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Environmental analysis of different packaging waste collection systems for Istanbul – Turkey case study

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ABSTRACT

Source-separated collection of recyclable packaging wastes has been a huge issue for cities such as Istanbul considering their socially, economically, culturally and environmentally cosmopolite structure. In order to apply an environmentally effective separation and collection, system has to be analyzed with a holistic approach including whole recycled packaging material amounts, source consumptions and related emissions. In this context, the aim of this study is to determine the environmentally optimum source-separated packaging waste collection system applicable in Istanbul, Turkey for the first time in literature. Eight scenarios for separated collection system were defined and all of them were compared with each other and with the existing system. To measure the efficiency of the system, some efficiency indicators were chosen and effectiveness related variables were determined to predict the participation rate. Calculations of the efficiency indicators for alternative scenarios were based on the existing system. The environmental analysis was conducted by using Life Cycle Assessment methodology. The results of this study showed that existing system was still one of the environmentally most promising scenarios. Following advantageous scenarios were Scenarios 5 and 6 which were two and three fractionated curbside collection systems, respectively. It is also seen that more fractionated scenarios were less beneficial than two fractionated scenarios. And finally, it can be concluded that with an increment on participation rate and changing collection material type, collection efficiency of curbside system would increase and be environmentally more beneficial.

1. Introduction

Municipal solid waste management system (MSWMS) is defined as "the discipline associated with the control of generation, storage, collection, transportation, processing and disposal of municipal solid waste, in a way that is governed by the best principals of public health and economic, engineering, esthetic and other environmental considerations" (Al-Maaded et al., 2012).

Management of a municipal solid waste (MSW) starts with the collection of waste generated in residential, multifamily, and commercial sectors. The MSW is then transported for separation and recycling, treatment, or disposal facilities (Weitz et al., 1999). Each stage of an integrated waste management system involves a different management-operation strategy for itself. To achieve an optimum efficiency in a MSWMS, it is important to analyze each stage's requirements. In this management process, a well-organized separate collection stage increases the entire systems' efficiency.

In Turkey, waste management has been a subject of legal arrangements since 1930s with the publication of "Public Hygiene Law" (UHK, 1930) and municipalities have been assigned as the main implementation authority with the publication of "Municipality Law" (BK, 1930). However, there were not any obligations on separation of recycling materials, until the publication of Regulation on Control of Solid Waste in 14.03.1991 on Official Gazette No.: 20814 (KAKY, 1991). Moreover, with the publication of Regulation of Controlling Packaging Waste in 2004, municipalities became responsible and within the scopes of negotiation with EU, there have been considerable improvements in solid waste management regulations in order to meet the targets in the European Union's Directive.

The recyclable packaging wastes in Turkey are mainly collected by door-to-door system, which is carried out by municipalities.

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However, a large proportion of recyclable packaging wastes are collected by scavengers, who are described by Sanneh et al. (2011) as the citizens with low to no income that collect materials either dispersed throughout the city or concentrated at dump sites. Agunwamba (2003) stated that because of the social, cultural, financial and environmental conditions, the implementation of the source separation of recyclable materials in Nigeria may not be an effective system considering the investment cost, requirement of public education and expertise of the system. Therefore, integration of the scavengers into the system was suggested as a solution. However, this is an uncontrolled and informal collection system which has numerous social disadvantages such as health risk, low income, child labor, etc. In addition, contamination of waste decreases efficiency of recyclable material. All these above stated issues have directly increasing effect on social and environmental impact, thus scavengers' method is not considered as an option for packaging waste collection system in this study.

Recently, Environment and Urbanization Ministry published Regulation of Waste Management (AYY, 2015) which includes "Waste bring centers and a plan of double type collection of household solid waste (organic waste and packaging waste)". Waste bring centers and double type collection system suggested by local authorities have been discussed as a draft circular from 2011 till now to determine the responsibilities of stakeholders and to achieve a source separated packaging waste collection system. However, although there are various changes in the law and regulations, there is not a well-defined waste management system which is fully-supported by the regulations yet. So, stakeholders such as municipalities and private companies cannot apply an effective separate collection of packaging waste which is the most important part of the waste management system. Therefore, local authorities are still trying to develop a sustainable packaging waste management policy. In order to achieve an effective packaging waste collection system, regional differences (urbanization), social awareness, economic conditions and environmental benefit should be analyzed in detail.

Gallardo et al. (2012a) indicated that efficiency of a separate collection system was influenced by a number of factors which are mainly environmental, economic, social, political, legal and technological factors. Also, to achieve an increment on the collection efficiency of recyclable materials, it was important to analyze citizens' behavior with regard to the various collection systems: the level of participation, quality of the waste collected, financial incentives, etc. For the social aspects of the system, Martin et al. (2006) carried out a detailed review of approaches taken in England to encourage households to participate in recycling and McDonald and Ball (1998), Read (1999), Dahlén et al. (2007), and Thomas (2001) also studied on public participation in England. For instance, Perrin and Barton (2001) found that providing the correct collection scheme design to households not only retains a higher proportion of households who anticipate using a curbside recycling scheme but also captures the traditionally "non-committed recycler" ensuring maximum participation rates and high diversions of recyclable materials. Kaciak and Kushner (2009) determined the factors that influence recycling behavior and examined the socio-demographic characteristics of participants in some regions of Canada. Also, Omran et al. (2009) and Otitoju (2014) researched the individual attitude of participants in Malaysia and Nigeria, respectively. Gellynck et al. (2011) identified 12 variables to increase recycling and reducing the residual household waste in Belgium. Also, Heravi et al. (2013) compared different recycling collection scenarios in Tehran, considering the source consumption, cost benefit, public acceptability, and risk assessment of the scenarios. Above given literature researches, mainly examined the efficiency of source separation system related with multiple variations. Generally, main purpose on these literature researches was to make an increment on the amount of recyclable materials or to determine reason of the current situation. However, even if increasing the amount of the recyclable materials have an important positive effect on the ecosystem; it has also a negative effect arising from the collection system which consumes resources and releases emissions. Therefore, it is important to analyze the system with a holistic approach.

