Book Chapter

Analysis of Municipal Solid Waste Collection Methods Focusing on Zero-Waste Management Using an Analytical Hierarchy Process

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Abstract

The need to transition from a consumption-based waste hierarchy to a resource-conserving zero-waste management system for sustainable resource management has become unavoidable in today’s world. In this study, five different methods for waste separation at source were analyzed using an analytical hierarchy process based on five commonly used waste disposal methods. As a result of the analytical hierarchy analysis, ratios of 0.347, 0.286, 0.200, 0.101, and 0.066 were obtained for the five separation methods (0.347 for separation with six-parameter separate collection and 0.101 for mixed waste collection). The ratio of 0.286, achieved for the triple-separation method, was chosen to meet the requirements of the zero-waste regulation in Türkiye, and a district in Istanbul was selected as the study area. A model based on the residence density was developed. Within the scope of the model, the neighborhoods in the study area were statistically divided into three classes. By choosing one neighborhood from each class, route optimizations were made for both the existing routes and triple separations.

The Network Analyst function in ArcGIS was used to determine the optimal routes based on the traveling distances and operational times of vehicles associated with each route. The results of the route-based analyses show that carbon dioxide emissions will increase by only 1.15% compared to the current situation, but the total amount will decrease in the long term if all waste management processes are carried out within the scope of zero-waste management.

Keywords

Analytical Hierarchy Process; Exhaust Emission; Route Optimization; Separation At Source; Solid Waste Collection; Geographic Information System; Zero-Waste Management

Introduction

In today's world, the need for the solid waste management system to evolve from production-oriented processes to environmental protection-oriented processes stands before us as an inescapable reality [1]. It is expected that waste generation will continue to increase in the coming years. It is already known that sustainable waste management is an important part of sustainable development, which aims to minimize negative environmental effects. Although the problems related to waste management extend from the past to the present, efforts made to meet sustainability objectives continue to increase [2]. We increasingly understand the necessity of considering the journey of waste from prevention to landfill, within the scope of the waste hierarchy, as part of the framework of the zero-waste philosophy [3]. In order to optimize the waste management system in terms of sustainability, and to move the system towards a more circular economy, a better understanding of the different stages of waste management is essential [4]. The recovery of resources not only creates an opportunity to expand the concept of zero waste, but also provides financial support for the entire process of municipal solid waste management (MSWM). However, there is no single waste management strategy, and it is essential to develop an appropriate MSWM system for each settlement, starting at the source [5]. It is well-known that the management of solid wastes under the guidelines of zero-waste management (ZWM) is vital [1].

ZWM is the most visionary waste management system of the last decade; however, this system aims to create 0% waste rather than 100% waste recovery. In order to achieve zero-waste societies, three strategic plans must be comprehensively developed: (1) sustainable production through cradle-to-cradle design and product management; (2) the collaborative and responsible consumption of natural resources; and (3) ZWM through resource conservation [1]. Waste is considered the end of the resource life cycle in traditional waste management. Contrary to this, it is considered a resource in transition or the intermediate phase of the resource life cycle in the ZWM system.

It is thought that the sustainability of the ZWM system is highly dependent on the separation of the waste at source and the separate collection of these components. The separation and separate collection of waste at source will enable the most efficient use of waste in a closed cycle [6]. Many developed countries, such as Japan, Germany, Singapore, and the USA, have achieved sustainable MSWM by starting waste separation at source to recycle the municipal solid waste (MSW) their residents generate [7]. Mixed collection and the disposal of solid waste not only create air, soil, and water pollution but also lead to a loss of energy and resources. Environmental knowledge and rules in a society are important factors that affect trends of waste separation at source. The trend of residents separating waste at source is positively influenced by policies focusing on environmental education and rulemaking [8]. It is a known fact that increasing reuse and recycling rates is made possible by separating waste at source. According to the results obtained from the relevant research, it has been shown that the lack of suitable conditions for waste separation may prevent individuals from participating in this process. It is understood that, when individuals are satisfied with the local conditions for waste separation, their attitudes towards waste separation and recycling depend on their personal attitudes [9].

It is possible to reduce both the quality losses of waste and the exhaust gas emissions through route optimization processes [10–15]. Moreover, the use of geographic information systems (GIS) in the planning of waste management processes [11,16–19] can contribute to the execution of waste management processes within the scope of ZWM due to their user-friendly nature and updatable flexibility. It is expected that the strategies developed for the management of waste in zero-waste-oriented cities are appropriate in the socioeconomic context, manageable in the sociopolitical context, and sustainable in the political–technological and economic–technological contexts. Increasing resource consumption and major shortcomings in resource recovery in many cities around the world have led some to conclude that the current development paradigm is absolutely unsustainable [6]. According to the results of one study, organic waste should be disposed of through composting; materials such as plastic, paper, and glass should be recycled; and sanitary landfill (SLF) should be adopted for disposal of the remaining waste [20]. Using MSW in recycling processes instead of sending it to landfills or using it to obtain new products or for energy recovery is an important approach in terms of carbon reduction [21,22]. Although there are many methods for the disposal of MSW, such as biological recycling, thermal recovery, and mechanical recycling, the amount of organic matter in the waste is always variable and uncertain. For example, a mixture of plastic waste and municipal organic solid waste can be recovered via heat treatment (e.g., incineration and pyrolysis) [23]; however, the mechanical recycling of plastic waste is known to be more sustainable. In addition, methods such as the combined anaerobic treatment of wastewater sludge and domestic organic waste are promising [24]. The combination of pretreatment technologies is designed not only to produce target products with high efficiency, but also to ensure that waste from different sources is used [22,25]. The products obtained within the scope of MSWM can be used not only in their own system but also in the improvement of sustainable urban landscapes and soil structure [26]. However, according to 2017 data, 52.1% of the MSW produced in the United States is still disposed of in landfills. That is, even in developed countries, the use of landfills for waste disposal dominates. Valuable products planned to be developed as a result of MSW disposal methods could not be adequately integrated with each other due to commercial practices, the local economy, and energy constraints [5]. Steps taken to eliminate these negative outcomes are increasing in number day by day. The European Union and Türkiye's target of 65% efficient waste separation and disposal by 2030 as the main strategy for MSW is promising [27]. In order to achieve these goals and to obtain quality products from the waste disposal process, the importance of separating waste at source and separate collections cannot be denied. Today, MSW is transported to transfer stations either mixed or separately accumulated. It should be pointed out that the classification of mixed waste is more difficult and requires more labor. At present, MSW sorting still involves a combination of manual and automated sorting and is gradually developing towards artificial intelligence (AI), robotic separation, and multisensory fusion [28,29].

