass, which can be used as animal feed or for other purposes [49].

The specific method chosen for dealing with collected food waste will depend on local regulations, available infrastructure, environmental considerations, and economic factors. Many communities are shifting toward more sustainable options like composting and anaerobic digestion to divert food waste from landfills and reduce its environmental impact [50].

4.2.4. Cost-Effective

Cost efficiency will be significantly improved through real-time monitoring of fill levels and optimized collection routes, coupled with a reduction in the number of IoT sensors. This sensor reduction will lead to reduced installation and maintenance expenses for the proposed system, ultimately enhancing the financial viability of waste management for municipalities and waste management entities.

4.2.5. Scalable

The cloud-based analytics system is designed to be scalable, providing the flexibility to expand the system's coverage as necessary. Furthermore, it exhibits adaptability to accommodate changes in population density and variations in trash generation rates and types. This adaptability allows for seamless adjustments to garbage collection routes, ensuring optimal waste management efficiency.

Therefore, the proposed methodology provides a holistic approach to waste management. It achieves this by incorporating technology, educating citizens about their crucial role in waste management, and offering incentives to promote community engagement. This approach aims to optimize the garbage collection process and enhance sustainability.

4.3. Enhancing QR Code by Integrating Additional Information

Garbage bins are equipped with QR codes containing extensive information, including (1) bin identification, (2) bin location, (3) bin size, and (4) waste type. The incorporation of supplementary data into these QR codes holds the potential to greatly boost the system's efficiency and effectiveness. This enhancement not only fosters accurate garbage disposal practices but also guarantees the upkeep and cleanliness of the bins. Moreover, it encourages increased public engagement in the waste management process.

Table 3 provides a descriptive overview of bin statuses based on bin-level measurements. It outlines different levels of bin fill, associated color codes, and corresponding bin statuses. The table categorizes bin statuses as empty (less than 20% filled, represented by the color blue), lightly filled (between 20% to 40% filled, represented by the color cyan), medium filled (between 40% to 60% filled, represented by the color green), partially filled (between 60% to 80% filled, represented by the color yellow), and full (80% or greater filled, represented by the color red). Table 4 showcases the bin-level and other relevant statistics encoded within a QR code. The table presents two sample instances of QR codes, each with a unique QR Code ID. For each QR code, the table includes features such as Bin ID, Location (latitude and longitude coordinates), Filled Bin Level (expressed as a percentage), Bin Status (descriptive status of the bin), Bin's Status by Color (associated color code), and an optional Description field for additional observations or issues. This table highlights the encoded information within each QR code, allowing the system to encode comprehensive data about the bin, including its location, fill level, and status, in the QR code.

Table 3. Description of bin status according to bin-level measurements.

Filled Bin-Level	Color Code for Bin-Level	Bin Status
Less than 20%	Blue	Empty
Between 20% and 40%	Cyan	Lightly filled
Between 40% and 60%	Green	Medium filled
Between 60% and 80%	Yellow	Partially filled
80% or greater	Red	Full

Table 4. Bin-level and other stats merged in the QR code.

QR Code ID	Features	Encoded Information
QR_Code1	Bin ID	XXXX
	Location	(Latitude_XXXX,Longitude_XXXX)
	Filled Bin Level	55%
	Bin Status	Medium filled
	Bin's Status by Color	Green
	Description (Optional)	Describe any other observation
QR_Code2	BIN ID	YYYY
	Location	(Latitude_YYYY,Longitude_YYYY)
	Filled Bin Level	95%
	Bin Status	Full
	Bin's Status by Color	Red
	Description (Optional)	Any other issues, e.g., QR unreadable

4.3.1. QR-Embedded GPS Data to Optimize Waste Collection and Cloud-Based Analytics

Our system additionally suggests incorporating both the GPS coordinates and a unique ID number into each garbage bin's QR code. This dual inclusion serves as a fail-safe measure, ensuring that even if the QR code becomes damaged or unreadable, the bin's precise location can still be determined using the user's mobile app coordinates. For instance, in the event that the QR code on a garbage bin is compromised, users can resort to their mobile app to access the bin's location by utilizing the GPS coordinates from their own mobile device when in proximity to the bin.

Waste management personnel can optimize garbage collection routes and schedules by leveraging GPS data acquired from both the bins and sensors. Through a thorough analysis of this GPS data, they can make informed decisions about the most efficient collection routes, resulting in fuel savings and a reduction in greenhouse gas emissions. Furthermore, the data collected by the cloud-based analytics system can be seamlessly integrated with the GPS information obtained from the bins and sensors. This integration offers a holistic view of the waste management system, encompassing vital details such as the precise location and fill level of each bin, the efficiency of garbage collection routes, and the overall impact of waste reduction initiatives.

