IoT-Based Smart Waste Management System (SWIMS)

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Abstract

Pakistan is dealing with a waste management crisis that is causing significant problems in the country. People fail to dispose of waste properly because of the absence of incentives, and institutions do not impose strict regulations since they do not stand to benefit from them, leading to overflowing bins. This prevents those who want to dispose of waste properly with little to no choice but to litter the surroundings. Government corporations cannot curb the rising problem due to tardiness, and mismanagement. This is why research shows that targeting the private sector will reap greater rewards. It will help reduce improper waste disposal and introduce competition, forcing government agencies to improve their standards. To understand the existing framework and improve on it, primary and secondary research was considered, after which a waste management framework was conceptualized, taking the principles of circular economy into account. This framework includes a smart waste bin to address the country's waste management problems. The five-layered IoT-based system makes recommendations from data acquisition, smart bin technicalities, and an Android application, including features that motivate individuals to dispose of waste properly, to a central hub, business model, and further recommendations to expand the framework into a scalable solution.

Keywords: Waste Management, IoT Architecture, Incentivized Solution, Circular Economy

1. Introduction

Pakistan generates 48.5 million tonnes of solid waste annually and 87,000 tonnes of solid waste daily, of which only 60-70% ends up being collected (Shafique & Clark, 2022). Pakistan's solid waste management (SWM) sector has struggled with improper waste collection, and dealing with the rapidly growing population and the issues that come with it. Various private and government studies (A. Iqbal et al., 2022; Rizvi et al., 2021; Shafique & Clark, 2022) have shown that Pakistan's SWM sector lacks structure, the use of modern techniques, and an inability to collect and manage waste effectively. While some efforts have been made to improve the sector recently, all of these have focused on manual sweeping A. Iqbal et al. (2022) and traditional methods. This paper proposes the use of a new modern framework to address these issues.

The incorporation of smart IoT-based waste bins, centralized hubs, an Android application, and public incentives combined with a CE (Circular Economy) based business model that profits all involved stakeholders is essential to strengthening the SWM sector of Pakistan.

This paper first conducts a literature review of existing studies that discuss and suggest solutions to solve similar issues globally. It then describes the existing problems in detail and moves on to the proposed CE and IoT-based framework and its advantages. Finally, it discusses possible limitations and concludes with future recommendations that can further add to the framework and the SWM sector in the long run.

2. Related Work

Many studies are focused on targeting government bodies to resolve the waste management crisis worldwide. Khan and Ali (2021) identify the problems in the current waste management system, which include constraints when it comes to administration, institutions, and finances, along with a lack of proper collection and disposal of municipal solid waste. They identify the lack of a holistic approach that could be used by city authorities to improve the waste management system in the city. A. Iqbal et al. (2022) hold the Pakistani government accountable for not prioritizing the SWM sector and suggest that the local government should draft the SWM Act and related policy in consultation with the Ministry of Climate Change for its implementation in all provinces. Abubakar et al. (2022) talk about obstacles to effective municipal SWM in low-income countries, including lack of awareness, technologies, finances, and good governance. They recommend a city-wide plan for an integrated SWM approach that emphasizes improving the operation of municipalities and local governments, strictly enforcing environmental regulations, and promoting positive public attitudes. Szpilko et al. (2023) suggest future research on policy development and community engagement, aligning with global sustainability goals in urban areas. They also emphasize the importance of addressing traditional methods and local contexts in waste management research for smart cities.

Some studies suggested using advanced technology to improve the current waste management system. Sosunova and Porras (2022) analyzed multiple published papers to identify common technology used in this sector. These include proximity solutions (e.g., RFID, near-field communication (NFC), and

Zigbee), mid-range technologies (e.g., Bluetooth and Wi-Fi), and wide-area networks (e.g., mobile networks and fixed Internet solutions). Karthik et al. (2023) discuss a smart bin with ultrasonic sensors, an ESP8266 Wi-Fi module for IoT-based communication, and PIC micro-controllers for a low-cost solution. Alsobky et al. (2023) suggest the use of waste collection vehicles equipped with intelligent monitoring technologies that can dynamically optimize the waste collection routes. They explore a variety of sensors used in waste bins and vehicles, including sensors to monitor the filling levels of the bins, weigh the trash bin, measure the volume of waste in the bin, identify the type of waste, and detect hazardous gases produced by waste.

Seker (2022) talks about Multi-Criteria Decision Making (MCDM) tools comprising both qualitative and quantitative aspects such as human resources and operational and financial issues. Fidje et al. (2023) discuss IoT solutions that can help optimize operations and manage resources for more efficient resource management to attain sustainability goals. Ziouzios and Dasygenis (2023) suggest that Greece should embrace new technologies like the Internet of Things (IoT) to protect the environment in an effort to improve the SWM sector. Vishnu et al. (2021) highlight an IoT-enabled solid waste management system to address the limitations of traditional waste management, incorporating trackers and sensors in bins along with an intelligent Graphical User Interface (GUI) for waste collection authorities to monitor the unfilled status of each waste bin. Pardini et al. (2020) propose a system that follows an IoT-based approach where the discarded waste from the smart bin is continuously monitored by sensors that inform the filling level of each compartment in real-time, along with IoT middleware providing information for collection with optimized routes using a web or a mobile application.

