



Eco Sethu: Smart Routing for Efficient Waste Management Systems

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Abstract : Rapid growth of urbanization has led to vast amount of waste generation, making it quite challenging to collect and dispose them efficiently. Traditional waste management methods rely on fixed schedules, which often lead to problems such as increase in operational costs, fuel consumption and environmental effects. This article presents Eco Sethu, a dynamic waste management system that uses various machine learning techniques and route optimization algorithm for efficient waste collection. In particular, the model initially predicts the household waste generated using the collected historical data and various performance metrics. Among all the other models, Random Forest model showed better performance with higher accuracy. These predictions were used as the input to the route optimization algorithm model, which is solved using the Traveling Salesman Problem and Nearest Neighbour Approach. This helps in reducing the travel distances and use the truck's capacity effectively. Additionally, a web application is also developed using Fast API and SQLite, providing real-time collection schedules, issue reporting, and waste segregation practices to increase community participation.

Keywords—waste management, route optimization, machine learning, Fast-API, nearest neighbor algorithm, traveling Salesman problem, web application.

I. INTRODUCTION

Proper waste management is necessary for sustainable urban development due to the rapid growth of urban population and the expansion of cities. Unlike the earlier times, when waste was just a minor issue and required a little thought for being disposed, proper management was not a major concern due to the population being smaller and vast amount of land was available to them. The environment could easily absorb the waste produces without any form of degradation since the volume was limited back then. At present, inadequate waste disposal have led to multiple issues, such as severe environmental degradation, public health hazards, water and soil contamination, spread of diseases. To overcome these challenges, proper waste segregation, collection and disposal are necessary to bring positive impact to the environment and other critical factors.

The collection of waste is one of the most difficult problems faced by authorities in cities. The current system relies on fixed schedules and daily collection leading to high operational costs and fuel consumption. When implementing these steps both economical and environmental aspects need to be considered.

This article presents a system which utilizes machine learning algorithm to predict the daily waste generated based on the historical data. The solution of this is used for route optimization, which generates optimal route by identifying the shortest route based on travel distances from depot to all the households.

Once the optimal route is generated, real time updates are provided to the residents via a website, including the collection schedule through SMS. After the updates are sent, the truck begins the collection process from the depot following this optimal route. Additionally, a query management system is integrated to allow residents to raise queries.

II. LITERATURE ANALYSIS

Navid Akbarpour (2021) [1] introduced a model that uses vehicle routing problem (VRP) for fleet movement from waste generation points to separate facilities and another for resource allocation to recovery plants. Utilizes chance constrained programming and four metaheuristic algorithms to minimize transportation and maximize recycled revenue in municipal solid waste management. This study incorporates stochastic optimization for vehicle routing, it overlooks dynamic waste generation patterns in real-time. Future work could enhance the model by integrating IoT- based sensors for adaptive route planning and improving the system's scalability for large cities.

N. Iqbal and D. Kim (2024) [2] introduced bibliometric and systematic review of 12 key publications on municipal solid waste collection optimization, identifying methods like GIS, IoT, and mathematical modelling. It highlights a focus on route optimization, emphasizing reduced travel distance and operational costs. This review identifies a lack of studies incorporating environmental factors like emissions and sustainable waste separation. Future research should integrate broader sustainability objectives, including fuel economy and ecological impact.

Bakhtiar Ali (2024) [3] focused on IoT-enabled system integrating TOPSIS for optimizing waste collection routes, considering parameters like waste volume, toxicity, and duration. It demonstrates a 14% reduction in total vehicle travel distance compared to single-parameter optimization approaches. The system lacks real-time adaptive features for unexpected scenarios such as route blockages or sudden waste surges.

Victoria Ruiz-Parrado (2021) [4] proposed a multi- objective optimization model for waste collection, minimizing route distances and maximizing waste collection. It employs evolutionary algorithms and real-world waste data from Jeju Island to design an intelligent route recommendation system. This study demonstrates efficient waste collection using predictive and optimization models, it lacks real-time IoT integration for dynamic waste tracking. Future enhancements could automate overflow detection and improve real- time route adjustments.

Teoh Ji Sheng (2020) [5] introduced a TensorFlow-based object detection model, ultrasonic sensors for fill monitoring, GPS for location tracking, LoRa communication for data transmission, and an RFID module for personnel identification to optimize smart waste management. The system faces limitations in handling real- time updates on waste levels and dynamic conditions such as traffic congestion. Future improvements could integrate more adaptive IoT features, enabling real-time waste management and dynamic route adjustments for enhanced efficiency.