The environmental, economic and social analysis of the municipal solid waste management systems is generally conducted using the Life Cycle Assessment methodology. Many of LCA applications in this field are focused on the use of this methodology as a decision support tool in the selection of the optimum system and it is commonly used through the world on any stages or whole stages of MSWMS (Özeler et al., 2006; Rives et al., 2010; Banar et al., 2009; Menikpura et al., 2012a,b; Hong et al., 2010; Bovea and Powellb, 2006; Skordilis, 2004; Soderman, 2003; Weitz et al., 1999; Rigamonti et al., 2009; Guereca et al., 2006; Gomes et al., 2008; Boer et al., 2007; Rebitzera et al., 2004). For example, Teerioja et al. (2012) compared social life cycle costs of a stationary pneumatic waste collection system to a vehicle-operated door-to-door collection system in Finland and found that traditional door-to-door system economically had more advantages than pneumatic system. Bovea et al. (2010) studied on the environmental life cycle of 24 waste management scenarios which were consisted of pre-collection (bags and containers), collection, transport, pre-treatment (waste separation) and treatment/disposal stages. Iriarte et al. (2009) quantified and compared the potential environmental impacts of mobile pneumatic, multi-container and door-to-door collection systems and found that, the collection system with the least impact was multi-container collection system whereas door-to-door and mobile pneumatic systems had the greatest impact at the urban subsystem level. Rigamonti et al. (2009) evaluated how different assumptions about recycling system influenced the LCA results of integrated waste management system and indicated that source-separated collected materials had a great influence of the whole management system as 15% decrease on the selection efficiencies resulted in 26% increase on global warming effect of the system. Larsen et al. (2010) carried out environmental and economic assessment of five alternative collection systems with the different efficiency for collecting recyclables in Denmark and found that curbside collection would be environmentally more beneficial than drop-off and bring centers. Giugliano et al. (2011) analyzed four scenarios of separate collection system including drop-off collection systems with 35 and 50% overall separation and curbside collection systems with overall separate collection value of 50 and 65%, and found that 50% separate collection system was the best performing scenario. Until this year, as Laurent et al. (2014a,b) indicated, only Banar et al. (2009) and Özeler et al. (2006) used the LCA methodology to determine the optimum municipal solid waste management system in Eskisehir and Ankara, Turkey. Recently, Erses Yay A.S (2015) published a similar study for Sakarya, Turkey. In these studies reported for Turkey, the entire municipal solid waste management system was analyzed. However, for Istanbul it is not always possible to reach realistic data to analyze the entire system since each stage of the MSWMS handled by different responsible institutions. For this reason, only collection, transportation and treatment processes of recyclable packaging waste were investigated to offer a solution to decision-makers from a more environmentally effective point of view. This study analyzes and compares the current and alternative scenarios in terms of environmental effectiveness of a separate collection system of recyclable packaging waste as a part of integrated waste management system for the first time in Turkey.

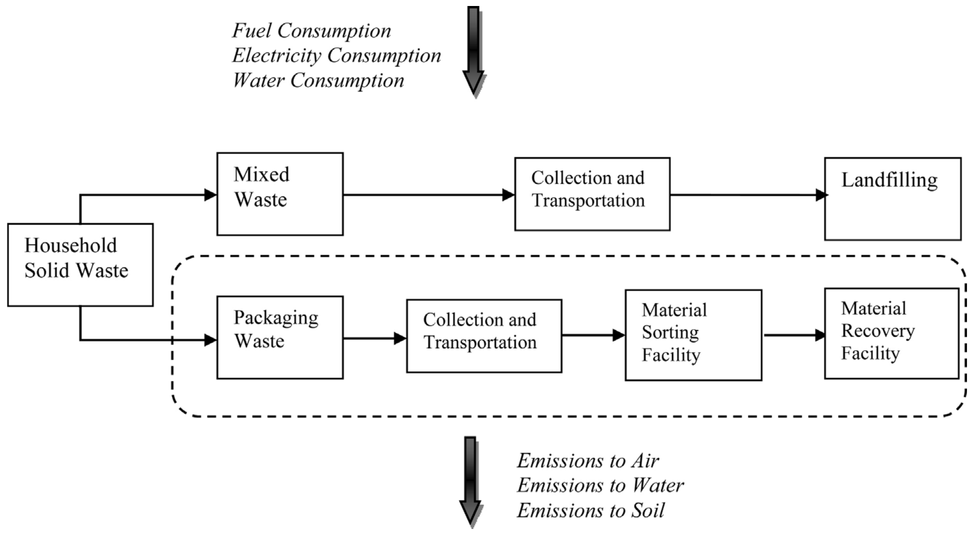

Fig. 1. Existing household collection system and system boundaries for the study.

2. Methodology

The Life Cycle Assessment methodology was used to evaluate an environmental comparison of the alternative scenarios with the current packaging waste collection system. According to ISO14040 (2006a,b) an LCA comprises four major stages: goal and scope definition, life cycle inventory, life cycle analysis and interpretation of the results. As an LCA software, SimaPro 8.0.1 was used to develop system modeling.

2.1. Goal and scope definition

The main objective of this study is to determine the environmental performance of the existing source separated collection system and proposed scenarios. The result of the study may assist decision-makers to apply the environmentally optimum scenario.

System boundaries and functional unit were also determined. Fig. 1 presents the existing household collection system. Household solid waste was collected in two fractions as mixed waste and recyclable packaging waste. In the scope of this study only the packaging waste collection systems were researched. It was assumed that the system boundary for the study starts when household solid waste delivered to any collection material by residents and it ends with the transportation of separated waste to the treatment facilities. The disposal system of the collected waste was out of the scope of this study. The functional unit was selected as 1 ton of recyclable packaging waste.

