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Developing an Effcient Framework and Mathematical Modelling for Municipal Solid Waste Management in India

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Abstract: An increase in municipal waste has become one of the biggest problems today. Managing waste is a big challenge for every country. Municipal waste management includes transportation and recycling of waste, which needs huge funds. Moreover, significant carbon emissions occur while transporting garbage from one site to another. Thus, this study focuses on reducing the cost due to municipal solid waste (MSW) transportation. The research aims to develop a mathematical model of the supply chain of MSW management. The process of segregation and recycling is also considered in this study. We consider six Indian states and identify the dumping location of the garbage. The study proposes an efficient framework for selecting the segregation hub location and location of MSW treatment plants. The outcomes would be beneficial to achieve an efficient waste management strategy with reduced cost. The numerical simulation results of the model provides the minimum transportation cost as Rs. 4.92×10^6 according to the locations selected for the study. The final strategic decisions is feasible under the constraint sets considered in the model.

***Keywords*:** municipal solid waste management, segregation process, cost optimization, mixed integer linear programming problem

Notations

q_{ij}	amount of garbage to be transported from i^{th} location to j^{th} segregation hub.
s_{ij}	amount of recyclable waste to be transported from i^{th} segregation hub to j^{th} treatment plant.
r_i	the amount of non-recyclable waste at segregation hub i.

Binary

x_i	1 or 0 based on the i^{th} segregation hub is open or closed, respectively.
z_i	1 or 0 based on the i^{th} treatment plant is open or closed, respectively.

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Parameters

C_{ij} cost of transportation per unit from i^{th} dumping ground to j^{th} segregation hub.
R_i segregation cost per unit at segregation hub i.
c'_{ij} cost of transportation per unit from i^{th} segregation hub to j^{th} treatment plant.
w_i capacity of i^{th} segregation hub.
w'_i capacity of i^{th} treatment plant.
D_i minimum amount of waste required for plant i to be operational.
A_i the minimum amount of estimated non-recyclable waste which can be generated from each segregation hub i.
F_i fixed cost of opening and maintaining i^{th} segregation hub.
F'_i fixed cost of opening and maintaining i^{th} treatment plant.

1. Introduction

Waste generation is rapidly growing in developing countries like India due to the continuous growth in industrialization, urbanization, and pollution. Lapse in the management of municipal solid waste (MSW) not only has effects on the environment only it's also causing some serious issues for humans and it also raises some other socio-economic issues that are important to discuss [1]. It means it is essential to magnify the processes of waste collection, segregation, and safe disposal. The process of Waste to Energy (WTE) by using technologies such as pyrolysis, gasification, and bio methanation can convert MSW to an appropriate source of renewable energy (electricity) [2].

1.1 *Municipal solid waste in India*

In India, the amount of waste produced is huge. According to the current data India produces about 42 million tons of municipal solid waste annually i.e., 1.15 lakhs metric tons per day (TPD) [3-4]. According to the study by the Planning Committee, 'Task Force on Waste to Energy' India would generate 450,132 TPD by the end of 2031 and 1,195,000 TPD by the end of 2050. TPD. The generation of per capita waste in India is about 670 grams per day which are increasing by 1.3 percent annually. As per the statistical data, Maharashtra is the state which produces the maximum waste i.e. 22,945.30 (MT) per year and Sikkim produces the least i.e. 74.70 (MT) per year [5]. Among the union territory, Delhi produced the maximum waste i.e. 10,470.60 (MT) per year and Lakshaadweep produces the minimum which is 32.6 (MT) per year [6]. Figure 1 represents the MSW generation from different states of India in 2021.

1.2 *Types of municipal solid waste*

MSW is divided into 3 categories that are (a) Biodegradable and organic waste which are capable of undergoing anaerobic or aerobic decomposition such as human waste, food waste, and paper waste. (b) Non-biodegradable and inert waste, cannot be broken down naturally but could be made degradable through some biological actions of microorganisms [7]. (c) recyclable and demountable waste which can be separated from the waste stream, and set aside for the purposes of recycling such as plastic bottles and containers [8].