Md. Shahariar Nafiz (2023) [6] introduced hierarchical deep learning approach combining Faster R-CNN for high- resolution object detection and classification of waste in food trays, along with the creation and release of a new dataset, Labelled Waste in the Wild, for further research and benchmarking. The system may struggle to classify waste effectively in real-world scenarios with varying lighting conditions or cluttered waste. Future improvements could focus on enhancing the model's robustness under such challenging conditions to ensure reliable waste sorting in diverse environments.

Surya Sahoo et al. (2003) [7] developed a route management system that took into account waste management concerns related to route for efficient waste collection. This system reduced operational cost and provided better customer services. By the end of 2003, the system had eliminated 984 routes, resulting in cost savings around \$18 and projected savings of \$44 million in 2004. Future enhancements could focus on expanding the system to different areas adding extra features to enhance the system.

M.A. Hannan et al. (2023) [8] introduces a route optimization model that reduces cost, labor and also environmental effects. This study utilizes particle swarm algorithm in a capacitated vehicle-routing problem (CVRP) model. Results showed that VRO improved waste collection efficiency by 26.08% at a 70% fill level, while achieving 44% cost savings and 17.6% carbon emission reduction. Future improvements could focus on including real-time data integration and enhancing model performance and making it adaptable to different urban environments

Alice B. P. Santos Neto et al. (2023) [9] conducted a study on municipal solid waste collection system. The analysis was done by studying 12 publications aiming to optimizing routes for transporting waste from collection points to the final destination with the goal of reducing the cost. The results showed that the current studies only consider to reduce travel distances and lack other factors such as environmental impact perspective, and others focus on use of GI, sensors and smart bins to optimize waste collection. Future research should focus on expanding route optimization criteria to include more on sustainable environmental impacts through it.

III.PROBLEM STATEMENT

As the urban population is increasing, the amount of waste being generated has increased significantly. Inadequate waste management have led to multiple issues such as severe environmental impacts, public health issues and contamination of both soil and water. To overcome these challenges, proper waste management is necessary to bring a positive impact. Waste collection is one of the difficult problems faced by authorities in the cities. The current system relies on fixed schedules, causing high fuel consumption and operational costs.

To address this issue, we have implemented a system that solves the route optimization problem. It uses a machine learning model to predict waste volume. The predictions along with distance matrix are used to get the optimal route. This helps in reducing fuel consumption and operational costs. A web-based application real time is also integrated to provide updates to the residents on collection schedules etc. and increase community engagement.

IV.METHODOLOGY

The proposed system involves two methods. The first method is to compare various machine learning models based on the historical dataset and performance parameters such as MSE and R^2 score etc. The model which performed best with higher accuracy was selected to predict daily waste generated at each and every collection point. The second method is the route optimization, where predicted waste volume is used to prioritize households based on the waste generated and are arranged in descending order while considering truck's capacity. It utilizes the Nearest Neighbour Algorithm to solve the Traveling Salesman Problem i.e. to find the shortest path based on distances between each household and the depot. Based on this, the optimal route is generated, and the truck starts collection process. Additionally, a web- based application is developed for real time updating to the residents including collection schedules, SMS alerts and features to report issues.

A. Data Analysis

For this study, a publicly available dataset was collected from an open - source Indian government website, which had waste quantity and related parameters of around 100 houses in the city of Pune was used. The dataset included the waste quantity, house ID's, neighborhood details, weather conditions, holiday indicators, daily waste accumulation and distances between each house to the depot.

Pre-processing was done to improve data quality by handling missing values, encoding and normalization of variables. Also, a distance matrix was computed based on the distances between different houses to the depot for proper route planning.

Lastly, the whole dataset was split randomly for training and testing. The training dataset included 70% of the data and other 30% was assigned for testing.

B. Machine Learning Model

Sustainable resource management and waste collection route optimization depend upon accurate waste generation forecasting. To find a suitable method for getting the quantity of waste generated daily, a number of machine learning models were evaluated. We assessed these models using key performance metrics such as F1 Score, R2 Score, Mean Absolute Error (MAE), and Mean Squared Error (MSE), Accuracy. The comparison's findings were used to select the model that minimizes errors while delivering best accurate result.