2.2. Inventory data collection

2.2.1. Definition of existing system and alternative scenarios

There were mainly four collection methods planned to be employed in this study which were the collection by scavengers, door-to-door, curbside, drop-off points. In the scavenger method, wastes are not separated at the source by citizens. Instead, they are all collected in a mixed waste bin and scavengers separate the recyclable wastes inside these bins. Since it requires a detailed social analyze, scavengers' method was not considered in the scope of this study. Door-to-door collection system is characterized by locating of bins, containers or bags at each door or other easily accessible area from buildings and this system requires a detailed collection schedule. In the curbside collection system, containers are located on the streets in the range of between 50 and 100 m and citizens are free to dispose waste at any time of the day or week. Drop-off collection system is also based on the location of stable containers on the street but at greater distances between 500 and 1000 m.

All scenarios were mainly based on the collection methods mentioned above. Additionally these scenarios were differentiated according to fractionated collection of the materials which requires different collection material for different waste fractions.

Instead of picking solely one of the collection systems, researchers are generally focused on the double or triple combinations of these collection systems according to the specifications of the waste. For instance Gallardo et al. (2012b) determined the best separate collection system between the eight collections systems used in Spanish towns. In these eight types of collection systems implemented in Spain wastes were separated into four or five fractions and collected from drop-off points and/or picked up door-to-door systems and/or collected at curbside. Similarly, Giugliano et al. (2011) used the combination of curbside and drop-off collection and proposed the collection of waste fractions on a mono or multi-material basis. Furthermore, Larsen et al. (2010) proposed five collections scenarios which included different combinations of collection of packaging waste at curbside, drop-off containers and recycling centers.

In this paper we suggested eight source separate alternative collection scenarios. A schematic overview of existing and alternative collection system is provided in Fig. 2. Detailed description of existing system and alternative scenarios are as follows:

Existing System (ES): Recyclable packaging waste was separated into 2 fractions. Mixed packaging wastes (paper-cardboard, glass, metal, plastic) were collected by door-to-door system and glass wastes were collected in drop-off points whereas unsorted waste were collected by curbside bins. Plastic bags were used to store mixed packaging wastes. In this system, packaging wastes which were disposed in mixed waste container by residents were picked from curbside containers by scavengers.

Scenario 1 (S1): Waste was separated into 2 fractions and the collection system was almost the same as the existing system. On the contrary of the existing system, addition to the plastic bags, containers were also used. Mixed wastes were collected in plastic bags and then stored in a plastic container which was located at the door of the building. This is the scenario suggested by the regulation.

Scenario 2 (S2): Packaging waste was not separated into fractions. Paper-cardboard, heavy-lightweight packaging waste (metal and plastic) and glass waste were stored in a plastic bag and collected by door-to-door collection system.

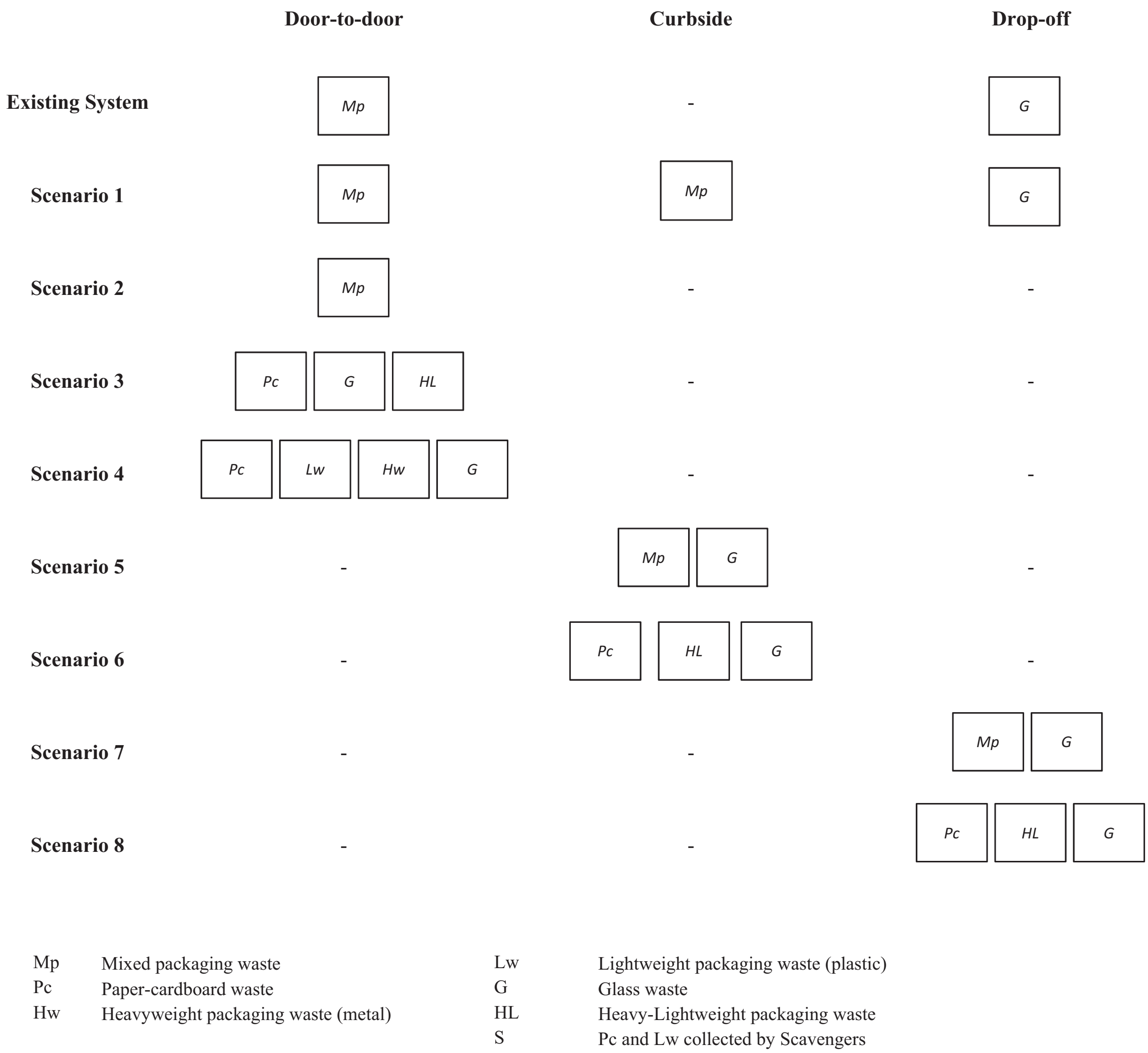

Fig. 2. Separation scheme of the existing collection system and alternative scenarios.