Studies on solid waste management have been developing rapidly in a sustainable and predictable manner over the last twenty years. Mathematical models used in planning sustainable waste management solutions in a predictable structure have an important function in this development process [30]. In the planning and operation of sustainable integrated waste management processes, optimization modeling [31–35], multi-objective approaches [36–39], multicriteria decision analysis [40–43], and artificial neural networks [44–47] are extensively utilized in a user-friendly format that can assist decisionmakers. Integrated waste management is complex, as it requires many processes starting with the generation of the waste and extending to its collection, transfer, and transportation, the treatment of leachate, biological recovery and the thermal recovery of waste, and the selection of waste disposal sites. Like other mathematical models, multicriteria decision analysis (MCDA) models are also used to provide sustainable and user-friendly solutions for such complex systems. In this study, the analytical hierarchy process (AHP), one of the MCDA models, was utilized for the analysis of the separate collection of solid waste from five different sources according to five waste disposal methods.

AHP is used as a decision-aiding method with a multicriteria methodology formulated to analyze a decision problem. The AHP aims to quantify relative priorities for a given set of alternatives on a ratio scale based on the judgment of the decisionmaker, and it also places emphasis on the importance of the intuitive judgments of a decisionmaker as well as on the consistency of the comparisons made with alternative solutions in the decision-making process. Since a decisionmaker bases their judgments on knowledge and experience and then makes decisions accordingly, the AHP approach concurs with the behavior of a decisionmaker. The strength of this approach is that it organizes tangible and intangible factors in a systematic way and provides a structured yet relatively simple solution to the decision-making problems. In addition, by breaking a problem down in a logical fashion from the large scale, descending in gradual steps, to the smaller scale, one is able to connect the small to the large, through simple paired comparison judgments [30,48,49].

Türkiye is among the countries in the upper-middle-income group [50]. The annual amount of solid waste generated in Türkiye is 32 million tons, according to the data obtained from 1395 municipalities [51]. Moreover, the daily solid waste generated per capita in Türkiye has been determined to be 1.16 kg per person per day. In total, 67.2% of the collected waste is sent to landfills, 20.2% to municipal dumps, 12.3% to recycling facilities, and 0.2% to municipalities that provide solid waste collection services. It is stated that this waste is disposed of by burning it in the open, burying it, or pouring into a stream or open land (Text S1, Figure S1). Unit solid waste production varies between 1.16 and 1.38 kg per capita per day, and the daily solid waste amount generated reaches 32.21 million tons [51] (see Figure S2). In Türkiye, studies on all aspects of sustainable waste management and minimizing environmental impacts are consistently progressing. One of the contributions to these studies is the Zero-Waste Regulation (ZWR), which aims to administer waste management processes with a focus on environmental and human health, in line with the effective management of raw materials and natural resources and sustainable development principles that has been in force since

2019. Regarding the ZWR in Türkiye, there are regulations, such as Article 13, related to the “establishment of a zero-waste management system” and Article 14, related to “features of waste collection, collection, and collection equipment” [52] (see Text S1). The other important regulation regarding waste management in Türkiye is the Waste Management Regulation (WMR), the purpose of which is to ensure the management of waste from generation to disposal without harming the environment or human health. This regulation also provides important information to municipalities and their stakeholders regarding managing waste in a sustainable structure by the municipalities in coordination. According to this regulation, all municipalities are obliged to establish and operate waste processing facilities within the framework of their responsibilities and contribute to the rising awareness of waste generators. Metropolitan municipalities are additionally obliged to establish an integrated waste management system and, if necessary, to contribute to the construction and operation of the transfer stations that district municipalities need [53] (see Text S1). There are 30 metropolitan and 519 district municipalities in Türkiye, and all municipalities try to carry out their waste management activities with a sustainable vision under the laws and regulations specified or not specified here, as well as others (see Table S1). Istanbul, one of the metropolitan municipalities in Türkiye, is also responsible for the construction and operation of the final disposal sites. The administration of Istanbul is implemented by 39 district municipalities under one metropolitan municipality (Figure 1).

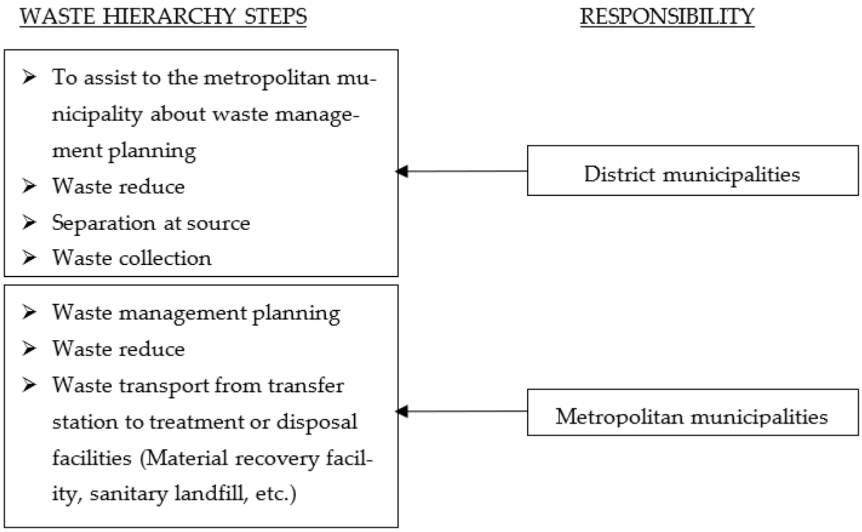

Figure 1: Municipal solid waste management of metropolitan municipalities in Türkiye.

As shown in Figure 1, while district municipalities have obligations as part of sustainable waste management practices under certain regulations, metropolitan municipalities also have obligations to manage waste disposal processes starting from waste transfer stations. One of the aims of this article is to assist Beşiktaş District Municipality, one of the district municipalities, in the sustainable waste management system in its surrounding areas, thus encouraging the metropolitan municipality to make the greatest contribution to the waste management process.