Papers also utilize machine learning models and algorithms in order to facilitate the waste management system. Cheema et al. (2022) use various sensors to monitor waste levels in commercial and residential bins. They also use a camera to carry out grid segmentation of images using VGG-16, a machine learning model, to identify the type of waste being thrown. A robotic arm then categorizes the waste into different containers based on the material detected. Limsila et al. (2023) use the YOLOv5 machine learning model inside a waste bin to classify recyclable material based on images. They achieved an impressive multiclass accuracy of 93.3% to provide a reliable inventory of the collected waste. Rahman et al. (2022) compare various machine learning models, including VGG-19, for waste classification. They were able to achieve an accuracy greater than 90% using a Convolutional Neural Network (CNN).

Some papers also propose using incentives to increase motivation amongst people to employ effective SWM strategies. Nepal et al. (2022) conduct a Randomized Control Trial (RCT) in Nepal to discover various issues in the SWM sector. The study placed a lack of awareness and at-source segregation as the main culprits of the loss of valuable recyclable materials and proposed introducing incentives and awareness campaigns to encourage people to segregate and dispose of trash responsibly.

A different technique was used by Yu et al. (2024) with the introduction of the Multi-Depot Waste Collection Vehicle Routing Problem with Time Windows and Self-Delivery Option (MDWCVRPTW-SDO). The problem was modeled as a mixed integer linear programming model to optimize investments, routing costs, and resident compensation to make the routing of waste collection trucks as smart as possible.

A few papers also discuss targeting the private sector to manage improper waste management. The International Trade Administration USA ITA (2024) has recognized opportunities in the Pakistani SWM sector by emphasizing that “the public and private sectors (in Pakistan) have or will initiate small-medium scale projects related to collection, transportation, and management of municipal and industrial waste” and that “the local market will continue to offer sizeable business opportunities”.

Circular economy was a popular concept emphasized by many papers. Cerqueira-Streit et al. (2023) and Hemidat et al. (2022) explain how rapid urbanization, inadequate regulation, and landfilling pose threats to the environment, society, and public finances and how CE can reduce the negative impacts. Techniques such as Life Cycle Assessment (LCA) play a crucial role in managing waste and utilizing resources sustainably (Alhazmi et al., 2021). According to a study by Wamba et al. (2023), the implementation of CE practices has the potential of reducing raw material consumption by 53% by 2050 and at the same time boosting economic growth.

Circular economy business models (CBM’s), policies, and technologies are a step in the right direction toward transitioning to a circular economy. Numerous smart bins such as BigBelly, Enevo, and SmartBin are integrating sensors and robots to assist with efficient waste management. Clark by AMP Robotics has been able to detect recyclable materials with an accuracy of 90%, is about 50% faster than a human, and has cut down reduction and sorting costs by another 50% (Rossi et al., 2020). Such technologies enhance business innovation and create room for unique business model development (Islam et al., 2022).

Another CE model proposed in a university in Karachi, Pakistan by J. Iqbal et al. (2020) incorporates selling the waste collected in institutes to local vendors for profit. That money can then be used to reinvest in the SWM industry for better services and a more sustainable future.

The idea of a hub for waste segregation has also been proposed by some papers. Centers, where waste is collected, segregated, and traded, show potential to optimize the SWM sector (Gall et al., 2020; A. Iqbal et al., 2022). Supervisors can be entrusted to handle the segregation of recyclable waste and cooperation with private and government bodies can be used to establish reasonable rates for trading and reincorporating valuable waste back into the system (Gall et al., 2020).

3. Problem

Many institutions struggle with improper waste disposal due to overflowing bins and public indifference. Lack of compliance and personal gain hinder the enforcement of regulations, leading to pollution ITA (2024) and higher recycling costs.

Waste management in urban areas of Pakistan is confronted with significant shortcomings, posing multifaceted challenges. Firstly, a lack of Incentives for responsible disposal causes improper waste disposal. Current waste disposal practices fail to motivate individuals to engage in responsible waste disposal. The absence of adequate incentives leads to haphazard waste disposal practices, including littering and improper waste handling. Secondly, developing countries have inefficient recycling practices, requiring more time and resources. Without a clear understanding of the materials available, private contractors and other authorities often resort to indiscriminate processing, which wastes resources and limits the recycling potential of institutional waste.

Thirdly, there is a lack of a holistic approach and model that tackles the SWM sector. The absence of a widely adopted business model that incorporates private contractors and institutions creates a situation where organizations tend to overlook the motivation of individuals for proper waste disposal, as there are few apparent advantages for them (J. Iqbal et al., 2020). Further study shows how approximately 16,550 kg of recyclable waste is produced per annum in Higher education institutions in Pakistan, which can be sold to generate a profit (J. Iqbal et al., 2020).

4. Methodology - a proposed framework

Figure 1 shows the fundamentals of the proposed framework for waste management. The system is based on a five-layered IoT architecture and provides an end-to-end, circular economy-based solution to minimize improper waste disposal with a single model that combines the interests of multiple stakeholders. Due to unreliable and inconsistent practices in the government-controlled waste management sector, a framework that boosts small-scale private-sector companies is ideal in the context of Pakistan. This increased competition may also encourage the government to improve its strategies for the waste management system. These layers will be further discussed in detail in the sections below.