Scenario 3 (S3): Waste was separated into 3 fractions. Paper-cardboard, heavy-lightweight (metal and plastic waste) packaging waste and glass waste were separately stored in plastic bags and collected by door-to-door collection system.

Scenario 4 (S4): Waste was separated into 4 fractions. Paper-cardboard, heavyweight (metal waste), lightweight (plastic waste) packaging waste and glass waste were separately stored in plastic bags and collected by door-to-door collection system.

Scenario 5 (S5): Similar to the existing system and Scenario 1, waste was separated into 2 fractions as mixed packaging waste and glass waste. However in Scenario 5, instead of door-to-door collection and drop-off points, wastes were collected in 2 different plastic curbside bins.

Scenario 6 (S6): Waste was separated into 3 fractions as paper-cardboard, heavy-lightweight packaging waste and glass waste. All these 3 fractionated waste were collected in plastic curbside bins.

Scenario 7 (S7): Scenario 7 was similar to Scenario 5. Wastes were separated in 2 fractions. The only difference was mixed packaging waste and glass wastes were collected at drop-off points in galvanized steel containers.

Scenario 8 (S8): In this scenario waste was separated into 3 fractions. Paper-cardboard waste, heavy-lightweight packaging and glass waste were collected at drop-off points in galvanized steel containers.

2.2.2. Research area and waste specifications

This study states the environmental impact of alternative recycling waste collection systems for Maltepe district located in the suburbs of Turkey's largest city Istanbul. It has a population of 452,099 inhabitants (ABPRSR, 2012) and in 2012 household solid waste generated was 162,569 tons (MBFR, 2013). The amount of waste is shown in Table 1.

Household solid waste is the sum of mixed solid waste (kitchen, garden waste, incinerable and non-incinerable waste) and packaging waste. Packaging waste amount is the sum of the formal and informal collection of packaging materials. Informal packaging waste amount is estimated. According to AYEP (2008), Maltepe district daily waste generation rate is 1.28 kg/capita-day. Calculation method expressed in Tai et al. (2011)'s study was used to determine the amount of packaging materials collected by scavengers. Table 1 shows the municipal solid waste generation for Maltepe Municipality and Table 2 shows the household waste composition.

2.2.3. Data for collection, sorting and recycling activities

In the existing situation, transportation of packaging waste is done in two stages. Firstly, waste are collected from sources and transported to the sorting facility, and then sorted materials are transported to the recycling centers. All transportation data such as fuel consumption, distance traveled, and vehicle types were taken

Table 1
Household solid waste generation for Maltepe Municipality (ton/year) (MBFR, 2013).

Household solid waste [Q_T]	Mixed solid waste [Q_M]	Recyclable waste [Q_R]	Recyclable waste [Q_F]	Recyclable waste [Q_I]
211,220	158,316	52,904	4253	48,651

Q_T: amount of total household solid waste ($Q_T = Q_M + Q_R$).
Q_M: amount of mixed solid waste collected by municipality.
Q_R: amount of total recyclable waste collected formal and informal ways ($Q_R = Q_F + Q_I$).
Q_F: amount of recyclable waste collected by municipality (formal collection).
Q_I: amount of recyclable waste collected by scavengers (informal collection).

Table 2
Household solid waste composition for Istanbul (KAAP, 2007).

Food waste	Incinerable waste	Non-incinerable waste	Paper waste	Glass waste	Cardboard waste	Plastic waste	Metal waste
34%	22%	19%	11%	6%	5%	2%	1%

Table 3
Transportation data for packaging materials (km/ton).

	Sorting facility		Recycling center	
	Transport distance (km/ton)	Fuel consumption (L/ton)	Transport distance (km/ton)	Fuel consumption (L/ton)
Paper-cardboard	33.33	17.49	20.00	8.09
Plastic	33.33	17.49	28.57	11.55
Metal	33.33	17.49	11.42	4.62
Glass	42.50	14.87	13.26	4.69

Note: Paper-cardboard, plastic and metal waste are sent to the same sorting facility, thus, transport distance and fuel consumption have the same value.

from municipality inventory. Table 3 gives the distance from collection point to sorting facility and from sorting facility to recycling center. In the existing system, packaging wastes except glass are collected in the same bag. Mixed packaging waste and glass waste are collected separately and transported to the different sorting facilities. Therefore, the travel distance for mixed packaging and glass waste are 33.33 km/ton and 42.50 km/ton, respectively. Electricity, water and collection material consumption are also taken from municipality inventory. Electricity and water consumption are 10.00 kWh/ton and 0.39 m^3/ton for mixed packaging waste and 9.00 kWh/ton and 0.41 m^3/ton for glass sorting facility, respectively.

One of the most significant differences between the existing system and alternative scenarios is the material use. Characteristics of basic collection materials are given in Table 4. All consumption data for the alternative scenarios were calculated based on the existing system. Further details about the calculations are explained in the following section.

2.2.4. Efficiency data

2.2.4.1. Measuring the efficiency of source separation system. In order to analyze the efficiency of the source separated collection system, there are some indicators determined and used to observe the systems' alteration (Gallardo et al., 2010; Tchobanoglous and Kreith, 2002; Thomas, 2001; Panaretou et al., 2014; Tai et al., 2011).

- Quantity of collected recyclables (kg recyclables/household or person)
- Quality of recyclables (contamination rate)
- Recycling rate (recovered material/the potential recyclable amount)
- Participation rate
- Willingness to participate (potential participation)
- Inhabitants' degree of satisfaction
- Capture rate (the source recovery factor)
- Diversion rate (the diversion rate is a measure of the total quantity of waste that is 'diverted' from landfill as a fraction of the total waste generated each year).

In our study, mainly, following indicators and equations were applied to determine the efficiency of the existing system and estimate the scenarios potential efficiency.