Until now, no research has analyzed the method of separate collection a source and separation at source depending on the residence density-based on waste disposal methods, which we explore in this article. Three questions that we attempt to answer with regard to ZWM are as follows:

1. Can separation at source be planned depending on the density of the residence? Preliminary studies by the authors and face-to-face interviews with residents [54] and business owners show that waste can be separated into fewer

components in residences than in workplaces. The number of independent residences and workplaces was obtained from the relevant municipality and classified and analyzed statistically as the residence density: workplace-dense neighborhoods (WDN), other dense neighborhoods (ODN), and residence-dense neighborhoods (Sections 2.1 and 3.1).

2. What effect do separation methods at source have on solid waste disposal methods? It is known that the more components in the waste that are separated at source, the higher the quality of the waste input to be disposed of in the disposal processes. We analyze which separation methods contribute to disposal methods, and at which rank these methods are positioned in the analytical hierarchy process (Sections 2.2, 2.4 and 3.2).
3. How do the exhaust emissions from the collection vehicle change quantitatively with route optimization? In the solid waste collection process, route optimization is achieved for both the existing mixed collection method and collection of the waste that is separated at source. The average exhaust emission loads generated by solid waste collection vehicles are calculated for both the solid waste mass collected and the route distance traveled by MSW collection vehicles. The exhaust emission loads of both recently optimized routes and solid waste collection vehicles' routes within the scope of ZWM are evaluated. The results obtained are discussed and compared (Sections 2.3, 2.5 and 3.4).
4. The structure of this paper is as follows: The methodologies of the proposed approaches are illustrated in Section 2. The results of sustainable ZWM are described in Section 3. Section 4 provides a comprehensive analysis of the results. Finally, Section 5 explains the conclusion and directions for future research.

Materials and Methods

The materials and methods of this study are examined under five headings: the method for estimating residence density, the method related to GIS, AHP-based methods, methods within the scope of zero waste, and methods related to exhaust emissions factors.

Material and Method for Estimating Residence Density

While the separation of waste is easier to achieve at residences, the collection of waste in separate components from residences may be more difficult than from workplaces [54]. Therefore, different methods of waste separation can be used in residences and workplaces. In any study area, a statistical analysis can be conducted with three classes in order to determine the density of residences based on the number of residences and workplaces. According to the statistical analysis methods [55,56], the study area can be classified based on the density of the independent units used as residences. This is referred to as the density of the residence or the residence density in this study. In this study, assuming that the number of classes is 3, it can be determined statistically into which density range each class falls (see Table S6).

As shown in Table S6, classes 1, 2, and 3 were defined as WDN, ODN, and RDN. Classes were created according to the statistical requirements, taking into account the number of residences and workplaces in each neighborhood (or any area where MSW occurs), and they are explained in detail here. The ratio of residence (RoR) is given in Equation (1) based on the number of independent residences (NoR) and the number of independent workplaces (NoW):

$$\mathrm{RoR} = \frac{\mathrm{NoR}}{\mathrm{NoR}+\mathrm{NoW}} \tag{1}$$

The number of classes (NoC) is given in Equation (2) depending on the number of samples (n).

$$\mathrm{NoC} = \sqrt{\mathrm{n}} \tag{2}$$

The class width (CW) can be calculated from Equation (3) depending on the class range (range = the largest value of the sample-smallest value of the sample) and the number of classes.

$$\mathrm{CW} = \frac{\mathrm{Range}}{\mathrm{NoC}} \tag{3}$$

Analytical Hierarchy Process-Based Methods

Various contemporary problems that require decision-making are often influenced by more than one criterion. In the solution of such problems, MCDM is used to evaluate criteria, prioritize alternatives and select the alternative with the best performance according to the effective criteria. MCDM methods, which have a user-friendly structure, are considered reliable tools in the waste supply chain and are evaluated in two main groups as alternative sorting methods and the criterion weight method [57–59]. Examples of alternative ranking methods include the technique for order of preference by the similarity to the ideal solution (TOPSIS) [60], complex proportional assessment (COPRAS) [61], and the measurement of alternatives and ranking according to the compromise solution (MARCOS) [62]. Examples of criterion weighting methods include the analytical hierarchy process (AHP) [63–66], analytical network process (ANP) [67], weight assessment ratio analysis (SWARA) [68], best worst method (BWM) [69], full consistency method (FUCOM) [70], and base criterion method (BCM) [71,72]. In order to determine the criterion weight, the decisionmaker(s) evaluates the criteria by making pairwise comparisons. The main difficulty with this approach is that it requires a large number of pairwise comparisons [57]. The AHP is a multicriteria methodology formulated to analyze a decision problem following a hierarchical structure. The application of AHP to solve a decision problem involves four main steps for a single decisionmaker (see Text S2, Table S2). Moreover, the determination of the most efficient MSW source separation method for this study using AHP is provided in Section 3.2 and the supplementary materials (see Text S2).

GIS-Based Methods

ArcGIS 10.5 was used in this study. GIS is a software program that creates, displays, and analyzes geospatial data, solves vehicle routing problems for the waste collection process, and shows the results. The ArcGIS Network Analyst function is used to determine the optimal routes based on the traveling distances and operational times of vehicles associated with each route. GIS has been used in several waste management studies, including optimizing municipal waste collection services [11,73–77].

Beşiktaş district was chosen as the study area. District-related data are processed and updated by using the Netcad 8.0 software. The data that can be used in ZWM studies on this platform, such as road, container, population, and neighborhood characteristics, were transferred to ArcGIS 10.5 (see Figures 2, S5, S11 and S12). The projection of the digitizing map used in this study was adjusted to the Turkish Coordinate System (GCS_WGS_84). Studies within the scope of GIS were carried out in three stages: (1) Using ArcGIS 10.5, the available data were collected: for example, street and street characteristics (width, direction, slope, etc.), container properties on streets (position, type, number, and volume), and the number of units of solid waste on the street. (2) We updated the container location, properties, and types on the ArcGIS platform, so as to be suitable for the MSW collection system infrastructure planned in any neighborhood based on ZWM. We conducted the optimization of the collection process of containers with certain capacities on the road network with certain vehicles using the ArcGIS network analyst function (see Text S8).