According to the Central Pollution Control Board (CPCB) of India annual report of 2018-2019, MSW constitutes 50% of biodegradable waste, 20% of organic matter, and 30% of inorganic matter [9]. Over the years the proportion of recyclable waste has risen by 17%. According to data from some municipalities the amount of biologically degradable waste ranges from 55 to 60% each year. The rapidly increasing amount of plastic waste is very dangerous, and it is directly significant to the environment [10]. According to the CPCB in India, the generation of plastic waste is 25,940 tons per day (TOD), or 3.46 million tons per year. To deal with this problem, a severe prohibition on the entry of plastic trash into India is ordered by the National Green Tribunal (NGT) since it is harmful to the environment [11].

1.3 *Segregation process of MSW in India*

There is currently no coordinated and well-planned procedure available in India for segregating waste, whether it is domestic or community-related. It is mostly carried out by an unorganized sector and sporadically by garbage producers [12]. Segregation and sorting operations typically take place under unsafe, unfavorable, and inefficient settings [13]. Waste collection, storage, and transport are essential components of every solid waste management (SWM) system, but cities face difficulties in this area. Municipalities in India are required to collect waste, and they are frequently given bins to distinguish between biodegradable and inert waste [14]. They are routinely jumbled, spilled, and publicly burned despite these measures [15]. More job possibilities, advancements in public health, and an increase in tourism will result from changes to waste management collection procedures and the Indian transportation system [16].

1.4 *Reuse, recycle, and treatment of MSW*

Recycling is the practice of removing items from garbage and used to make new products. Non-segregated waste is simultaneously disposed of in public trash cans, where recycling is unlikely. According to United Nations Environment Program (UNEP), 2004, composting is reportedly one of the acceptable treatments used in underdeveloped Asian nations [17]. Composting is performed to recycle approximately 10% to 12% of the waste materials time in India, whereas, less than 10% waste is processed by using this technique in other South Asian countries. The last stages of SWM in Southeast Asian emerging nations are frequently open dumping and landfills [13]. Around 50% of the waste is dumped openly, whereas 10-30% is dumped in landfills, less than 15% is composted, and 2-5% was burned [18].