4.1. The Perception Layer

Starting from the bottom, the first IoT layer of the framework consists of smart waste bins. The bins use IoT-driven sensors and RFID authentication to give ordinary individuals point-based incentives for throwing trash inside the bin. The smart bin has a weight sensor that tells us the exact weight of the garbage, along with sensors that help categorize the materials into plastic, paper, metal, and glass, and a 16x2 LCD to guide the user on whether they need to wait for verification, etc. Additionally, level sensing is done via ultrasonic sensors to ensure that waste bins are cleared out before they reach their maximum capacity. A locking mechanism has been derived and attached inside the bin to ensure that users do not try to misuse the technology.

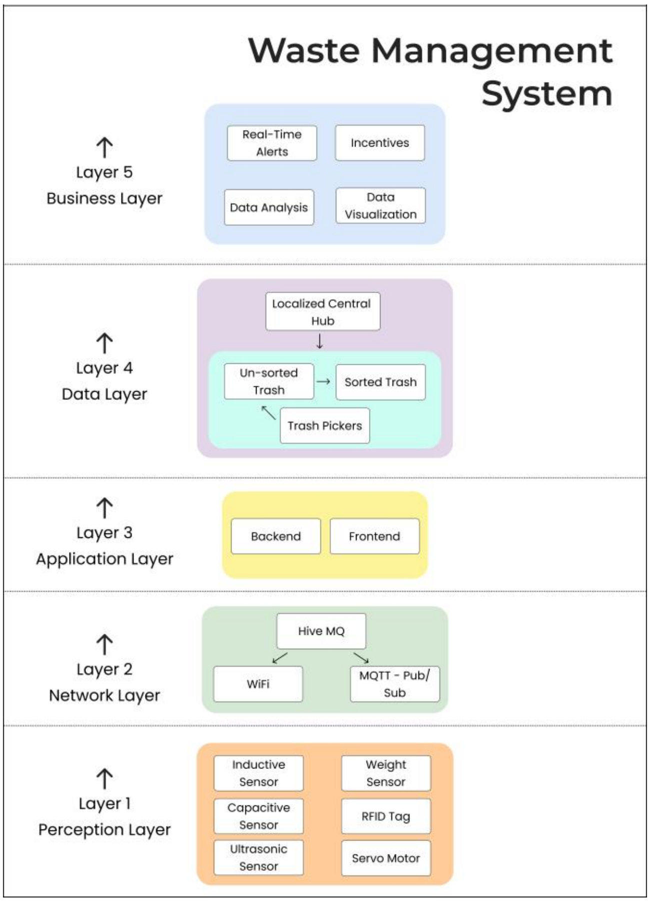

Figure 1: Detailed Framework of the Waste Management System.

4.2. The Network Layer

The second layer of this framework includes a cloud-based system for transporting the data acquired from the sensor to the database used. There are multiple ways to send data, including WiFi, Bluetooth, and cellular. Since the project scope is limited to institutions and restaurants, using Wi-Fi was feasible as these places generally have their own high-speed Wi-Fi connections. Since data must be sent over a network, multiple protocols can be used based on the project's specific needs. While assessing protocols like MQTT, CoaP, and HTTP, MQTT fits the model best. This was because of its publish-subscribe model, which included a third-party broker to mediate the data transfer. It is also lightweight, ensuring smooth running on the Arduino and allowing for a lower latency. The third-party broker being used in Hive MQ allows a secure connection through SSL certificates and direct socket connections with the database being used. The core processing unit at each bin is the Arduino Mega 2560, which has a built-in ESP8266 module. The ESP8266 is a system-on-a-chip (SOC) microchip that allows various microcontrollers to connect to the WiFi and can allow 2.4GHz connections per the 802.11bgn standard set by IEEE. In addition to this, the ESP8266 has a complete TCP/IP stack and can also carry out data handling and processing before sending it to the cloud, thus acting as a complete IoT gateway that communicates data between the individual bins at the edge and the application's users.

4.3. The Data Layer

The third IoT Layer of this framework discusses a localized central hub that acts as a waste storage site and a center of waste data w.r.t. the locality. For every designated area, such as Faisal Town, DHA, Johar Town, etc., there can be a site where the nearby institutions can dump their trash. The gathered data is then stored in MongoDB and processed for better visualization. This proposed framework allows smooth workflows between the institution and the waste collection site, making the process much simpler for them.

4.4. The Application Layer

The fourth IoT layer in this framework discusses the mobile application. The application can operate on both IoS and Android devices. The application's basic purpose is to track users' points and connect contractors and institutes for conducting business. The application utilizes the latest technology stack (MERN Stack). The database is MongoDB, which is used to store the user's information as well as real-time data from the hardware. React is used on the front end even supporting web pages on mobile apps. Lastly, Express builds servers on the backend, where Nodejs handles and combines these technologies.