Specific waste generation rate, $[GR]_i$: The ratio between the weight of potential packaging waste and weight of total household municipal solid waste.

$$[GR]_i\,(\%) = \frac{\text{weight of potential recyclable packaging waste}}{\text{weight of total municipal household solid waste}} \tag{1}$$

Public participation rate, $[PR]_i$: This indicator presents the percentage of the people who participates the source separated collection system.

$$[PR]_i\,(\%) = \frac{\text{population that participates the separation system}}{\text{total population of application area}} \tag{2}$$

Source Separation Rate, $[SR]_i$: The ratio between the weight of source separated recycling waste and the weight of total household solid waste.

$$[SR]_i\,(\%) = \frac{\text{weight of source separately collected waste}}{\text{weight of total municipal household solid waste}} \tag{3}$$

Effective separation rate, $[ESR]_i$: This indicator presents the effectivines of citizens, who participate the system. In the participation rate, it is assumed that citizens separated their waste in 100% efficiency. Source separation rate shows how much waste are separated. So the ratio between them gives the efficiency separation rate.

$$[ESR]_i\,(\%) = \frac{\text{Public Participation Rate}}{\text{Source Separation Rate}} \tag{4}$$

Wastage rate, $[WR]_i$: Wastage rate is defined as the ratio between the weight of residual material remain from sorting of collected packagings and weight of total source separately collected recycling waste.

$$[WR]_i\,(\%) = \frac{\text{weight of wastage materials in collected recyclables}}{\text{weight of source separately collected waste}} \tag{5}$$

Table 4
Material characteristics.

Material	Collection system	Volume (L)	Weight (kg)	Material
Galvanized steel container	Drop-off	2	87	Steel
Plastic container	Curbside	1.1	100	HDPE
Plastic bag	Door-to-door	0.019	0.01	LDPE

Packaging Waste Rate, $[PWR]_i$: Packaging waste rate is defined as the percentage of packaging material sent to reprocessing facilities.

$$[\mathrm{PWR}]_i\,(\%) = \frac{\text{weight of sorted recyclable packaging waste}}{\text{weight of total municipal household solid waste}} \quad (6)$$

On a voluntary collection system, public participation rate is directly and indirectly related to several factors such as collection frequency, materials collected, collection day, size of housing, compulsory separate collection, socio-economic level, education and promotion, economic factors, socio-demographic characteristics, publicity and information provided to residents, history and context of scheme, collection vehicle, provision of collection container (Gallardo et al., 2012a; Dahlén and Lagerkvist, 2010; Thomas, 2001; Woodard et al., 2005; Lober, 1996). For instance, White et al. (1995) indicated that citizens' motivations were easily influenced by collection frequency so it affected the system directly. Also, Noehammer and Byer (1997) found that increment on the number of separated fraction decreased the participation rate. Another important factor is the property-close collection system. Gallardo et al. (2012a) showed that in Spain participation rate of the citizens decreased when distance to the deposit point increased. In the same way Dahlén et al. (2008) made an observation on different household waste collection system design in Swedish and found that when separated packaging collected from the points close to the property, higher amounts of sorted metal plastic and paper packaging collected than drop-off points.

In this study, on calculation of the scenarios' participation rate, we assumed that there were no changes on the socio-economic and education level of the citizens and socio-demographic characteristic of the studied area. Collection day and collection frequency were also not taken into account. It was assumed that only distance to collection point and number of fractions affected the participation rate of the citizens. However, as a result of fractionated collection of the packaging materials, different wastage rates were estimated. Due to the mixed collection of packaging materials such as paper-cardboard, plastic, metal and glass waste, wastage rate should be included to calculations.

At first, selected indicators were calculated for the existing scenario. Specific Waste Generation Rate and Source Separation Rate were calculated by using releated equations and the resulting data is given in Table 1. The challenging part was the calculation of participation rate (PR). PR was assumed to be related to only two variables such as number of the participated buildings and apartments. Because of the voluntary-based collection system, not every building on the streets and not every apartment in buildings were a part of the system. However, as a result of address-based collection system, it was known how many buildings and apartments participated to the system. So participation ratios were determined by using these data.

On the estimation of the scenario indicators, first participation rate and then separation rate were determined. PR values of the scenarios were estimated by considering the socio-demographic characteristics of the area, education level and willingness of the citizens. In accordance with these results, collection rate was calculated by using Eq. (7).

$$\frac{[\mathrm{PR}_a]_i}{[\mathrm{PR}_a]_0} \times \frac{[\mathrm{PR}_b]_i}{[PR_b]_0} \times \frac{[\mathrm{ESR}]_i}{[\mathrm{ESR}]_0} = \frac{[\mathrm{SR}]_i}{[\mathrm{SR}]_0} \quad (7)$$

The estimated participation, collection, wastage and treatable material rate used in the scenarios are presented in Table 5. Potential amount of recyclable matter was taken 25% of the total amount of waste generated in all scenarios and years. For the estimation of the participation rate, existing system's collection rate was calculated as 2% then participation rate was calculated as 8%. For the scenarios 1, 2 and 3 participation rates were determined based on data from the existing system and targets aimed by Turkish Legislative Decree whereas for the other scenarios literature reviews were used. Moreover, for each scenario it was assumed that participation rate would be increased year by year considering the increment on the social awareness of citizens.

2.2.5. Calculation of emissions

All mobile emissions were calculated using IPCC Trier 1 methodology (IPCC, 2006). Emission factor were taken from EEA (2013). Airborne emissions were calculated using Eq. (8).

$$E_i = \sum_j \left(\sum_m (\mathrm{FC}_{j,m} x\, \mathrm{EF}_{i,j,m}) \right) \quad (8)$$

where

E_i: 'emission of pollutant i (g)
$FC_{j,m}$: fuel consumption of veichle category j using fuel m (kg)
$EF_{i,j,m}$: fuel consumption-specific emission factor of pollutant i for vehicle category j and fuel m (g/kg).