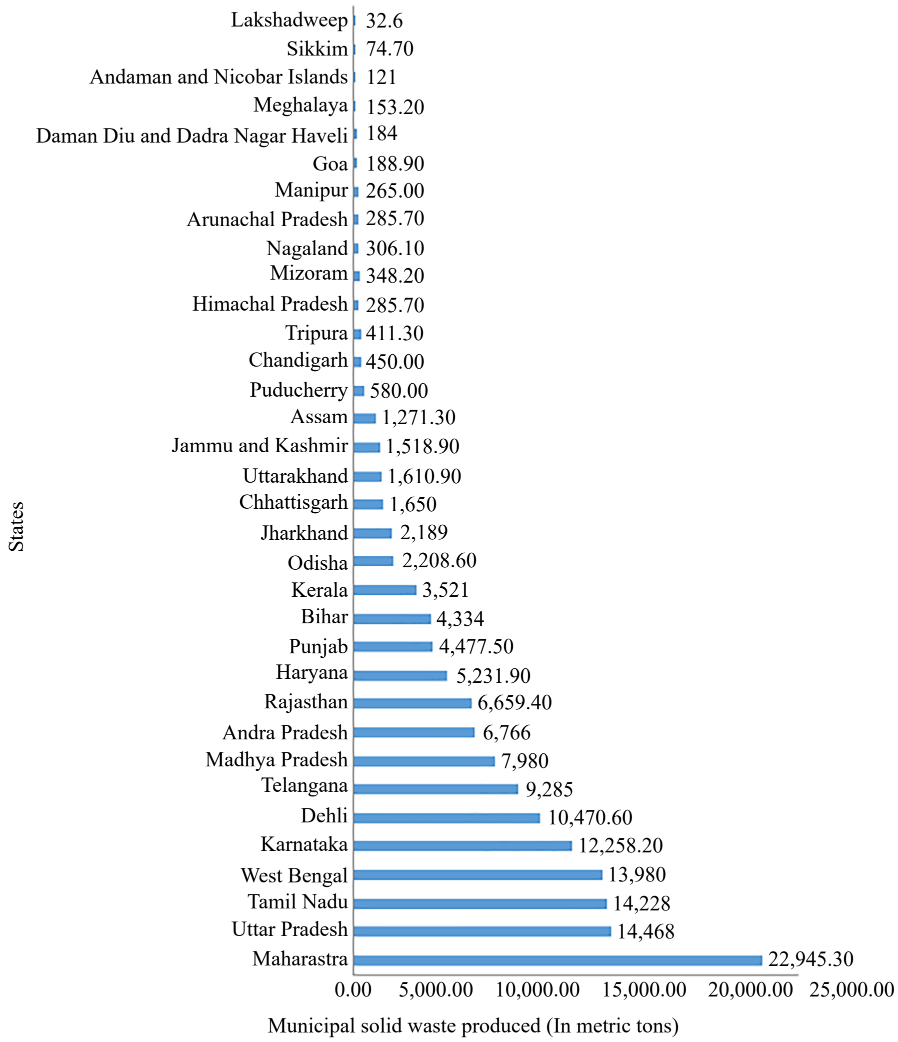

Figure 1. MSW generation in India in 2021 (statewise)

1.5 *Contribution and research gap*

In this section the contribution of this research with proper gaps is illustrated with some points. The points are given below.

- There is a few researches conducted on the MSW management in India. Some studies exist in the literature but, a proper framework and strategic decision-making is missing. This study fulfills this gap by introducing a structured strategic framework for a suitable MSW management system.
- This study proposed the dedicated segregation hubs for every dumping locations to manage the recyclable and non-recyclable waste properly as an unique approach. This consideration was not assumed in any existing literature.
- The locations (Gujarat, Rajasthan, Bihar, Uttar Pradesh, Maharashtra, and Karnataka) used in this study are unique and were not utilized in any other existing literature.

2. Proposed framework and model formulation

We propose a model for municipal waste management and reducing transportation costs in India. There are 29 states in each state there are many dumping yards but there is no proper segregation center for waste management. Therefore, we propose a model in which the process of selecting the location of the segregation hub is shown which can minimize the garbage transportation cost. Moreover, the recyclable items are collected and shifted to garbage recycling plants. We divide this process into 3 stages that are (i) Collection of waste from the dumping yard (ii) Segregation of recyclable and non-recyclable waste collected from the dumping yard (iii) Shifting of segregated waste to diffierent treatment plants.

In our proposed framework, a set of locations is considered in which many garbage dumping yards may be located. The location can be considered as a state or combination of two or more states in India based on the amount of garbage generated from that state. If the amount of MSW is huge, then a single state can be considered one location otherwise two or more states can be considered as a single location. Each state would be assigned to a segregation hub. The hub is selected in such a way that the minimum distance should be covered from the location to the hub. The segregation hub is dedicated to separating recyclable and non-recyclable items. In the next step, the recyclable items would be sent to treatment plants throughout the country.