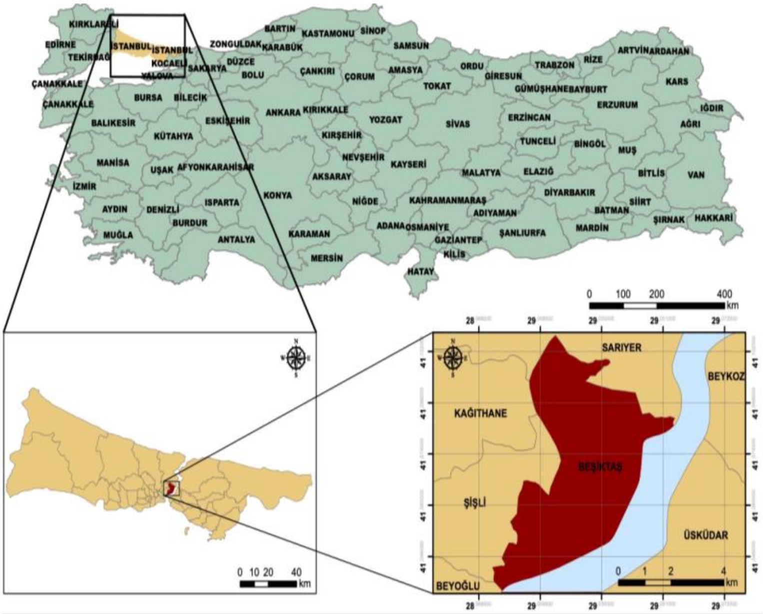

Figure 2: The map of the study area and neighborhoods.

Zero-Waste-Based Materials and Methods

In this study, based on the minimum requirement of ZWR in Türkiye [52], all aspects of separation at source (see Text S3; Figures S3 and S4) were examined, and the optimization of the solid waste collection process was evaluated within the scope of this option. In order to plan waste separation at source, a district of Istanbul, which is the biggest metropolitan city in Türkiye, was selected. Istanbul Metropolitan City has 39 district municipalities, and one of them is Beşiktaş district (see Text S4). The variation in the amount of MSW generated daily (Figure S6), weekly (see Figure S7), and monthly (see Figure S8) is presented in Text S4. Regarding the separation process at source, 11 components obtained during the analysis of the material groups of the MSW generated in Beşiktaş were taken into account. The analysis of the material groups of solid waste generated in Beşiktaş district (see Text S4, Table S4) was conducted according to the ASTM standard [78].

Emission Factor-Based Materials and Methods

It is known that the type of treatment selected for MSW disposal has both economic and environmental costs. In this regard, the unit cost per ton of treated waste is generally reported both per unit of money, and per ton of carbon dioxide emissions [79–82]. In a study performed by Medina-Salas [20], it was shown that if organic waste is subjected to composting treatment, while plastic, paper, and glass are recycled and other types are sent to landfills, environmental costs decrease (environmental costs are −0.284 tons of carbon dioxide per ton of MSW; economic costs are USD 49 per ton of the MSW) [20]. In addition, the same costs are also important for MSW collection and transportation processes. Emissions from existing solid waste collection and hauling systems were estimated based on data obtained from observations in situ, records analyzed, and the other GIS database. The engines of trucks used for solid waste collection in the study area are either Euro 2 or newer. In this study, exhaust emissions were estimated for both the optimized present routes and the optimized ZWM-based routes, using the data obtained from a study performed by Barnaud et al. [83] (see Text S9). Carbon dioxide, nitrogen oxides, hydrocarbons, carbon monoxide, and particulate matter emissions were estimated as grams per route traveled (from Equation (S11)) and grams per ton of MSW collected (from Equation (S12)).

Results

Existing data related to the collection of solid wastes separately at source showed that it is possible to meet the minimum requirements of the ZWR. In addition, projections expected to be obtained as a result of the optimization of the existing mixed-collection system are examined in detail in this section. Although separate collection containers were placed for recyclable waste for the purposes of separate collection, the waste was not separated at source as expected. Containers allocated for recyclable waste were collected using separate collection vehicles and delivered to recycling centers. Today, mixed solid waste is transported to the Baruthane transfer station, which falls under the remit of Beşiktaş Municipality, and from there to the

Seymenler Sanitary Landfill, which is the responsibility of the Istanbul Metropolitan Municipality.

Determination of Residence Density in the Sample Study Area

In this study, Beşiktaş district was selected as the sample residential area in order to conduct a statistical analysis according to the residence density. In this case, n = 23 (number of neighborhoods in the adjacent area of Beşiktaş District Municipality), the lowest value of the RoR was determined to be 0.3114 and the highest value was 0.9374 (from Equation (1) and presented at Table S5 in Text S5). The number of classes was calculated as 4.79, and the integer value was taken as 5 (NoC = 5 from Equation (2)). The distribution range was calculated to be 0.626. Moreover, the class range (from Equation (3)) was calculated to be 0.2087 and 0.1252 for class numbers 5 and 3, respectively. The results provided in Table S6 are obtained by completing similar calculations for all classes. As shown in Table S6, the neighborhoods in Beşiktaş district are grouped into three classes: Class 1 (0.3114–0.5201), Class 2 (0.5201–0.8315), and Class 3 (0.8315–1.229). The number of neighborhoods per class is shown in column 5 in Table S6. Information about which group the 23 neighborhoods in Beşiktaş district belong to is shown in Table S5 in Columns 7 and 8. For example, since the residence ratio of Konaklar neighborhood is 0.8871, it is in the third class. As shown in Column 5 in Table S6, Class 3 is considered to fall within the scope of the RDN.

Determination of the Most Efficient Source Separation Method Using AHP

The arrangement of a top-down municipal solid waste management system and motivational actions to determine residents' separate sorting behavior from the bottom up are both believed to be practical approaches to promoting source separation. Research on sorting techniques is only a complement and alternative to source separation deficiencies [5]. No matter which MSW management system is used, there will be waste that needs to be managed in every location where people live.