The following models were assessed for waste volume prediction: Random Forest, K-Nearest Neighbors (KNN), Support Vector Regression (SVR), and Decision Tree. Among them, Random Forest scored the best, with the lowest prediction errors with an MAE of 1.6222 and an MSE of 4.1095. While Random Forest performed better and had less errors, KNN performed poorly. It is the best choice for waste prediction because of its accuracy and also consistently outperformed those of SVR and Decision Tree.

Random Forest's results has ability to handle complex data relationships and non-linear patterns. Since waste output is determined by various factors, including household location, population density, weather, and past garbage disposal habits, Random Forest results are more accurate. By using several decision trees, Random Forest reduces bias and variance and ensures the best results in a range of circumstances, unlike other models that could perform badly or overfit when dealing with diverse data distributions. Figure 4.1. illustrates the stepwise process for evaluating machine learning models in waste volume prediction.

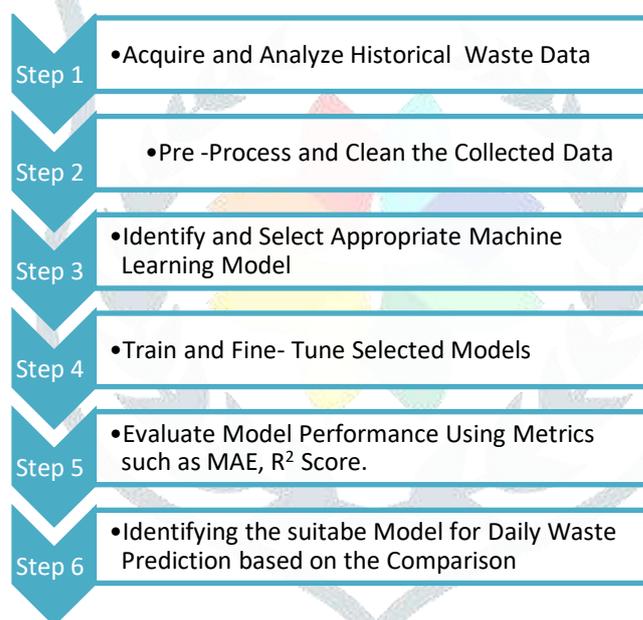


Figure 4.1: Sequential Steps for Waste Prediction Model Selection and Evaluation

C. Route Optimization

The suggested system maximizes waste collection by reducing travel distances without compromising on efficiency, especially for high-waste-generating households. Initially it prioritizes target households based on estimated waste accumulation and ranks them in a decreasing order of waste generation. Based on both the predicted waste and the distances between each household and the depot, households are added to the route iteratively while ensuring that the total waste load stays within the truck's capacity limits. The prioritization strategy ensures that the highest waste-generating households are targeted achieving both efficiency and complete utilization of resources . To address the routing complexity the system models the Traveling Salesman Problem (TSP) as it involves identifying the shortest path required to visit a specified set of locations only once before returning to the starting point. The Nearest-Neighbour Routing Algorithm is utilized as a workable optimization algorithm. This algorithm begins the route at a specified depot and, iteratively, chooses the nearest unvisited household such that the aggregate waste load is within the truck capacity limits. This strategy minimizing unnecessary travel efficiently and maximizes operational efficiency. Figure 4.2. represents the flowchart of the proposed waste collection process, highlighting key stages from data gathering to the final optimized.