4.5. The Business Layer

The fifth and final IoT layer of this framework revolves around the entire business model of the smart waste bin. A minimal cost of buying the bin and incentives to motivate institutions are needed to ensure they spend money on IoT-driven waste bins. In this case, that incentive and motivator are profit. The bins are placed inside multiple institutions depending on their needs. When the user throws waste inside them, they receive points based on the weight of the waste thrown. Points are generated based on the weight and material of the garbage thrown and can be used to redeem vouchers and food stamps. Institutions receive a profit by selling their trash to private contractors through the app. This profit can help meet the expenses of partnering with companies for vouchers while the remaining profit goes to the institution itself. Not only is this minimizing the waste around campus by motivating individuals, but it also generates the institution a hefty profit. Institutional waste will go to the nearby hub, based on their location. Workers can sort the unsorted waste inside the localized central hub, thus generating more jobs in the waste management industry. Since the waste management industry operates on a daily wage system and rates tend to fluctuate every day, real-time information about the weight and material can help with profit and cost calculations. Private contractors will know the exact material (plastic, paper, metal, glass) and weights of different kinds of trash available for purchase at every local hub. However, within the limited scope of the FYP prototype (which lacks the implementation of an actual central hub), private contractors will know about the waste generated inside institutes directly. This will minimize blind buying and provide contractors with a guaranteed flow of work, which helps them know that they'll ultimately earn some revenue. Private Contractors will know what resources they require for daily operations, which will help them save costs by improving the overall efficiency of their small-scale business. Private contractors can then sell this sorted waste to large-scale industries or other processing units for reincorporation into the economy. This has the potential to significantly increase waste collection, reduce generation, and promote a circular economy mindset amongst different stakeholders in the country.

5. Implementation

A working prototype of the smart waste bin was designed and created to implement data gathering and processing along with a mobile application to handle different users, rewards, and visualizations of the gathered data. This required hardware and software elements to work in a synchronized manner so efficient functionality of the proposed framework could be established.

5.1. Hardware Implementation

The Arduino Mega 2560 and the ESP8266 were responsible for gathering data from the various sensors and processing it before it could be transferred to the HiveMQTT broker to be used by the mobile application. Figure 2 shows the general hardware block diagram for the prototype. The following sections discuss the sensors and their interfacing in greater detail.

5.1.1. Micro-Controller

The prototype developed as part of the research uses the Arduino Mega 2560 WiFi microcontroller, which combines the

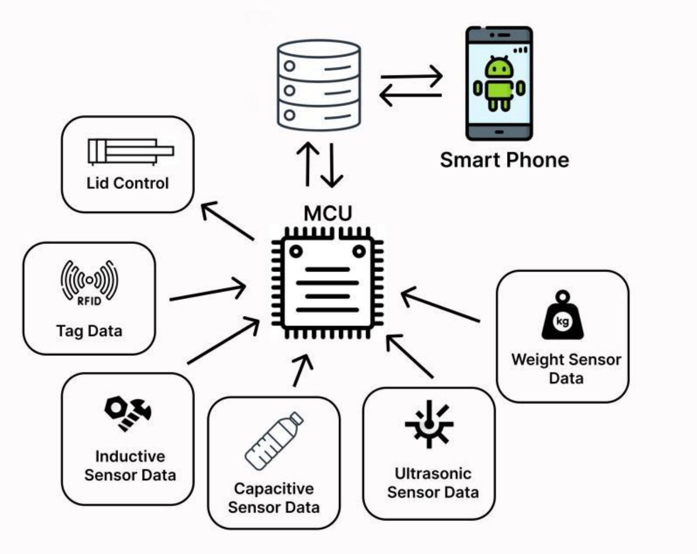

Figure 2: Hardware Block Diagram.

Atmega2560 with the ESP8266. The board has 54 digital I/O pins, 16 analog inputs, and a 16MHz oscillator powered by a single USB port or a standard power jack. This allows for the interfacing of multiple sensors, which is particularly useful for the IoT-based waste bin, which collects different types of data through many different sensors. The ESP8266 microchip has a Tensilica L106 32-bit RISC processor and can connect to WiFi networks to transmit data across the internet. Combining these increases processing power while achieving extra-low power consumption. Every user will have their unique account to see the points they have earned and redeem their vouchers, which means there needs to be a way to identify who is throwing the waste inside the bins. In order to do that, an RFID tag is assigned to every student. This can be given separately or incorporated with their student cards, which could help make throwing waste inside the bins more accessible. The MiFare MFRC522 RFID Card Reader/Writer Module reads the unique tags so the Arduino can send them to the HiveMQTT broker for verification. These were used with 13.56MHz MiFare RFID Tags. When the individual scans their RFID tag, the reader reads it and stores it in the hardware. The hardware sends the data over Hive until it comes back as verified. If the RFID tag is verified, meaning it is already registered with our system, the bin automatically unlocks; however, if the RFID is not verified, it remains locked.

5.1.2. LCD

An LCD attached to the front of the bin was imperative to guide the user. It will tell the user to scan their RFID tag when the bin is unlocked and when the RFID is not verified, so it will remain locked. This will ensure that the user is not left confused about what they need to do or why the bin isn't opening. The LCD used was a 16x2 Character LCD Display for Arduino, as it is easy and efficient to interface and use. A potentiometer was connected with it to adjust the brightness and thereby see the text clearly on the screen.