That the generated wastes should be managed in the location where they are generated is one of the most important facts that this article aims to emphasize. Because of the waste hierarchy and zero-waste vision, it is necessary to determine which type of collection method benefits each type of disposal method. Five disposal and five collection methods, which are well known and widely applied around the world, are compared in Table 1.

Table 1: Comparison of MSW collection methods with separation at source methods based on MSW disposal methods.

Separation Scenarios [1]	**Municipal Solid Waste Treatment or Disposal Methods**				
	Material Recovery Facility (MRF)	**Composting Process (CP)**	**Biometanization Process (BMP)**	**Thermal Process (TP)**	**Sanitary Landfill (SLF)**
Scenario 1	+	+	+	+	+
Scenario 2	+	+	+	+	+
Scenario 3	+	+	+	+	+
Scenario 4	+	-	-	-	+
Scenario 5	-	-	-	-	-

[1] Separation methods at source. Scenario 1: six different bins (paper, metal, plastic, glass, kitchen organics, and others). Scenario 2: four different bins (paper, metal + plastic + glass, kitchen organics, and others). Scenario 3: three different bins (paper + metal + plastic + glass, kitchen organics, and others). Scenario 4: two different bins (paper + metal + plastic + glass + kitchen organics, and others). Scenario 5: only one bin (mixed MSW, all waste in the same bin).

Table 1 presents how MSW disposal methods are affected by a source conservation perspective relative to waste separation methods at source. Detailed explanations for the interactions of five different decision points (or scenarios) are provided in Text S1. The model prepared according to the waste hierarchy and zero-waste-oriented inferences expressed in Table 1 are provided in Figure 3.

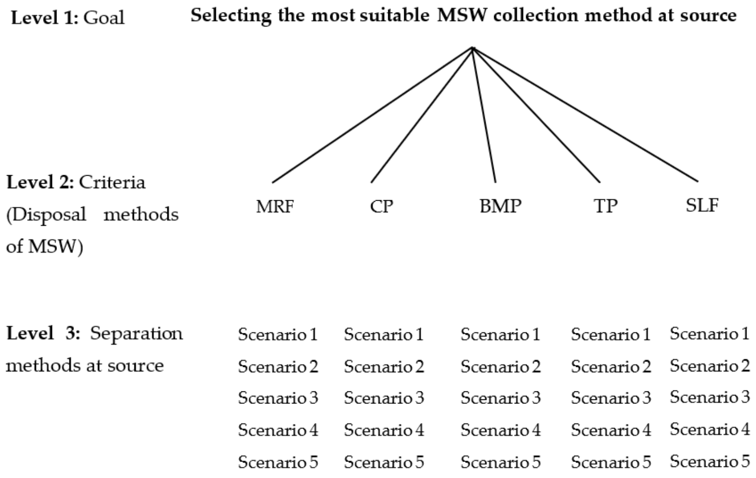

Figure 3: Hierarchy of the model

As shown in Figure 3, MSW collection methods were considered decision points in this study. In addition, MSW disposal methods are criteria that affect decision points. For Step 3, the decisionmakers have to indicate criteria for each decision alternative in terms of how it contributes to each decision. In this context, pairwise comparisons and a synthesized matrix for the factors (five MSW disposal methods) affecting the decision points are provided in Table 2 and Table 3, respectively. Detailed information and calculations related to the data are provided in Text S2.

Table 2: Pairwise comparison matrix for five MSW treatment methods.

	MRF	**CP**	**BMP**	**TP**	**SLF**
MRF	1	3	3	9	9
CP	1/3	1	1	8	8
BMP	1/3	1	1	8	8
TP	1/9	1/8	1/8	1	2
SLF	1/9	1/8	1/8	1/2	1
Sum	1.89	5.25	5.25	26.50	28.00

Table 3: Synthesized matrix for five MSW treatment methods.

	MRF	CP	BMP	TP	SLF	Priority Vector
MRF	0.53	0.57	0.57	0.34	0.32	0.466664
CP	0.18	0.19	0.19	0.30	0.29	0.229005
BMP	0.18	0.19	0.19	0.30	0.29	0.229005
TP	0.06	0.02	0.02	0.04	0.07	0.043121
SLF	0.06	0.02	0.02	0.02	0.04	0.032205
						Σ = 1.00

$\lambda_{max} = 5.223$; CI = 0.05498; RI = 1.12; CR = 0.00611 < 0.1 OK.
The priority matrix obtained as a result of the analysis of the decision points and the factors is provided in Table 4. The status of each collection method according to the waste hierarchy vision for MSW disposal methods is shown in the table. According to Table 4, Scenarios 1 (0.347), 2 (0.286), and 3 (0.2) can be recommended.

Table 4: Priority matrix for evaluating the MSW collection method.

	MRF (0.467)	CP (0.229)	BMP (0.229)	TP (0.043)	SLF (0.032)	Overall Priority Vector
Scenario 1	0.3883349	0.312509	0.312509	0.262412	0.352445	0.347
Scenario 2	0.3079550	0.269651	0.269651	0.262412	0.228916	0.286
Scenario 3	0.1614122	0.238072	0.238072	0.232412	0.181269	0.200
Scenario 4	0.1073456	0.089884	0.089884	0.108626	0.155182	0.101
Scenario 5	0.0349523	0.089884	0.089884	0.134137	0.082188	0.066

In the calculation of the overall priority vector in Table 4, the priority vector was formed as a result of the pairwise comparison of the priority vectors. The priority vectors obtained at the end of the consistency analysis of the decision points and the criteria affecting the decision points are taken into account. The value calculated as 0.347 in Table 4 is obtained by treating the elements in each row with values corresponding to the criterion affecting the decision points in turn (0.467 × 0.3883349 + ... + 0.032 × 0.352445 = 0.347).