2.3. Life Cycle Impact Assessment

After inventory analysis, impact assessment step follows. CML-IA method was used to determine the environmental impacts of the systems. Following impact categories were selected to indicate the environmental effects of the compared systems: Abiotic resource depletion (minerals and fossil fuels), acidification, global warming potential (20a and 100a), Ozone layer depletion, photochemical oxidation creation potential, eutrophication. Definition of impact assessment indicators is illustrated in Table 6.

Moreover, single score analysis were performed via EDIP, IMPACT 2002+, EPS, RECIPE (endpoint) methods which are the most widely used Life Cycle Impact Assessment (LCIA) methodologies on solid waste management systems (Laurent et al., 2014b).

2.4. Interpretation

Generally, in this step, all findings are analyzed, completeness, sensitivity and consistency checks are performed and conclusions, limitations and recommendations are drawn in agreement with goal/scope of study. Interpretation stage of this study is discussed in the following sections.

Table 5
Calculated and estimated indicators of existing system and alternative scenarios.

Scenario	Participation rate (%)	Source separation rate (%)	Wastage rate (%)	Recyclable waste rate (%)
Existing system	3.20	2.09	18.51	1.70
Scenario 1	3.87	2.53	18.51	2.06
Scenario 2	3.53	2.30	40.00	1.38
Scenario 3	2.89	1.89	8.20	1.73
Scenario 4	2.89	1.89	7.90	1.74
Scenario 5	2.59	1.69	18.51	1.38
Scenario 6	2.59	1.69	8.20	1.55
Scenario 7	1.80	1.18	18.51	0.96
Scenario 8	1.80	1.18	8.20	1.08

Table 6
Definition of impact assessment.

Impact assessment indicators	Definition	Unit	Method
Abiotic resource depletion	Related to extraction of minerals and fossil fuels due to inputs in the system	kg Sb eq MJ	CML-IA
Acidification	Related to nitric acid, sulfuric acid, sulfur trioxide, hydrogen chloride, hydrogen fluoride, phosphoric acid and hydrogen sulfide	kg SO_2 eq	CML-IA
Global warming potential			
(20a)	in	kg CO_2 eq	IPCC 2007
(100a)	Related to emissions of greenhouse gases to air		CML-IA
Stratospheric ozone depletion	Related to emissions of CFCs	kg CFC-11 eq	CML-IA
Photo-oxidant formation	Related to formation of reactive substances (mainly ozone)	kg C_2H_4 eq	CML-IA
Eutrophication	Related to mainly with CH_4 and CO_2 emissions	kg PO_4^{3-} eq	CML-IA

3. Results and discussion

3.1. Collection and transportation analysis

The results of collection and transportation analysis are given in Table 7. Considering the fuel consumption, S5 where waste was collected in 2 fractions with curbside collection system, had minimum fuel usage amount. On the other hand, in the four fractionated door-to-door collection system (S4), fuel was used almost 3 times higher than S2. Also it is clear that all door-to-door collection systems had more fuel consumption than curbside and drop-off systems. Compared with curbside collection system, there was also a clear difference on drop-off fuel usage. Material consumption amounts of scenarios were differentiated with material type. Among the galvanized steel container used-scenarios, S5 had the minimum material usage where S8 had the maximum. This mainly depended on collected waste amount and then waste fractionation. Similarly, in plastic bag used-scenarios, one-fractionated scenario (S2) had minimum material consumption whereas four-fractionated scenario (S4) had maximum consumption. Water and electricity consumptions were related with only sorting activity. Therefore, fractionation of waste at source was the dominating factor. When wastes were collected in three and four fractions (Scenarios 3 and 4), sorting activity was minimized. In Scenario 2, wastes were collected in a single fraction, and so water-electricity consumption increased. In the same way, landfilled waste amount was related with fractionated collection. If wastes were separated efficiently, wastage amount would decrease. Hence, landfilled waste amount would also decrease. Because S3 and S4 had minimum wastage amount, landfilling was also minimum while S2 had the highest landfilled waste amount. As seen in Table 7, advantageous scenarios were S5, S4 and S3 regarding the consumption data.

3.2. Environmental impact analysis (EIA)

Waste collection, transportation and sorting analysis input data were introduced to SimaPro software to quantify the environmental impact indicators according to the existing system and alternative scenarios. Table 8 summarizes the results of existing system and each scenario in terms of eight impact indicators mentioned in Section 2.3. The results of CML-IA method were schematically shown in Fig. 3a–h.

In this study avoided impacts are bigger than added impacts because the recycling system saves raw material, decreases energy and water consumption and also avoids the emissions related to these activities. Consequently, impact assessment indicators may have negative values suggesting environmental benefits.

3.2.1. Abiotic depletion potential (ADP)

The contribution to the abiotic depletion impact category is mainly due to the extraction of minerals and the fuel consumption during the collection and transportation of the waste to the sorting and finally to the recycling center. Considering the abiotic depletion associated with mineral consumption, the baseline scenario impacts slightly differed from the scenarios S2, S3, S4 whereas scenarios S1, S5, S6, S7, and S8 were significantly different (Fig. 3a). The main difference between these scenarios was metal consumption due to the container usage.

In Fig. 3b energy related abiotic depletion was shown. Environmental profile was almost the same for existing system and all scenarios. However, ES, S5 and S2 were the first three environmentally beneficial scenarios whereas S4, S8 and S3 were the least effective. Since the collection and transportation system for each scenario was not the same, consumptions of resources such as fossil fuel and electricity were also different.

3.2.2. Acidification potential (AP)

The net contribution to this impact category was dominated by the fuel consumption associated with the collection and transportation of waste. ES and S6 had the least score on acidification because the fuel consumption and related emissions (NO_x, SO_x and NH_3) were less than other scenarios. However, S4, S8 and S3 had the biggest score on acidification (Fig. 3c).