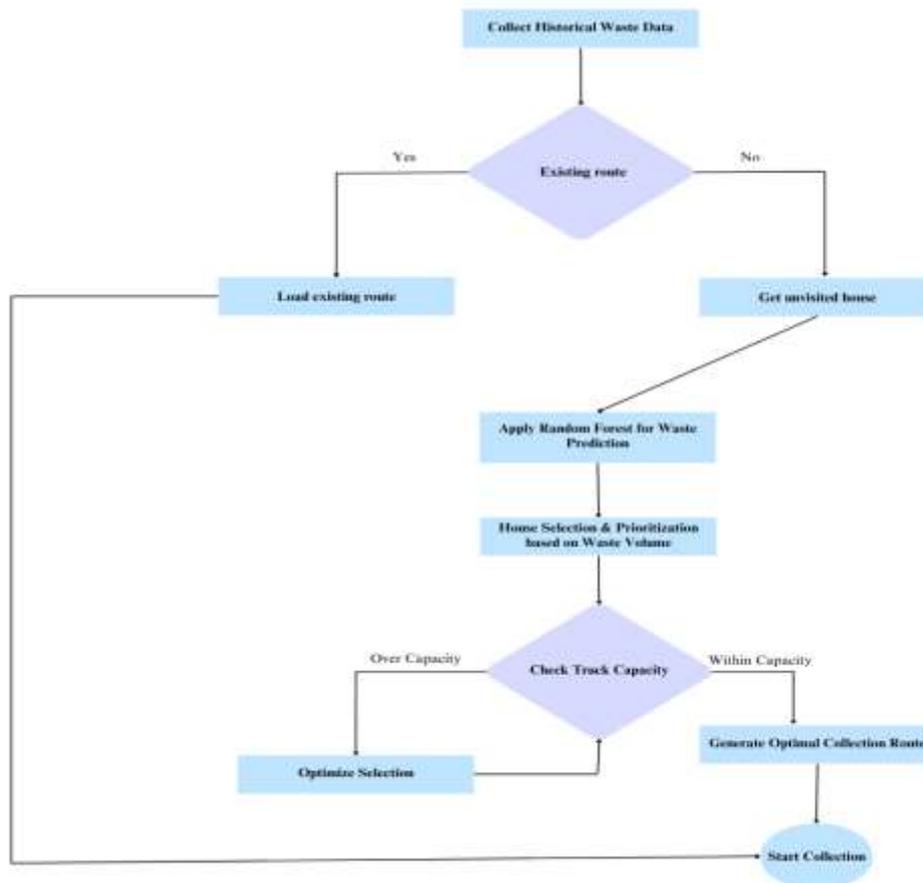


Figure 4.2: Route Optimization Flowchart

D. Web Application

A web-based system was created to increase the user participation. This system consists of numerous features, such as interactive dashboards, automated notifications, and continuous monitoring, are combined in this system to ensure that local authorities and residents have access to the waste collection information.

The web application uses machine learning algorithms for garbage prediction and route optimization makes the online application crucial to speeding up the trash management process. To manage vast volumes information about number of houses, waste production patterns, and most efficient waste collection routes. Managing all this data requires a strong database management system is necessary. SQLite was selected as the main database because of its lightweight design and easy for integration and data processing. The database maintains information such as household details, historical details, past collection records. The system dynamically updates the last visited timestamps and history of visitations of the houses. An organized database structure enables fast data retrieval and also facilitates communication between web and backend services.

Fast-API was selected because of its scalability, high performance in handling real time data and also provides smooth communication between database, machine learning models, and also web interface. The Waste prediction API utilizes a trained Random Forest model to estimate household waste volumes. On the other hand Route Optimization API minimizes fuel consumption and travel distance by calculating the efficient collection routes. The Visit Tracking API updates collection statuses and maintains the past collection records. To ensure secure safe data transfer, and smooth backend web integration, Cross-Origin Resource Sharing (CROS) has been enabled.

The web application mainly has two interface one is for user and other for admin. So it provides an benefits for both the parties. Also, Twilio integration enables automated SMS reminders, while query management allows resident to report the issues.