Zero-Waste Management in the Study Area

Based on AHP analyses, the first of the waste separation scenarios at the source (Scenario 1) was primarily suggested for optimizing disposal methods (see Table 4). However, in this study, Scenario 3, which scores 14% lower than Scenario 1 and is recommended in third place, was chosen for the study area, Beşiktaş district (see Text S4). The reasons for choosing Scenario 3 are as follows: (1) The ZWM-oriented waste needs (MRF, CP, BMP) for the disposal facilities established in Istanbul; (2) the necessity of adapting the Beşiktaş district to the ZWM regulation in a short timeframe; (3) the existing infrastructure in the district is suitable for triple separation; and (4) the necessity of making additional investments if Scenario 1 given priority (because the collection vehicles in the district are designed for mixed wastes or only one type of waste). Solid waste collection in Beşiktaş district (see Figure 2 or Figure S5) is carried out using instant routes based on field observations. Most of the time, collection vehicles have one route that covers several neighborhoods. For this reason, rather than determining the existing routes, this study prioritized determining how the optimized routes would be mapped out in the case of mixed collection in particular neighborhoods. Previous studies [11,83–85] have determined that both the route distance and route time will decrease if the collection process is optimized. In this study, a total of seven routes in three neighborhoods were optimized (routes 1 to 7), and the route duration and route distances were determined in the case of mixed collection, as presented in Table S7 (and in Text S6). In total 16% of the population in Beşiktaş district lives in the areas where these optimized existing routes are located. As an alternative to the existing optimized routes, 15 new routes (routes 8 to 22 in Table S8) have been optimized for Scenario 3 of “separation at source”, according to the ZWR. It is determined that Scenario 3, obtained from the AHP analysis, is used for these 15 optimized routes in study area. The number of containers was calculated for Scenario 3, which is the minimum requirement of the ZWR, considering 3 of the 23 neighborhoods in Beşiktaş district. In Scenario 3 of “separation at source” (Figure S3), we set out to collect four kinds of waste recyclables (paper, metal, plastic, and glass), organic kitchen waste, and other wastes in three different containers.

The required number of containers was calculated considering both the solid waste mass percentages and the specific weights of each waste component (from Table S4). In the calculation of the number of containers, the average MSW masses collected on the existing routes were taken into account. The mass percentages and specific weights of the waste components were used to calculate the number of containers. Containers with a volume of 0.77 m^3, which is the most common size used in Beşiktaş district, were selected to examine the separation of waste at source. The mean waste mass percentages of the four recyclables (metal, plastic, glass, and paper) and the other six components (see Table S4) were calculated using Equation (S7). The mass percentages of organic kitchen waste are taken as $i = 5$ from Table S4. The mean specific weight of the four recyclable components and the other six components were calculated using Equation (S8). The specific weight of organic kitchen waste is taken as $i = 5$ from Table S4. By choosing 3 out of 23 neighborhoods in Beşiktaş district, the number of containers and the collection vehicle volume required to model Scenario 3 of separation at source for the amount of waste generated by 15 routes were calculated using Equations (S9) and (S10) and are shown in Tables S9 and S10, respectively.

Within the framework of this study, based on the concept of ZWM, these neighborhoods are grouped into the three classes described in the Section 2.1: RDN, WDN, and ODN, considering the number of residences and workplaces in them. Konaklar neighborhood is classified as RDN (current routes: 1–3; new routes based on the ZWM: 8–13), Sinanpaşa neighborhood is classified as WDN (current routes: 7; new routes based on the ZWM: 20–22), and Nisbetiye neighborhood is classified as ODN (current routes: 4–6; new routes based on the ZWM: 14–19). It is understood from Table S9 that 355 containers, each with a volume of 0.77 m^3, are required for the establishment of Scenario 3 of separation at source in the three neighborhoods. In this study, the routes where organic materials are collected separately are designated as 8, 9, 14, 15, and 20. The routes where the waste comprising the four recyclable materials (paper, plastic, metal, and glass) is collected are designated as 12, 13, 18, 19, and 22. The routes where other waste is collected are 10, 11, 16, 17, and 21.

Exhaust Emission Factors of Municipal Solid Waste Collection in the Study Area

Here, we evaluate the data related to possible exhaust gas emissions on the routes optimized within the scope of zero waste-based separation at source and the MSW collection models with containers. Generally, when comparing to the existing routes with the optimized routes, it is expected that the route and route times are shorter for the optimized ones [83,86]. Possible emissions from collection vehicles are estimated based on route distance. In this study, it is possible to have longer durations and distances than the existing routes, since the routes have been planned according to the zero-waste approach, and therefore separation at source is foreseen. These efforts to conduct sustainable waste management will also be beneficial for the sustainability of the environment in the long run, as waste that is separated at source will be included in the reproduction processes under the waste hierarchy, and the possible negative environmental effects that may occur in this process will be minimized. Diesel fuel is utilized to operate the trucks used in the collection processes in the study area. Exhaust emissions are likely to occur in both the optimized existing routes (routes from 1 to 7) and the new optimized new routes determined within the scope of ZWM (routes from 8 to 22), in grams per route traveled (from Equation (S11)) and grams per ton of MSW collected (from Equation (S12)), as shown in Figure 4 for carbon dioxide emissions and in Figure S10 for the other emissions.

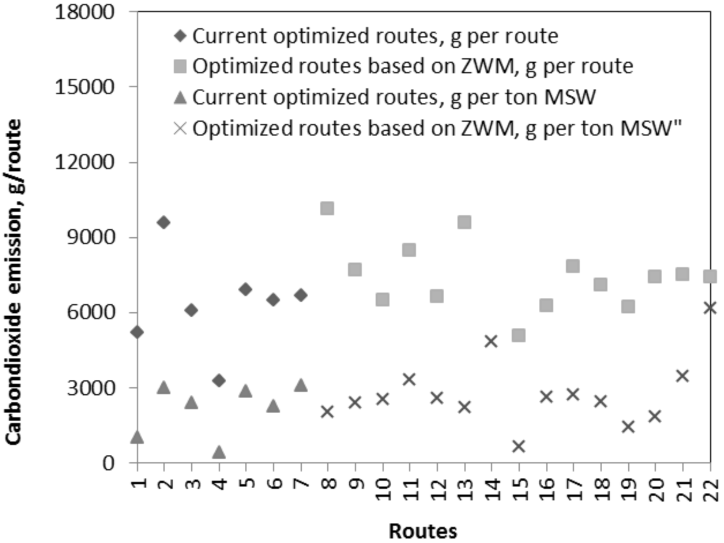

Figure 4: The amount of carbon dioxide emissions from exhausts in MSW collection processes depending on the vehicle collection routes.