5.1.3. Locking Mechanism

A tower pro servo motor MG-946R, combined with the ultrasonic distance sensor, is being used to make a locking mechanism. The motor has a 4.8V – 6V DC rating, so Arduino Mega's 5V is insufficient. An external supply makes it much safer, preventing the USB ports from burning. Hooks and a metal wire were also required as the physical component of the lock. The bin unlocks when the user scans the RFID card and the tag is verified. The Tower Pro Servo Motor rotates, hence unhooking the hooks. Once the individual has thrown the waste inside and closed the lid, the ultrasonic sensor detects the distance between the lid and the sensor, locking when the distance falls below a certain threshold.

5.1.4. Weight Sensor

To keep track of the amount of waste thrown, an HX711 Weighing Sensor was used, coupled with two load cells for accurate weight measurement. Since the waste management industry uses waste weight to conduct daily business, the weight sensor was a requirement. When the user throws trash inside the bin, the weight sensor measures it and sends that data further to Hive. The waste is then thrown inside the bin from a tray once the weight measurement has been completed. The exact model of the bin will be discussed below. 50 kg load cells were used to measure up to 50 kg of trash inside the bin, which was more than enough according to the bin's storage capacity.

5.1.5. Material Categorization Sensors

To allow institutions and private contractors to see exactly what is inside the bin, an Inductive Proximity sensor E2E-X18ME1-M1, an E2E Series 18 mm Sensor, and a Capacitance Proximity Sensor LJC30A3-H-Z/AY Switch PNP NC DC were used. The inductive sensor detects metallic materials by generating eddy currents due to electromagnetic induction. This 18mm sensor provides a decent detection range and is rated at DC 12-24V. This was primarily used to detect metals. A capacitive proximity sensor was used to detect different types of materials, such as plastic, paper, and glass, based on the variances in the capacitance readings of each material. This sensor has a 25mm sensing distance. The sensor has an adequate detection range with relatively low power requirements, rated DC 6-36V. Cumulatively, plastic, metal, glass, and paper were the four major categories of classification since these are important to private contractors for profit and the primary materials commonly thrown inside institutions.

5.1.6. Level Sensor

HC-SR04 Ultrasonic Sensor was used to measure the level of waste thrown to be cleared before reaching the maximum capacity. The sensor measures distance using ultrasonic waves. It emits a wave and waits to receive the echo back from the object. The time duration for this echo is used to calculate the distance, providing an accuracy of 1 mm for every 10 cm. Once the waste levels reach more than eighty percent, the private contractors are notified. Figure 3 shows the complete flow of hardware operations.

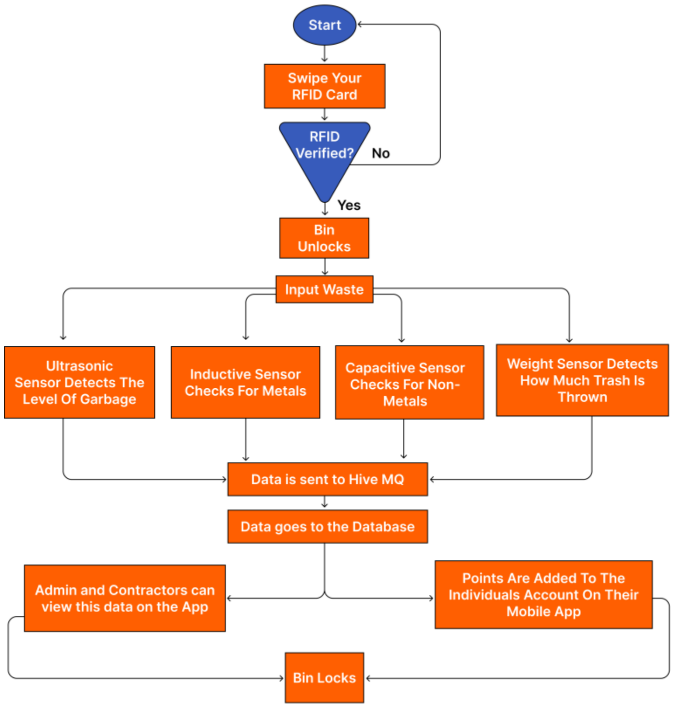

Figure 3: Flow of Hardware Operations.

5.1.7. Bin Model and Schematics

A 50L plastic pedal waste bin is a commonly used bin in educational institutes with a sufficient holding capacity of 30 - 40 Kg. Because of its plastic body, it is much cheaper than its larger counterparts and suitable for placing hardware components. The pedal makes accessing the bin easier without using one's hands to open the lid. A general visualization of the sensor placement inside the bin and its dimensions can be seen in figure 4.