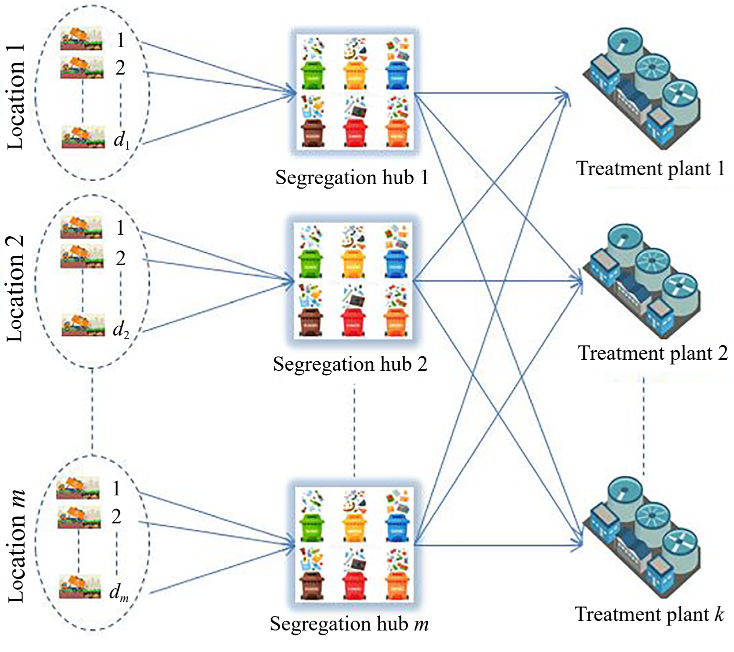

Figure 2. Proposed framework for MSW management

The detailed graphics of our proposed model is described is Figure 2. According to 2, in the rirst stage, mnumber of dumping zone/location is considered. Every dumping zone/location contains d_i number of small dumping yard ($i = 1, 2, ..., m$). In detail, location 1 has in total d_1 number of small dumping yard. Similarly, location 2 has d_2 number of small dumping yard and so on. Every location is assigned with a dedicated segregation hub which implies location 1 is assigned to segregation hub 1 and so on. In the second stage, the garbage from each location must be transported to the assigned segregation hub which is solely dedicated to that location. Thus, the waste excavated from location 1 cannot be shifted to any other segregation hub other than segregation hub 1 and similarly, waste from location 2 and 3 will only be transported to segregation hub 2 and 3, respectively. In the third stage, waste materials are segregated for recyclable and non-recyclable waste in the segregation hubs. In the fourth stage, only recyclable items are transported from segregation hub to treatment plants. In this scenario, i^{th} segregation hub ($i = 1, 2, ..., m$) can be assigned to any one of the j^{th} treatment plant ($j = 1, 2, ..., k$). An important observation is that not necessarily all hubs has to assigned to all plants. Some hubs and plants may be closed also in order to reduce the total cost.

We consider there are m locations each having a diffierent number of dumping grounds. Each location is assigned to one dedicated segregation hub. The garbage at each location should only be transported to the preassigned segregation hub. Thus, the total cost of transportation from the dumping zones to the segregation hubs is shown in equation 1.

$$TC_1 = \sum_{i=1}^{d_1} C_{i1} q_{i1} + \sum_{i=1}^{d_2} C_{i2} q_{i2} + \ldots + \sum_{i=1}^{d_m} C_{im} q_{im} \tag{1}$$

Each segregation hub separates the recyclable and the non-recyclable items from the waste materials. The total cost of segregation is shown in 2.

$$TC_2 = \left(R_1 \sum_{i=1}^{d_1} q_{i1} + R_2 \sum_{i=1}^{d_2} q_{i2} + \ldots + R_m \sum_{i=1}^{d_m} q_{im} \right) - \sum_{i=1}^{m} R_i r_i \tag{2}$$

The recyclable items should be transported to the treatment plants at various places. The total cost of transportation from the segregation hubs to the treatment plants is shown in 3.

$$TC_3 = \sum_{i=1}^{m} \sum_{j=1}^{t} c'_{ij} s_{ij} \tag{3}$$

Additionally, a fixed fee should be incurred to open and maintain the segregation hubs and treatment plants. The cost of which would be evaluated as $\sum_{i=1}^{m} F_i x_i$ and $\sum_{i=1}^{t} F'_i z_i$. Terefore, the combined total cost for transportation and segregation of the entire system is given by equation 4.