Figure 4 shows the carbon dioxide emissions generated by both the optimized existing mixed solid waste collection routes (Routes 1 to 7) and the triple separate collection routes at source (Routes 8 to 22) optimized for zero waste. It appeared that Route 2 (9580 g/route) had the longest route (10.7 km) with the highest carbon dioxide emissions of the routes with optimized existing mixed collections, and Route 7 (3099 g/ton MSW) had the least waste collection (2160 kg/route). The lowest carbon dioxide emissions (3264 g/route; 425 g/ton MSW) were calculated for Route 4, with the shortest route distance (3.7 km) and the most waste collected (7680 kg/route). In the source optimization, according to the principle of zero waste, the most carbon dioxide emissions occurs in Routes 14 (15,258 g/route) and 21 (6052 g/ton MSW), where the least waste is collected (1198 kg/route) in triple separate collection routes. The lowest carbon dioxide emissions were calculated for Route 15 (5053 g/route) and Route 19 (1533 g/ton). Since the emissions are calculated according to the distance of the route and the amount of solid waste collected on that route, the changes in the other emissions shown in Figure S10 can be seen to exhibit similar trends.

Costs of Municipal Solid Waste Collection

Solid waste is taken from the places where is generated, and it is collected and hauled to a transfer station or transported to disposal centers [87,88]. Most of the existing research has focused on waste management costs; few studies have considered environmental impacts together with the costs of collection or transportation. Most of the research focuses on final disposal. In real terms, while 50–75% of waste management costs are spent on collection and transport in developed countries, this rate can reach 70–90% in developing countries [77,88,89]. The MSW collection process is the most important part of waste management. For this reason, many studies have been carried out on the subject, and the costs determined in some of them are given in Table S11 of Text S7. According to the supplementary Table S11, the MSW collection costs vary from country to country or region to region but are between USD 9.3 and 31.53/t MSW. In the same table, the total costs of collection, transportation, and storage are shown as USD 24 to 99.47/t MSW. According to some studies [90,91] performed on five common methods of solid waste collection (organic waste, paper, plastic, glass, and others), SLF, incineration, and composting costs are USD 72/t, USD 14.53/t (plastic or paper), and USD 47/t (organic waste). Additionally, in the same studies, solid waste recycling costs were determined to be USD 93.89/t, USD −67/t, and USD 20.12/t for plastic, paper, and glass, respectively. Naturally, most route optimization efforts result in the minimization of both route distance, duration and exhaust emissions [10,11,84]. It is understood that the routes of the solid waste collection vehicles in the study area are very different from the routes created as a result of optimization using GIS tools. Because of the current collection system, the vehicles travel through more than one neighborhood on the same route, and instant route changes are decided in the field. Therefore, it was not possible to obtain any route information to compare to the optimized routes. Consequently, we aimed to determine the most suitable routes for the collection of solid waste at the waste collection points in any neighborhood, and the route optimization was conducted accordingly. In calculating the collection costs, the current collection system and annual expenditures were taken into account. Calculated unit costs represent the cost of the processes of collecting solid waste and transporting it to the transfer station. On the optimized routes, vehicles reach the first solid waste collection point by traveling an average of 3276 m from the garage, and reach the Baruthane Solid Waste Transfer Station, by traveling an average of 24,112 m from the last waste collection point, which is located in Şişli and has been in service since 1995. Solid waste collection is known to be the most important cost item in the management processes. Hence, the unit costs of the solid waste collection process in Beşiktaş district were also calculated. In this study, the current solid waste unit costs were calculated considering the annual working hours and are given in Table S12 of Text S7. As shown in Table S12, vehicle fuel cost, etc., ranges between USD 0.07 and 0.41 per minute of collection time depending on the vehicle’s capacity. The total cost varies between USD 0.1 and 0.47 per minute of collection time. In addition, other data regarding all the optimized routes in the three neighborhoods selected within the scope of this study in Beşiktaş district are shown in Table S13 and Figures S13–S28. As shown in Table S13, while the distance from the first container point to the garage on the existing routes ranges between 0.52 and 8.1 km, it ranges between 0.7 and 6.4 km on the routes optimized within the scope of zero waste. While the distance from the last container point to the transfer station on the existing routes ranges between 6.4 and 15.8 km, on the routes optimized for zero waste, it ranges between 27 and 33.1 km. Additionally, whereas the MSW collection vehicle’s speed on the existing routes ranges between 19.2 and 35.74 km/h, it has been determined that it ranges between 27.97 and 28.66 km/h on the routes optimized according to zero waste.

Discussion

Solid waste management has a complex structure in terms of the components that need to be managed and its area of influence. Each region may have a different solid waste management system depending on its own social, environmental, and climate structures. It is expected that the studies to be carried out will have a synergetic effect with the existing solid waste management. This study also aimed to optimize the contribution of small settlements to integrated waste management systems.

Beşiktaş district is one of the 39 districts of Istanbul that contributes to the integrated waste management system. Despite its resident population of 175,190 [92], it is frequented by over 2 million people during the day. Within the scope of the zero waste management system, Beşiktaş district also contributes to the integrated waste management system of the Istanbul metropolitan municipality, as do the other 38 districts. The collection of waste and its transportation to the transfer station are among the duties of the Beşiktaş Municipality, as is the case for all district municipalities.

Within the scope of Istanbul integrated waste management, waste is treated using five different disposal methods [93,94]: MRF, CP, BMP, TP, and SLF. It is clear that the quality of the waste to be transported to the established disposal facilities depends on the separation at source and separate collection processes implemented by the district municipalities [52,53].

In this study, we conducted an analysis that can be applied to all settlements; it determines which waste disposal method is suitable for a given source separation method. It was concluded that the separation of solid waste at source in six different containers and their separate collection constitutes the most appropriate solution for ZWM. Thus, the workload in MRF facilities will be reduced, and material recyclable waste will be integrated into secondary production processes with minimum losses. It will be possible to evaluate organic wastes efficiently in the BMP and CP processes. In this case, the burden of both the TP and SLF disposal methods, and therefore the effects of these facilities on global warming, will be reduced.

When conducting an evaluation specific to Türkiye and Istanbul, under the principles of zero waste, the minimum requirement of the zero-waste regulation is to collect waste separately in at least two different containers. If the minimum requirement of the zero-waste regulation is implemented in Türkiye [52], it means that 60% of the waste goes to MRF facilities. The remaining

40% will be evaluated in CP, BMP, and SLF facilities, and the load of these facilities will be reduced. The glass problem in CP facilities will also be largely eliminated, and the compost quality will increase.