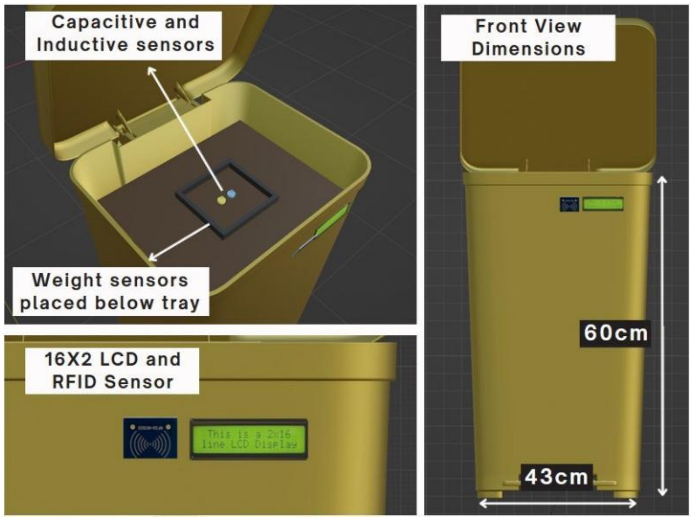

Figure 4: Bin Schematics.

5.2. Software Implementation

This section discusses in detail the various aspects of the mobile application, HiveMQTT broker, backend, and frontend, along with the database structure being utilized to store information regarding the processed data and users.

5.2.1. User Personas

Taking into account thorough research, three primary user personas were identified.

- Trash Thrower.
- Institutes/Restaurants, etc.
- Local Contractors.

People who throw trash in the dustbin can see their points and performance live on our app. The app will help them get access to vouchers by redeeming their points. This becomes the basis of motivating individuals to throw waste inside the bin. In the second view, institutes can see the list of contractors available and those with whom they have contracted. They will also be able to see the amount of waste and categorized materials in the institution at any time. This allows them to track what is being sold and the profit they will possibly get. They will also be able to see which vouchers are more popular and can further renew contracts with third-party eCommerce companies. Thirdly, the local contractors can see the dustbins' status when they pick them up. They will see the material in those dustbins to know precisely what they are purchasing and the profit they will receive as well.

5.2.2. MongoDB

MongoDB is the database of choice for the prototype that uses a no SQL approach, which makes it faster as it uses microservices. It can scale depending on the load on the database. Additionally, it handles requests to the database and scales itself when needed. It is a database that we have used to store all the information from the users and the hardware, such as the weights of the thrown trash, etc. The data is updated in the model depending on the need. Based on the requirements of the waste bin, our database consists of three main schemas: User, Contractor, and Individual. MongoDB also has sockets that were used to connect it with HiveMQ to handle the data sent from the hardware. The connection is constantly opened, and the database is updated when data comes from the hardware.

5.2.3. Backend

A backend algorithm was developed to generate points for users. The implemented algorithm considered the weight of the waste thrown and assigned points based on it. The points per gram were decided based on the profitability of the material in the market. The following was concluded:

- Metal —1.5 points per 1 gram—one empty metal can is approx. 14 g, so 21 points were received per can.
- Plastic—1 point per 2 grams—one 650ml empty plastic

bottle weighs approx. 22-25g, so 12.5 points were received per bottle.

- Glass—1 point per 50 grams—one glass bottle weighs approx. 390g, so 7.8 points were received per bottle.
- Paper—1 point per 2 grams—one A4-sized paper is approx. 2.5g, so 1.2 points were received per sheet.

This point system incentivizes individuals to throw waste inside the bins and improve collection from the source. They can save up their earned points to redeem various vouchers and gift cards.

1. *Express:* Express is the latest technology for creating routes on the server side, which can be utilized from the frontend requests to the backend. In the context of the smart bin, it involves multiple routes:
    - Authentication Routes.
    - Updating Points Routes.
    - Deducting Points Routes.
    - Admin Routes.

    Each of them has multiple APIs incorporated to ensure the efficient functioning of the application.

2. *Node Js:* NodeJs is a major tool used on the backend side, handling multiple libraries in the application, connecting databases with routes, and placing Express on top. It is the latest technology for making web applications and is equipped with the power to develop native Android and iOS applications. All the backend algorithms and code are written in JavaScript and compiled with the help of NodeJs.

3. *Javascript:* This application uses JavaScript on the backend side. This equips the application to perform extremely hard tasks efficiently. JavaScript is both a server-side and client-side language. The complete schema (a model for defining what our users will have, i.e., CNIC, name, age, etc) for MongoDB is written in this language. Cookies have been used in the backend to help users stay logged in for up to 5 days. Moreover, a JSON web token (JWT) is stored in cookies with encryption using Bcrypt. This makes the app secure from potential hackers.