V. BLOCK DIAGRAM

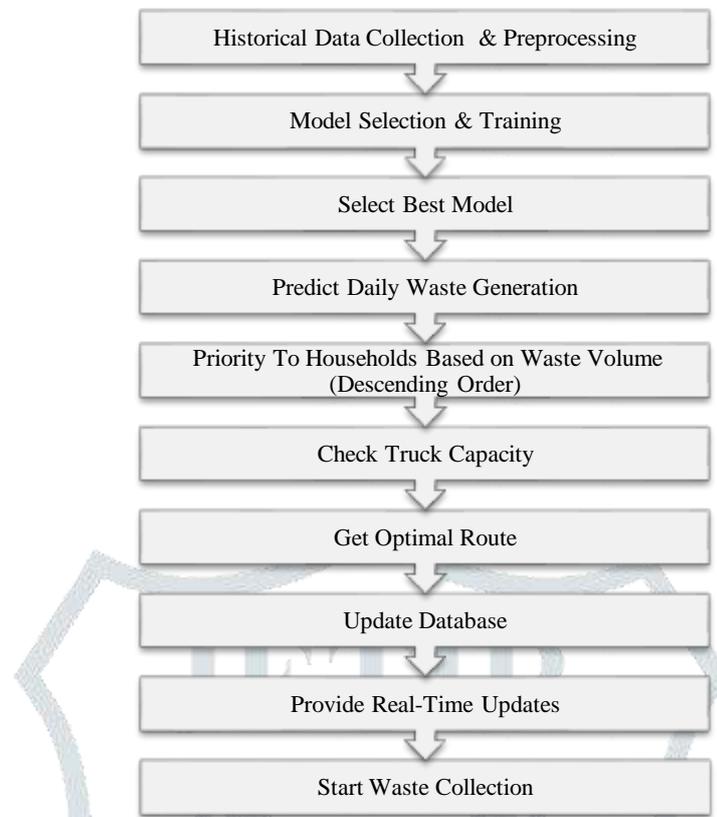


Figure 5.1: Block Diagram

The Figure 5.1. shows block diagram of waste collection process. Firstly, it involves collection of dataset and preprocessing, which includes cleaning and improving the quality of the dataset. Next the dataset is randomly split into training and testing. Various machine learning models suitable for this are selected and evaluated based on performance metrics. The model that performed well with good accuracy and less errors is selected. The selected model is then used to predict the daily waste generated in each household. Based on this, the houses are prioritized in descending order. The truck's capacity is also checked to prevent overloading. If the waste volume exceeds the truck's capacity limit, adjustments are made by removing the selected houses. After this, the optimal routes for collection are generated and updates are given to the residents through the website. Finally, the truck is sent for collection.

VI. RESULTS

This section shows the result for the route optimization problem. Firstly, various machine learning models were chosen and their performance was evaluated and the model outperformed was used for daily waste volume prediction. Second, optimization of existing routes to reduce the travel distance and fuel consumption. Finally, the system's user engagement through a web-based application is assessed.

A. Comparison Of Various Machine Learning Model

The main tools for assessing the performance of the machine learning models in the waste volume prediction problem include Mean Absolute Error (MAE), and R^2 Score, which are used below to present the results for the evaluated models. However, it is also useful to consider additional performance metrics for a more comprehensive comparison. Since waste generation patterns vary across different households, relying solely on accuracy may not fully represent the model's predictive performance. Therefore, the following additional performance metrics are considered:

- Mean Squared Error
- Accuracy
- F1 Score

1. Mean Absolute Error (MAE) and Mean Squared Error (MSE):

Table I: Mean Absolute Error (MAE) and Mean Squared Error (MSE) of the four Models.

Models	Mean Absolute Error (MAE)	Mean Square Error (MSE)
Decision Tree	2.336760	8.524010
Support Vector Regression (SVR)	2.053695	6.646207
KNN	1.912020	5.760314
Random Forest	1.622762	4.109545

Initially, these were considered as the primary evaluation metrics to identify which model produced the most errors in waste volume prediction.

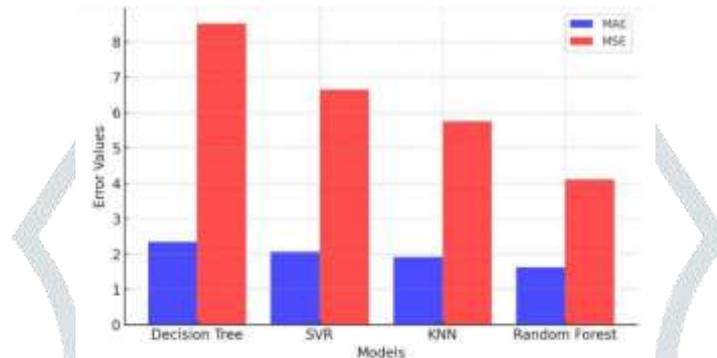


Figure 6.1: Performance Comparison of Machine Learning Models for Waste Prediction

The above Figure 6.1. compares the Mean Absolute Error (MAE) and Mean Squared Error (MSE) for different machine learning models. Among all the models, the Decision Tree recorded the highest error values, with an MAE of 2.3367 and an MSE of 8.5240, indicating poor performance, whereas the Random Forest model outperformed all others with lowest MAE of 1.6228 and an MSE of 4.1095, making it the most preferred model for waste prediction.