$$\begin{aligned} TC_{tot} = {} & \sum_{i=1}^{d_1} C_{i1} q_{i1} + \sum_{i=1}^{d_2} C_{i2} q_{i2} + \ldots + \sum_{i=1}^{d_m} C_{im} q_{im} + \left(R_1 \sum_{i=1}^{d_1} q_{i1} + R_2 \sum_{i=1}^{d_2} q_{i2} + \ldots + R_m \sum_{i=1}^{d_m} q_{im} \right) \\ & - \sum_{i=1}^{m} R_i r_i + \sum_{i=1}^{m} \sum_{j=1}^{k} c'_{ij} s_{ij} + \sum_{i=1}^{m} F_i x_i + \sum_{i=1}^{k} F'_i z_i . \end{aligned} \tag{4}$$

The objective is to find the minimum cost of equation 4 under the following set of constraints.

Constraint set 1:

$$\sum_{i=1}^{d_j} q_{ij} \le w_j x_j ; j = 1,\ 2,\ \ldots,\ m \tag{5}$$

Constraint set 2:

$$\sum_{i=1}^{m} s_{ij} \le w'_j z_j ; j = 1,\ 2,\ \ldots,\ k \tag{6}$$

Constraint set 3:

$$\sum_{j=1}^{k} s_{ij} = \sum_{j=1}^{d_m} q_{ji} - r_i;\ i = 1,\ 2,\ \ldots,\ m \tag{7}$$

Constraint set 4:

$$\sum_{j=1}^{k} s_{ij} \geq D_i;\ i = 1,\ 2,\ \ldots,\ k \tag{8}$$

Constraint set 5:

$$\sum_{j=1}^{d_m} q_{ji} > r_i;\ i = 1,\ 2,\ \ldots,\ m \tag{9}$$

Constraint set 6:

$$r_i > A_i;\ i = 1, 2, \ldots, m \tag{10}$$

$$q_{ij}, s_{ij}, r_i \geq 0, x_j, z_j \in \{0, 1\}.$$

2.1 *Discussion on constraints*

Constraint set 1 are designed for capacity constraints which indicate that the quantity of waste materials transported from each location must be less that or equal to the capacity of the segregation hub dedicated to that location only. In this regard, this must be observed that the number of location and number of segregation hubs must be equal. The term $\sum_{i=1}^{d_j} q_{ij}$ defines the total amount of waste to be transported, generated from each small dumping site of the j^{th} location. Constraint set 2 defines the capacity of each treatment plant. The amount of waste transported to j^{th} plant from all the segregation hubs, must be less or equal to the capacity of that plant. Constraint set 3 implies that the amount which is to be transported to the plants from i^{th} segregation hub, must be equal to the recyclable amount left in that hub. Constraint set 4 defines the minimum requirement of waste materials of each treatment plant to open and run the factory properly. Constraint set 5 illustrates that the total amount of waste generated in each location must be greater than the non-recyclable amount of waste segregated from that location. Constraint set 6 states that 100% waste which is to be transported from each location to its dedicated segregation hub, cannot be recycled. There must always be some amount of non-recyclable waste.

3. A case study with 6 Indian states

We consider 6 Indian states namely, Maharashtra, Karnataka, Rajasthan, Gujarat, Bihar, and Uttar Pradesh. We merge 2 states to form one location, displayed in Table 1. In Figure 3, all selected dumping zones, proposed segregation hubs, and treatment plants are shown. We propose 3 segregation hubs in 3 different states such as Sangli, Maharashtra; Dungarpur, Rajasthan; and Ghazipur, Uttar Pradesh. These locations are selected based on the availability of empty land. Sangli is dedicated to the states of Maharashtra and Karnataka. Dungarpur is selected for the state of Rajasthan, and Gujarat. Ghazipur is dedicated to Bihar and Uttar Pradesh. We selected 3 treatment plants namely, Chandrapur Super Thermal Power Station, Maharashtra, Kota Thermal Power Plant, Rajasthan, and Kahalgaon Super Thermal Power Station (KHSTPP), Bihar.