4.3.2. QR-Embedded Trash Bin History for Efficient Maintenance

Incorporating a bin maintenance and cleaning history within the QR code offers valuable insights for waste management staff. This data facilitates strategic planning of routine bin maintenance, ensuring bins are well-maintained and clean. Consequently, this contributes to a cleaner and more efficient waste management system, enhancing overall hygiene and aesthetics within the community.

4.3.3. QR-Embedded Contact Information

The QR code can be extended to include contact details for the waste management team, such as phone numbers or email addresses. This addition allows the public to easily report issues with the bin or seek additional information, fostering greater user engagement and participation in maintaining cleanliness. It also contributes to the overall effectiveness of the proposed waste management system HTCS.

4.4. Sustainability Considerations

While we have predominantly discussed waste collection optimization, we recognize the interconnectedness of various stages in waste management. Sustainability considerations, including feasibility, circular economy integration, and environmentally responsible practices, are integral to achieving a more holistic and eco-friendly waste management system. Our proposed HTCS is financially viable, environmentally responsible, and socially acceptable, making it a sustainable waste management system.

Financial Feasibility: Our proposed system takes into account the potential cost savings achieved through optimized waste collection routes, reduced fuel consumption, and minimized electronic waste from IoT devices. These financial considerations make our approach economically feasible for municipalities and waste management authorities.

Environmental Impact: By minimizing the deployment of energy-intensive IoT devices and leveraging human collaboration, our system reduces energy consumption and electronic waste generation. Additionally, optimizing collection routes reduces carbon emissions, contributing to a lower carbon footprint.

Social Acceptance: Encouraging citizen engagement and participation in waste management fosters a sense of community responsibility. This social aspect aligns with sustainable practices by promoting a sense of shared ownership and responsibility for waste reduction.

5. Conclusions and Future Work

In this research, we present an innovative approach to revolutionizing trash collection, integrating human collaboration with advanced technology to enhance the efficiency of waste collection, sorting, and disposal. Our holistic trash collection system (HCTS) incorporates QR-coded bins, a mobile app, and IoT sensors to promote waste reduction, boost recycling rates, and elevate community cleanliness and sustainability. With the implementation of the holistic trash collection system, the potential for substantial long-term cost savings in waste management becomes evident. This system not only reduces startup costs but also minimizes ongoing expenses by effectively crowd-sourcing waste level detection through QR codes, thereby limiting the utilization of IoT devices. Additionally, optimized garbage collection routes contribute to substantial cost reductions over time. The environmental benefits of our system are equally significant. By encouraging recycling and promoting efficient waste disposal practices, it can significantly reduce the volume of waste destined for landfills. Furthermore, the system's efficient use of technology reduces e-waste and minimizes greenhouse gas emissions associated with waste collection vehicles, thanks to improved garbage collection routes. We have incorporated a user-friendly interface design to enhance the overall usability and efficiency of the holistic trash collection system. Additionally, we recommend the introduction of a reward system to incentivize user participation and active engagement with the application. Our system's architecture is incredibly adaptable and can be customized to meet the unique requirements of various communities. Moreover, it seamlessly integrates with existing waste management infrastructures, such as garbage trucks, waste transfer stations, and recycling facilities, reducing the necessity for new infrastructure. Thus, our proposed system has the potential to revolutionize waste disposal practices and offer a promising solution to the escalating challenges of waste management.

Future research should focus on extensive real-world implementations to gauge the system's practicality and user acceptance while harnessing behavioral insights to develop strategies that positively influence individuals and communities, encouraging active participation in sustainable waste management practices. This can lead to refined data analytics and optimization algorithms for dynamic waste collection routes, alongside exploring environmental impact assessments and integration with broader smart city initiatives, ensuring the system's long-term sustainability and its contribution to urban development.

While our research primarily addresses advanced holistic trash collection, it lays the foundation for a more sustainable waste management system by efficiently gathering valuable data on waste generation. In future research and development, there is a need to further explore the treatment and disposal aspects of waste management. The integration of innovative recycling and treatment technologies is essential to close the loop and further enhance the sustainability of waste management practices. Future work also needs to delve into the environmental and economic assessments of these technologies to provide a more comprehensive view of their sustainability, including a reduction in environmental impacts, the promotion of recycling and reusing materials, and minimizing the overall carbon footprint of the entire waste management system.

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