2. R² Score, F1 Score and Accuracy:

Followed by the initial error analysis, R² Score, F1 Score, and Accuracy were analysed to assess the overall performance of the machine learning models in waste prediction. The table II presents numerical values for the key performance metrics of each model.

Table II: Tabular representation of model performance metrics, including R² Score, Accuracy, and F1 Score.

Models	R2 Score	Accuracy	F1 Score
Decision Tree	0.296155	0.638630	0.642243
Support Vector Regression (SVR)	0.452890	0.749452	0.671677
KNN	0.525816	0.741507	0.704846
Random Forest	0.620613	0.765890	0.726973

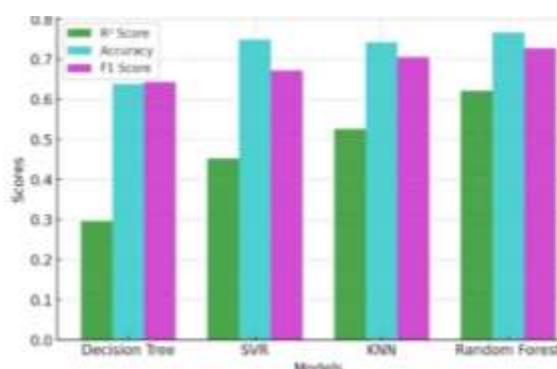


Figure 6.2: Performance evaluation of different machine learning models using R² Score, Accuracy, and F1 Score.

Based on Figure 6.2. the Random Forest model delivered the best results, achieving the highest R² Score of 0.6206, Accuracy of 76.59%, and an F1 Score of 0.7269, making it most reliable model for waste prediction.

B. Route Optimization

Since a higher R² Score indicates that the model better understands and predicts how different factors affect waste generation, and a lower Mean Absolute Error (MAE) signifies more accurate predictions with fewer errors, these metrics were the primary performance indicators used to determine the best model. Based on these evaluations, the Random Forest model outperformed all others, making it most suitable choice for predicting waste volume and aiding in efficient route optimization.

C. Website Integration

The web-based system provides separate user and admin interfaces, making it convenient for both parties. Each interface includes different navigation panel.

1. User Interface:

The user section consists of the website features two navigation panels.

The first panel provides general information about waste management practices to encourage user participation, as shown in Figure 6.3. The second panel focuses on user-specific functionalities, allowing residents to check house visit information by selecting their house number and raising queries related to waste collection, as shown in Figure 6.4.

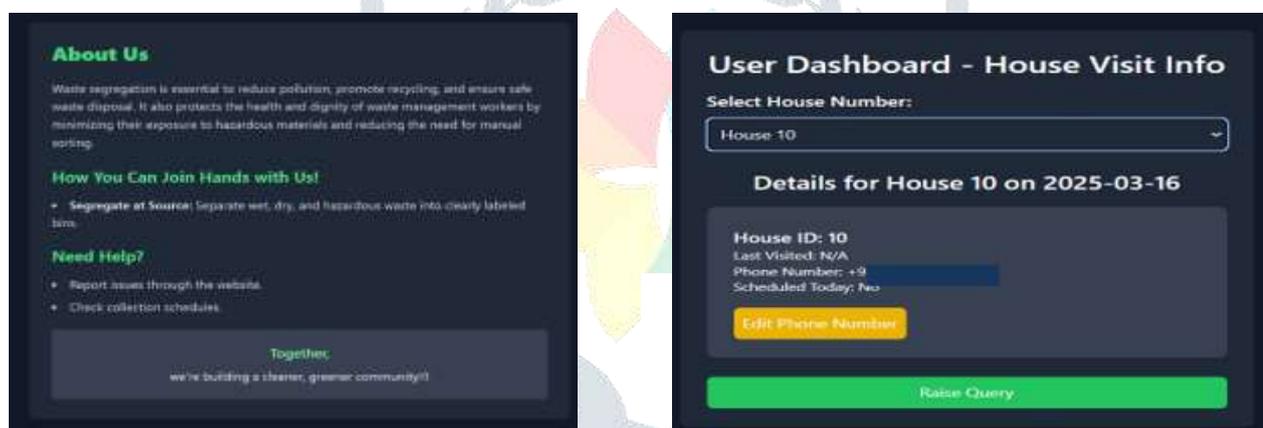


Figure 6.3: Waste Management Awareness Panel

2. Admin Interface:

The admin section consists of four navigation panels.