Table 1. Location details

Location	1	Maharashtra Karnataka
Location	2	Rajasthan Gujarat
Location	3	Bihar Uttar Pradesh

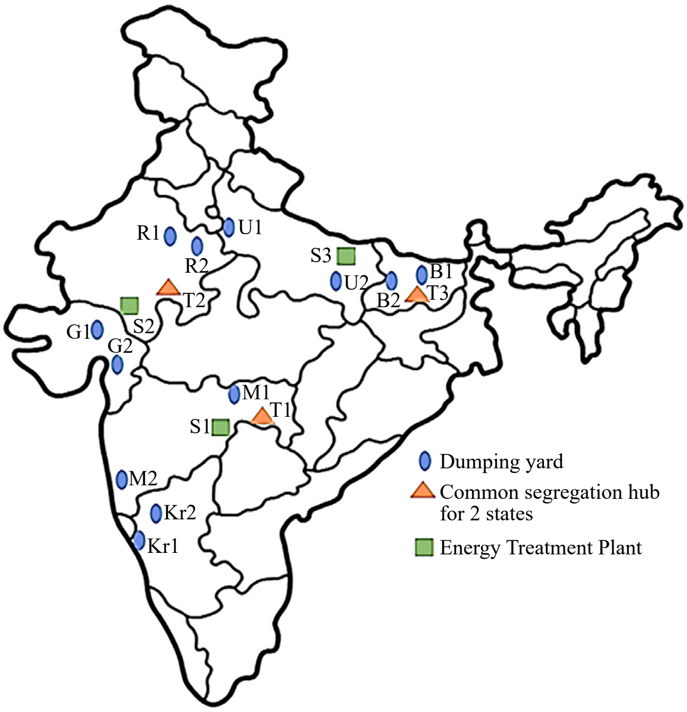

Figure 3. Locations of dumping yards, proposed segregation hubs, and treatment plants (M1 = Dumping yard, Bhandewadi, Maharashtra; M2 = Dumping yard Chiplun, Maharashtra; Kr1 = CMC dumping yard, Shirwada, Karnataka; Kr2 = Town Municipal Corporation Garbage dumping yard, Badami, Karnataka; R1 = Waste Dumping Ground Jaipur, Rajasthan; R2 = Alwar garbage dumping yard, Rajasthan; G1 = AMC Dumping yard, Ahmedabad, Gujarat; G2 = Garbage Dumping ground, Vadodara, Gujarat; B1 = Dumping yard Nagar Munger, Bihar; B2 = Solid waste disposal yard Khusrupur, Bihar; U1 = Dumping ground Kakod, Uttar Pradesh; U2 = Govt authorized dumping site, Varanasi, Uttar Pradesh; T1 = Sangli, Maharashtra; T2 = Dungarpur, Rajasthan; T3 = Ghazipur, Uttar Pradesh; S1 = Chandrapur Super Thermal Power Station, Maharashtra; S2 = Kota Thermal Power Plant, Rajasthan; S3 = Kahalgaon Super Thermal Power Station (KHSTPP), Bihar)

3.1 *Numerical simulation*

The optimization model is a mixed integer linear programming problem. We assign T1 for M1, M2, Kr1, and Kr2. T2 is assigned for R1, R2, G1, and G2. T3 is dedicated for U1, U2, B1, and B2. The data set for the transportation costs between the dumping sites and segregation hubs are shown in Table 2. Each cost is calculated in Indian rupee. The notations for dumping yards, segregation hubs, and treatment plants are described in Figure 3. Table 2 illustrates the transportation cost from each small dumping site of a particular location to the dedicated segregation hub for that location. The capacity of the segregation hubs T1, T2, and T3 are 1,000 Mt, 2,000 Mt, and 1,500 Mt, respectively. In the similar manner, the maximum treatment capacity of the treatment plants S1, S2, and S3 are 9,000 Mt, 800 Mt, and 900 Mt, respectively. The lower limits of non-recyclable waste are assigned as 10 Mt, 12 Mt, and 14 Mt, respectively for S1, S2, and S3. The transportation costs between segregation hubs and treatment plants are given in Table 3. The optimal results are obtained by using Matlab 2014a.