5.2.4. Frontend

The application frontend is built on ReactJS, a framework for writing complex frontends. ReactJS uses reusable components technology, allowing us to write code for one component on a page that can be used in any part of the application. This makes it reliable and efficient. All Figma designs for various screens are converted into ReactJS using JavaScript XML (JSX), which allows us to write HTML and JavaScript simultaneously in a single file. The front-end styling is done through CSS. A language for customizing and making HTML static pages appear more appealing and dynamic. The app also uses the Model–view–controller (MVC) structure to help any other open-source programmers work on it efficiently. The classes

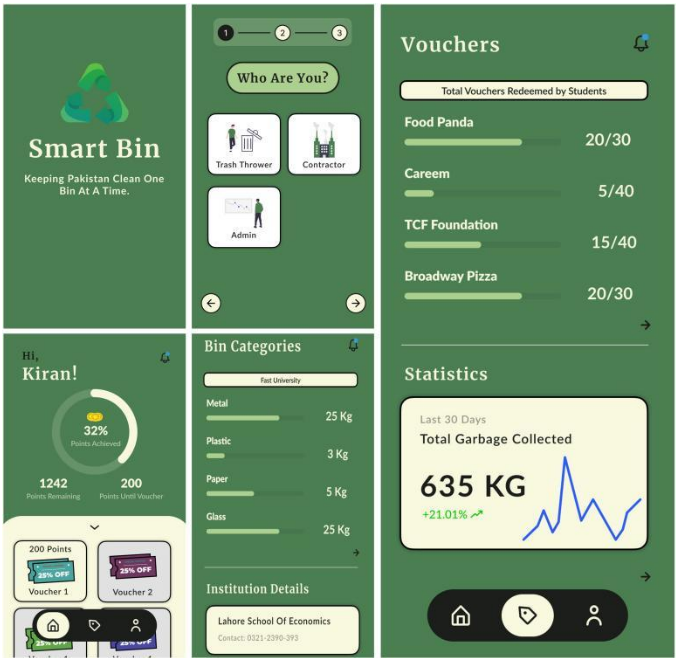

Figure 5: Application prototype created in Figma.

are well-named and commented on to ensure easy updation of the application in the future. Utilizing the latest Redux toolkit then allows us to store all the different states of the application in one place/container. This way, accessing and storing the backend on the front side is easy and efficient.

5.2.5. Data Analysis

In addition to the functionalities mentioned in section 5.2, the application will allow for data analysis and visualization using the data we collect from our bins and the localized hub. A prototype of this can be seen in Figure 5. This can help private contractors be aware of market trends as they can visualize the data through the application. It can further optimize contractor businesses by presenting insight into what waste is most commonly thrown and what generates the most profit, allowing them to improve their business model using the application. The application will also enable contractors and institutions to see nearby hubs, potentially optimizing transportation and fuel costs.

6. Results

This section discusses testing results after the implementation of a prototype smart bin. The smart waste bin was part of an academic project at FAST-NUCES and the testing phase consisted of a small sample size of objects of varying materials and weights. Objects were weighed and categorized using the prototype to determine the overall accuracy and error of sensors interfaced in the waste bin.

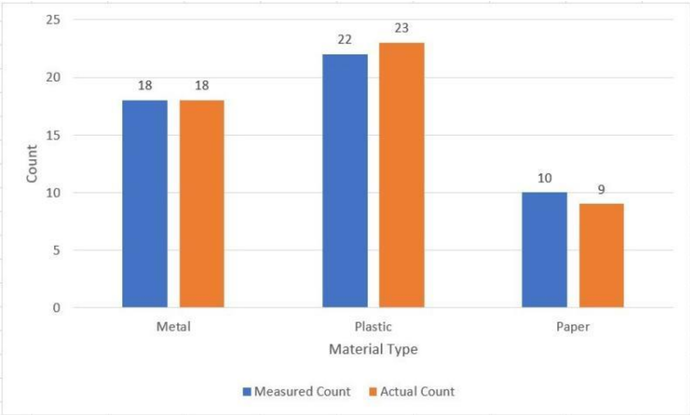

Figure 6: Measured vs Actual Material Counts

6.1. Weight Testing

Different items were weighed one at a time using the sensors inside the bin. Standard error was calculated from the measured data in table 2. The standard error was expressed as follows:

$$SE = \frac{\sigma}{\sqrt{N}} \quad (1)$$

where,

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{n}(X_i - \bar{X})^2} \quad (2)$$

The measured weight values showed a standard error of 1.73% or 5.62 grams about the actual weight values. These differences are visualized in figure 7.

6.2. Material Categorization Testing

The same 50 objects were also categorized into 3 different materials i.e. "Metal", "Paper", and "Plastic". The categorical data shown in table 3 was converted into numerical before standard deviation and general accuracy could be calculated. Accuracy was expressed as follows:

$$Accuracy = (1 - \frac{|Actual| - |Measured|}{Actual}) * 100 \quad (3)$$

The categorization sensors achieved an overall accuracy of 94% with a standard error of 0.034. Table 1 shows individual accuracies and errors of each material category with individual counts being visualized in figure 6. The inductive sensor successfully detected each metal object correctly, whereas the capacitive sensor miscategorized only one plastic object as paper.