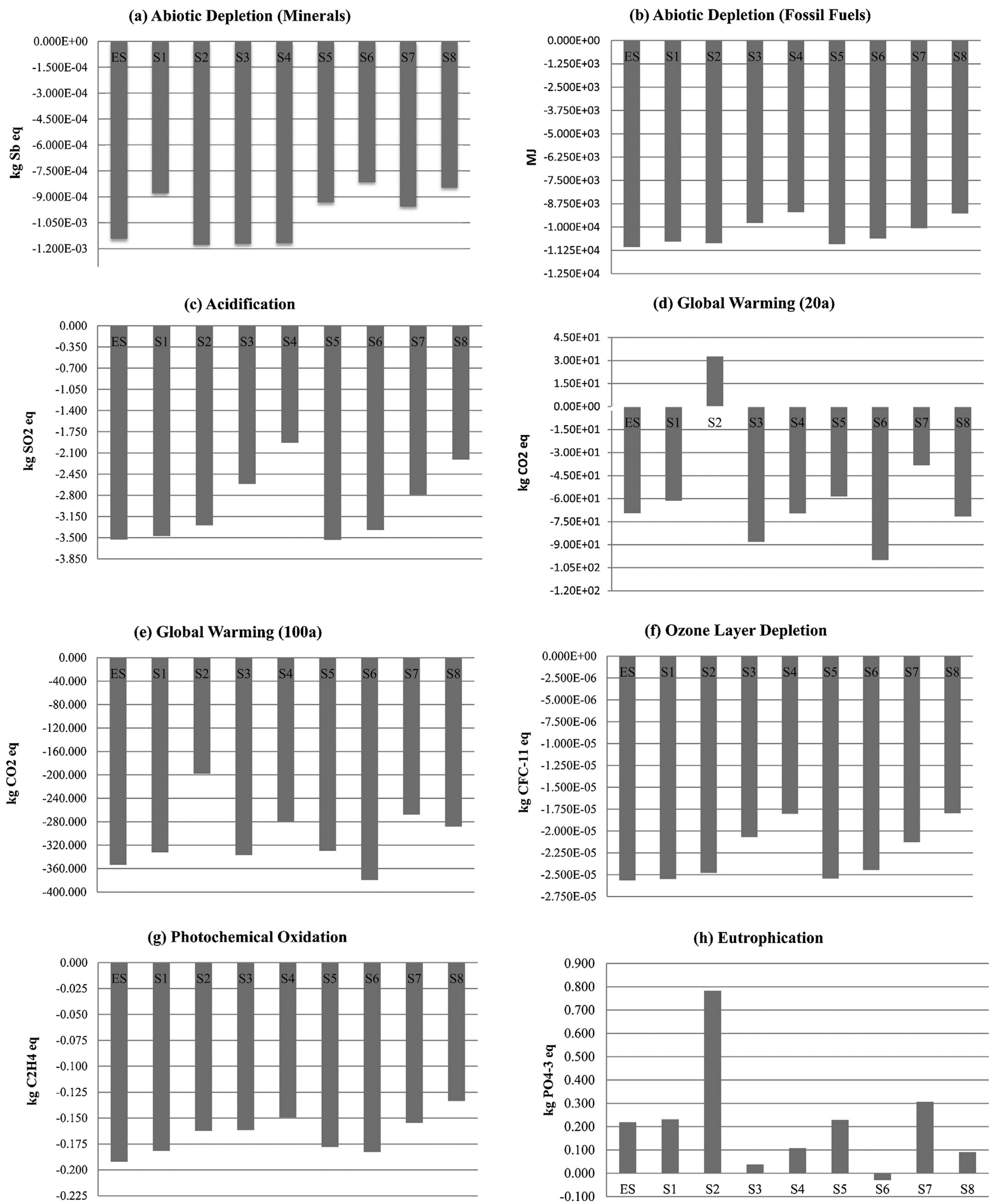

Fig. 3. Comparative analysis of alternative scenarios and existing system in terms of (a) abiotic depletion (minerals), (b) abiotic depletion (fossil fuels), (c) acidification, (d) global warming (20a), (e) global warming (100a), (f) ozone layer depletion, (g) photochemical oxidation (h) eutrophication.

Table 7
Resource consumption and avoided product data of existing system and alternative scenarios.

	Avoided product (kg)	Landfilling (kg)	Water consumption (m^3)	Fuel consumption (kg)	Material consumption (p)	Electricity consumption (kWh)
ES	0.871	0.314	0.396	10.111	275.973	9.760
S1	0.871	0.314	0.396	14.037	218.682	9.760
S2	0.876	0.524	0.458	11.079	185.128	11.723
S3	0.865	0.211	0.353	17.356	324.222	8.675
S4	0.864	0.211	0.352	30.831	335.201	8.663
S5	0.864	0.321	0.396	44.349	0.059	9.760
S6	0.863	0.213	0.353	13.378	0.090	8.675
S7	0.864	0.321	0.396	27.269	0.096	9.760
S8	0.863	0.213	0.353	40.147	0.146	8.675

Table 8
Impact assessment results of existing system and scenarios.

Impact category	Unit	ES	S1	S2	S3	S4	S5	S6	S7	S8
Abiotic depletion	kg Sb eq	−1.14E−03	−8.79E−04	−1.18E−03	−1.17E−03	−1.17E−03	−9.32E−04	−8.13E−04	−9.55E−04	−8.45E−04
Abiotic depletion (fossil fuels)	MJ	−1.11E+04	−1.08E+04	−1.09E+04	−9.78E+03	−9.21E+03	−1.09E+04	−1.06E+04	−1.01E+04	−9.27E+03
Global warming (GWP20a)	kg CO_2 eq	−6.95E+01	−6.14E+01	3.26E+01	−8.81E+01	−6.96E+01	−5.86E+01	−1.00E+02	−3.82E+01	−7.16E+01
Global warming (GWP100a)	kg CO_2 eq	−3.54E+02	−3.32E+02	−1.98E+02	−3.37E+02	−2.80E+02	−3.29E+02	−3.79E+02	−2.68E+02	−2.88E+02
Ozone layer depletion (ODP)	kg CFC-11 eq	−2.56E−05	−2.55E−05	−2.48E−05	−2.07E−05	−1.80E−05	−2.54E−05	−2.45E−05	−2.13E−05	−1.80E−05
Human toxicity	kg 1,4-DB eq	−2.22E+02	−1.47E+02	−2.34E+02	−2.26E+02	−2.24E+02	−1.58E+02	−1.24E+02	−1.64E+02	−1.33E+02
Terrestrial ecotoxicity	kg 1,4-DB eq	−3.89E−01	−3.22E−01	−3.78E−01	−4.10E−01	−4.12E−01	−3.52E−01	−3.26E−01	−3.56E−01	−3.30E−01
Photochemical oxidation	kg C_2H_4 eq	−1.92E−01	−1.82E−01	−1.62E−01	−1.62E−01	−1.49E−01	−1.78E−01	−1.83E−01	−1.55E−01	−1.33E−01
Acidification	kg SO_2 eq	−3.53E+00	−3.47E+00	−3.29E+00	−2.61E+00	−1.93E+00	−3.54E+00	−3.37E+00	−2.79E+00	−2.21E+00
Eutrophication	kg PO_4^{3-} eq	2.19E−01	2.31E−01	7.83E−01	3.82E−02	1.08E−01	2.29E−01	−2.91E−02	3.07E−01	9.09E−02