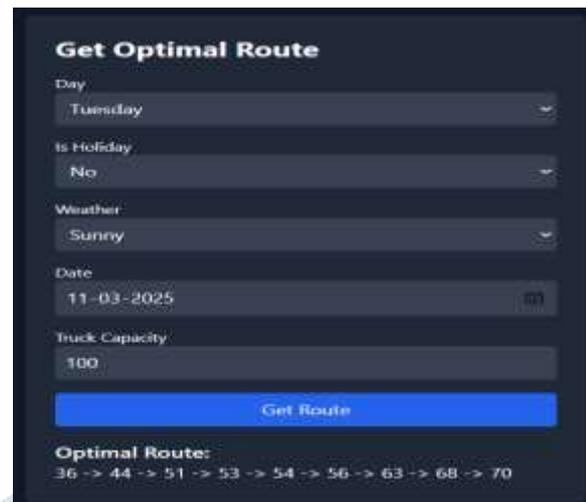


Figure 6.5: Waste Management Dashboard – House Visit Scheduling

Figure 6.6: Optimal Route Generation.

The first panel is waste management dashboard which allows administrators to enter a date, generating a list of houses scheduled for waste collection on that day, along with their expected visit times and contact details, while also providing an option to send SMS notification to residents for better coordination, as shown in Figure 6.5.

The second panel is the Optimal Route section which helps to determine the best waste collection route based on selected conditions. Users can input the day, holiday status, weather, date, and truck capacity. After clicking "Get Route," the system generates an optimized route for waste collection. The displayed route lists the sequence of house IDs for efficient collection, as shown in Figure 6.6.

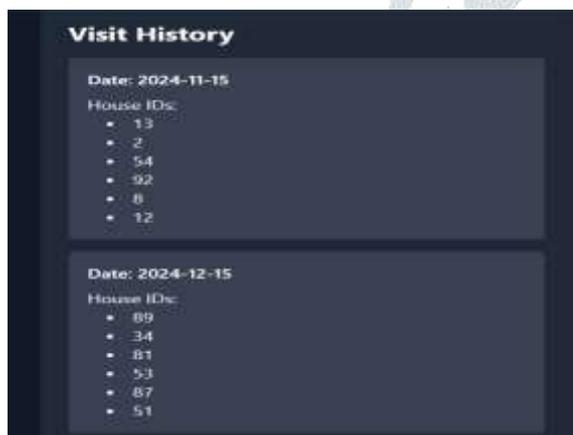


Figure 6.7: Visit History

Figure 6.8: Query Management System

The third panel is the Visit History which provides a record of past waste collection activities. It lists multiple entries, each corresponding to a specific date. Under each date, the House IDs indicate which households were serviced on that day, as shown in Figure 6.7. The fourth panel is the Query Management section which records user complaints related to waste collection. It includes details like House ID, phone number, query description, status, and creation time, as shown in Figure 6.8.

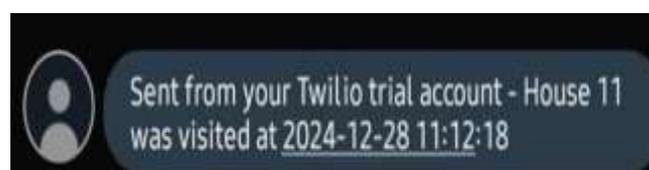


Figure 6.9: SMS Notification for House Visit Confirmation

A confirmation message is sent to the phone via Twilio, stating the house number and the exact timestamp of the visit, ensuring clear and timely communication, as shown in Figure 6.9.

VII.CONCLUSION

The system represents a prime instance how machine learning approaches and route optimization could potentially improve urban waste aggregation process. Through the use of these comprehensive methods, the system overcomes the inadequacies in Traditional approaches for managing waste. By comparing various predictive models, Random Forest appeared to be the most reliable based on the historical data and performance metrics. The findings were incorporated into a route optimization model utilizing Traveling Salesman Problem (TSP) and Nearest Neighbor Algorithm to determine the shortest and most efficient routes for waste collection. Additionally, integration of user-friendly application enhanced community participation and sustainable practices among residents. The result illustrates how efficient routing combined with machine learning effectively improves waste collection operations, resulting in lower fuel consumption and a positive environmental impact. This approach enables cities to make smarter decisions and utilize resources effectively for better waste management practices.

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