Material	Accuracy (%)	SE (%)
Metal	100	0
Plastic	91.30	8.70
Paper	88.89	11.11

Table 1: Individual Accuracies and Standard Errors

Index	Actual Weight (g)	Measured Weight (g)
1	870.21	779.77
2	73.99	66.9
3	680.45	581.99
4	2.8	1.46
5	420.21	415.58
6	220.12	181.9
7	249.04	224.51
8	2.45	1.75
9	531.94	435.17
10	68.09	60.32
11	1.1	1.63
12	863.44	950.45
13	424.95	379.54
14	0.91	0.4
15	392.34	311.39
16	390.12	410.4
17	528.8	471.4
18	435.13	392.36
19	1.86	0.8
20	498.21	423.31
21	589.54	610.54
22	881.21	781.17
23	1.06	1.93
24	2.03	1.01
25	2.89	1.72
26	289.21	223.95
27	396.59	355.95
28	265.6	232.94
29	501.24	437.27
30	664.29	591.31
31	328.04	297.16
32	888.8	787.16
33	192.7	168.57
34	77.22	69.37
35	155.02	139.41
36	1.25	1.71
37	283.82	254.38
38	779.61	692.14
39	402.18	351.11
40	140.07	124.3
41	556.87	485.46
42	446.06	395.14
43	451.54	392.88
44	1.98	1.7
45	118.59	103.58
46	646.13	580.63
47	231.7	208.04
48	831.32	753.61
49	398.28	394.5
50	870.83	769.2

Table 2: Actual vs Measured Weights

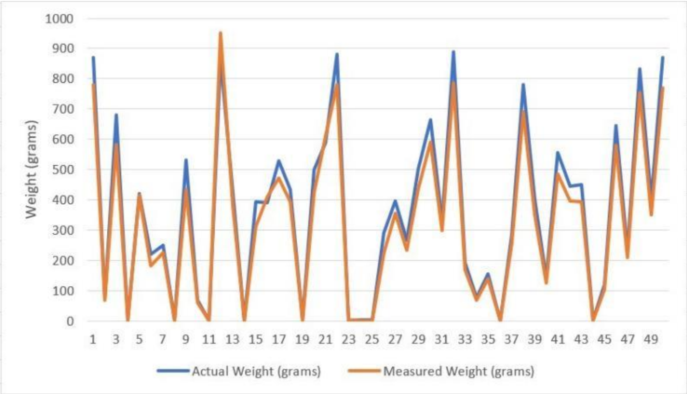

Figure 7: Measured vs Actual Weights

Material	Measured Count	Actual Count
Metal	18	18
Plastic	22	23
Paper	10	9

Table 3: Measured vs Actual Material Counts

7. Discussion and Future Recommendations

Certain aspects of the proposed framework require more time and money to implement to maximize its efficiency. The recommendations mentioned in this section act as blueprints for future work to further improve the effectiveness of the framework and the waste management sector.

7.1. Physical Waste Storage

The existing system requires the implementation of an actual physical site that acts as a local hub for waste storage and sorting. Adding such a site in collaboration with government or private firms can significantly improve the waste management sector, allowing all parties to view trash flow centrally. Waste can be sorted manually, and knowing what and when to purchase will save time and fuel. Additionally, the hub can bridge the gap between contractors and institutes while simultaneously creating more job opportunities for workers in the waste sector.

7.2. Machine Learning Models

The application of various data analysis techniques will also work well if integrated with the centralized hub mentioned in section 4.3. Various ML models and algorithms can be used to gain useful insights from the large amount of data generated at these sites. Waste flow, generation, reincorporation, and transactions can help stakeholders make well-informed decisions, benefitting businesses and the collective waste management sector of Pakistan.

7.3. Incorporating Local Municipalities

This framework may also include local waste management municipalities such as Lahore Waste Management Company (LWMC) or Sindh Waste Management Company (SWMC). An extensive database that provides useful insight into waste generation and collection trends across different localities or cities can greatly assist the government in creating useful, data-backed policies based on the principles of a circular economy. This may lead to a more positive and quicker shift in Pakistan's waste management sector.

7.4. Combined Use of Sensors For Better Accuracy

To improve the categorization accuracy for plastic and paper objects, an ultrasonic sensor can be used in combination with the existing capacitive sensor. Certain capacitive sensors may lack the sensitivity required to differentiate between every plastic and paper object accurately. The ultrasonic sensor, however, can detect subtle changes in material type by measuring small changes in the time taken for sound waves to be reflected to the sensor. This data combined with the capacitive sensor can further improve plastic and paper categorization accuracy respectively.

The prototype made use of two load cells together to measure the weight. This particular setup required the object to be still for a few seconds before weight could be measured accurately. However, a combination of 4 load cells can greatly improve the measuring speed as well as the accuracy of the results.

Lastly, testing can be conducted on a larger sample size consisting of a greater variety of objects to get better error and accuracy results which can further help optimize the workings of the waste bin.

7.5. Rewards System

The existing point system may be further refined by including a tier-based system. Based on the amount of waste thrown, there can be three tiers: bronze, silver, and gold. After throwing a certain amount of trash, the user can move up tiers, which gives them access to better rewards that can be redeemed using their points. Badges can be given to meet recognition needs and gamify the waste-throwing process. Additionally, for people who throw recyclable materials, additional benefits and milestones could provide them access to exclusive rewards. This can help promote sustainability and curb the use of non-recyclable materials.

8. Conclusions

In summary, this framework is built heavily around concepts of a Circular Economy (CE) that encourages recovery and reincorporation of materials back into the system. Our framework makes collection and reuse easier and more accessible for all involved stakeholders. Furthermore, increased transparency and incentives combined with awareness regarding sustainable practices can also induce behavioral change amongst the general public, possibly driving future policies towards CE practices.

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