Table 2. Transportation costs between dumping sites and segregation hubs in Indian rupee

	M1	M2	Kr1	Kr2	R1	R2	G1	G2	U1	U2	B1	B2
T1	11,519	2,158	4,661	2,489	-	-	-	-	-	-	-	-
T2	-	-	-	-	6,516	8,426	2,291	2,932	-	-	-	-
T3	-	-	-	-	-	-	-	-	5,016	2,683	10,771	949

Table 3. Transportation costs between segregation hubs and treatment plants (in Indian rupee)

	S1	S2	S3
T1	12,342	12,188	12,556
T2	15,451	5,033	12,662
T3	27,768	23,116	5,661

4. Discussion and concluding remarks

There is no proper waste management infrastructure available in India. India lacks a structured segregation process too to segregate the recyclable and non-recyclable waste. However, separate waste bins are installed in various places, but people are very less aware of this. In the current study, we developed a proper framework to manage waste from dumping to treatment. This research considers 6 Indian states and developed a strategy to build dedicated segregation hubs for each pair of states. Moreover, we identified suitable places to build the segregation hubs. The study reflected that dedicated segregation hubs can efficiently separate the recyclable and non-recyclable waste. The recyclable waste would be transported to the treatment plants. A mixed integer linear programming problem is developed to minimize the total transportation cost of the entire system.

The results of the numerical simulation are illustrated in Table 4 and 5. It is clearly observed that each segregation hub and each plant must be opened to be operational. To minimize the total cost, the following network design must be maintained. From location 1, only M2 should transport waste materials to T1 only with an amount of 10 Mt. From location 2, waste should be transported only between G1 and T2 with an amount of 212 Mt. Similarly, from location 3, only B2 should transport waste to plant T3 with an amount of 414 Mt. In addition to this, the optimal network between segregation hubs and the treatment plants are as follows. Only T2 an T3 shall transfer waste to S1, S2, an S3. In this regard, T2 should transfer only to S2 with an amount of 200 Mt whereas, T3 should transfer S1 and S3 with an amount of 100 Mt and 300 Mt, respectively. Moreover, the total cost is calculated as Rs. 4.92×10^6. This is also observed that the condition for feasibility is conserved by the outcomes of the model after the numerical simulation.

Table 4. Results for segregation hubs to plants (× represents no transportation takes place, the digit implies the amount of waste in metric ton (Mt) to be transported)

	S1	S2	S3
T1	×	×	×
T2	×	200	×
T3	100	×	300

Table 5. Results for locations to segregation hubs (× represents no transportation takes place, the digit implies the amount of waste in metric ton (Mt) to be transported)

		T1	T2	T3
Location 1	M1	×	×	×
	M2	10	×	×
	Kr1	×	×	×
	Kr1	×	×	×
Location 2	R1	×	×	×
	R2	×	×	×
	G1	×	212	×
	G2	×	×	×
Location 3	U1	×	×	×
	U2	×	×	×
	B1	×	×	×
	B2	×	×	414

The research can be extended by considering the types of treatment plants to treat a particular type of waste. As a significant amount waste is transported through different vehicle transportation, a huge amount of carbon emission occurs during this process. An effort must be incorporated to reduce the carbon footprint [19-20]. Furthermore, the use of artificial intelligence and autonomation technology can also be incorporated in the study [21-22]. Moreover, carbon emission through transportation can also be considered as future scope of research to extend this study [23-24].

Conflict of interest

The authors declare no competing financial interest.

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