Regarding the modeling of MSW separation at source depending on the residence density, within the framework of this study, a method was proposed for the density-dependent separation of solid waste at source. It was observed during the field study that there may be no concern on the part of residents regarding the separation of MSW into two components (recyclables and other nonhazardous MSW) in settlements. On the contrary, in workplaces, the number of components of waste separated at source within the framework of a zero-waste management plan may be higher than in settlements. Based on the results of these observations and other research [54], the neighborhoods in Beşiktaş district are divided into three classes depending on the residence density: RDN, WDN, and ODN. This classification can be easily applied to and modeled for all settlements. The neighborhoods in Beşiktaş district were classified according to the specified method, and analyses were conducted according to the requirements of ZWM for one neighborhood from each class.

Future studies are needed to determine the efficiency of the source separation process according to the housing density modeled here. No study on this subject was identified in the literature. Therefore, the suggested methods should be updated by receiving feedback from households (through surveys).

Regarding MSW disposal methods with AHP depending on source separation, no analysis of source separation methods based on waste disposal is available in the literature and this is the first study on this subject. In the evaluation process with AHP, expert knowledge was used to determine the source separation method in which the most suitable material for MSW disposal methods can be obtained at the highest rate. The information obtained in the AHP process, which was planned in the light of expert experience [95], suggests that the more waste component separated at source, the higher the sustainability of the disposal methods. In this study, AHP is used to analyze the decision problem regarding MSW separation methods at source based on MSW disposal methods. AHP is one of the MCDM methods introduced to obtain criterion weights [59]. For the MSW assessment, five decision point and five criteria were identified in this study. The results show that Scenario 1 (MSW separation at source with six different bins, the separate collection of sorted waste, and its transportation to MSW disposal centers) is the most important decision point. One of the MCDM methods used to obtain criterion weights is BCM, which was used for sustainable waste management alternatives. The three main criteria identified include economic, environmental, and social criteria [59]. According to the obtained results, direct profits and reduced landfill are the most important criteria for assessing sustainable waste management alternatives. In another study, the method employed for the evaluation of the effective criteria for choosing a location for waste disposal was the spherical fuzzy BCM [57]. The results obtained from the study show that the model can produce more accurate results under uncertain conditions.

As for the GIS-supported route optimization of MSW collection, it is a known fact that the minimization of MSW collection costs, in both existing waste collection routes and routes planned under the scope of ZWM, will be made possible by route optimization. Field studies carried out within this context show that the collection and transportation costs can be significantly reduced by route optimization [11]. Due to the high share of waste collection costs in the integrated solid waste management system, numerous studies have been carried out on the route optimization of the collection process [10]. The capacity and number of vehicles play a decisive role in the optimization of the route, which aims to collect the waste by traveling the shortest distances [87]. Depending on how many components the waste is divided into at source, the characteristics of the waste collection vehicles to be used stand out as important variables in the process of minimizing the costs during route optimization [88]. Since the aim is sustainable waste management and thus the use of the fewest natural resource use and minimum environmental damage, high collection costs may be acceptable.

Regarding the exhaust emission factors of MSW collection vehicles within the scope of ZWM, MSW is one of the main factors that contribute to climate change, which is the main concern of various municipalities around the world. In addition to organic solid wastes and disposal processes, collection and transportation processes also contribute to this situation. Although there are studies on the use of electric vehicles, most of the vehicles employed in MSW collection processes are diesel fueled. The exhaust emissions of the diesel-fueled MSW collection/transport trucks constitute a significant source of environmental pollution [84]. By optimizing the route, it is possible to reduce the exhaust emission load [86]. Variables such as the time spent on the collection and transportation processes, the distances covered, and the terrain structure can be identified as the main parameters affecting the exhaust emission [96]. In these processes, in which diesel vehicles are still heavily used, emissions reductions, route optimization, and the capacities of the vehicles used in collection operations play a decisive role. It is clear that the minimization of exhaust emissions will be achieved in waste management systems with larger capacities and decreased collection frequency and route optimization. The data obtained in this study and the modeled approaches are related to the sources or people producing the waste. Therefore, it is necessary to receive feedback from them at regular intervals in terms of system updates and the continuity and efficiency of separation at source. Separating MSW into at least two categories, and preferably three, in residences, and into at least three and preferably six categories, in workplaces, will help prevent waste quality losses during the disposal processes. Collecting MSW in at least three different containers, and preferably collecting it into six in the workplaces, will also help prevent recyclable waste quality losses in disposal processes.

Conclusions

Prioritizing resource conservation-oriented ZWM instead of a consumption-oriented waste hierarchy can be considered a refreshing approach to MSWM, which has a complex structure. According to the results obtained from this study, the current collection vehicles, containers, etc., are sufficient to establish a new MSW collection system based on Scenario 3. Moreover, we also calculated exhaust emissions of the MSW collection vehicle for both the existing collection system and the collection process optimized in this study. According to the results, greenhouse gas emissions may increase when Scenario 3 is implemented. However, when Scenario 3 is implemented, it is predicted that there will be a significant reduction in greenhouse gas emissions considering that recyclable waste will be easily separated in MRF, organic kitchen waste will be recovered at CP or BMP plants, and fewer organic materials will be sent to SLF. According to the results obtained from the studies carried out, the sustainability of the waste management system passes expert assessments, to which all stakeholders will contribute. It is thought that the contributions of all stakeholders regarding waste management processes can be obtained through face-to-face or online surveys. Integrating the data to be obtained into mathematical waste management models will be beneficial for a sustainable ZWM system. In other words, the more components are separated at source, the more high-quality secondary products can be obtained, and the disposal processes can be carried out with a focus on resource conservation. In this study, it was assumed that separation at source was carried out with high purity. It is assumed that the waste is collected separately and taken to the most appropriate treatment processing location. However, in reality, even if the waste is collected separately, the purity percentage is low. In addition, the expected waste does not reach the waste disposal centers at the required level. In future, all stakeholders must be informed about waste production and management within the scope of the planned models and their feedback must be taken onboard.

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Supplementary Materials

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