3.2.3. Global warming potential (GWP)

The greenhouse gases, such as methane escaped from the landfill gas collection systems and carbon dioxide emitted from consumption of fuels were responsible for global warming. Considering the global warming potential (GWP20a), a clear difference was found between S6, S3, S8 and others. Due to the cumulative impact of the landfilling and fuel consumption, S6 had the minimum score where S7 and S2 had the highest environmental impact (Fig. 3d).

As seen in Fig. 3e, for GWP100a, S6 was still the best scenario whereas S2 was the worst. Although Fig. 3d and e numerically seemed different, the ranking of the scenarios for GWP20a and GWP100a were the same. Environmental effects of these two indicators only differed in the time period being 20 years and 100 years, respectively.

3.2.4. Ozone layer depletion potential (ODP)

Ozone layer depletion potential had a similar tendency to acidification potential because both impact indicators were mainly associated with the transportation activity. Among the collection systems, S4, S8, S3 and S7 had the highest fuel consumption amounts. Therefore, these scenarios had the biggest contribution to ozone layer depletion. In contrast, ES, S1, S6 and S5 were the most beneficial scenarios (Fig. 3f).

3.2.5. Photochemical oxidation creation potential (POCP)

Photochemical oxidation creation potential impact category depends largely on the amounts of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxide (NO), ammonium (NH_3) and non-methane volatile organic compounds (NMVOC). The most dominating inputs for photochemical oxidation were fuel consumption, material consumption and finally landfilling. Therefore, S6, ES and S5 were the first three environmentally beneficial scenarios whereas S8 and S7 were the last (Fig. 3g).

3.2.6. Eutrophication potential (NP)

Landfilling was the main factor for eutrophication potential. As stated in Fig. 3h, S6, S3 and S8 were the most beneficial scenarios compared with the others where S2 had the highest environmental impact.

In brief, with respect to the air pollution indicators (GWP, POCP, AP, ODP) ES and S6 seem to be the best alternatives. Considering the water pollution indicators (EP) best results achieved in S6 whereas resource consumption indicators (ADP) showed that S2 was more beneficial to avoid mineral resource consumption and ES was advantageous on avoiding fuel consumption. In general aspect, the existing system (ES) may be considered to be one of the best performing method among the alternative scenarios followed by the curbside collection systems S6 and S5; on the other hand S2 was the environmentally least favorable.

In the light of the facts mentioned above, each impact assessment indicator was analyzed individually complicating the decision-making process for authorities in MSWS. In order to propose a rational solution, the scores must be aggregated to reach a cumulative value. For this reason, four different single score evaluation methods were also performed in this study and explained in the following section.

3.3. Impact assessment methodology analysis

In order to check the consistency of CML-IA method results, four diverse impact assessment methods namely EDIP, IMPACT 2002+, EPS, and RECIPE (E) were also conducted. The results of each method were shown in Table 9 and then ranked according to their environmental performance in Table 10. Even CML_impact assessment method results did not reveal a significantly favorable scenario, the single score results indicated that the existing scenario was the best option in four different aspects. Similar to CML-IA results curbside

Table 9
Single score results of different impact assessment methodologies.

Method	ES	S1	S2	S3	S4	S5	S6	S7	S8
EDIP	−8.69E−01	−7.95E−01	−6.53E−01	−7.78E−01	−5.87E−01	−8.02E−01	−8.26E−01	−6.29E−01	−6.12E−01
IMPACT 2002	−1.91E−01	−1.82E−01	−1.73E−01	−1.66E−01	−1.47E−01	−1.86E−01	−1.84E−01	−1.63E−01	−1.47E−01
EPS	−4.06E+02	−2.56E+02	−4.04E+02	−3.96E+02	−3.76E+02	−2.79E+02	−2.18E+02	−2.71E+02	−2.03E+02
RECIPE_H	−1.49E+01	−1.38E+01	−9.93E+00	−1.33E+01	−1.08E+01	−1.39E+01	−1.50E+01	−1.11E+01	−1.09E+01

Table 10
Rankings of single score results of different impact assessment methodologies.

Ranking	EDIP	IMPACT 2002+	EPS	RECIPE (E)
1	ES	ES	ES	ES
2	S6	S5	S2	S5
3	S5	S6	S3	S1
4	S1	S1	S4	S6
5	S3	S2	S5	S2
6	S2	S3	S7	S3
7	S7	S7	S1	S7
8	S8	S8	S6	S4
9	S4	S4	S8	S8

collection system (S5 and S6) was the secondly well performing scenario in all methods except EPS methodology.

4. Conclusion

In this study, a comprehensive analysis of source separation, collection and transportation system of packaging wastes was performed via LCA methodology for the first time in Istanbul, Turkey. The results are expected to construct a reference point for further studies and policies to be developed by decision-making authorities.

The major findings of this study are:

- The environmental performance of existing system has better scores for five out of eight indicators calculated with CML-IA method. However, the ranking may change according to which indicators are taken into consideration by decision-makers. For this reason, there is not a best option claimed in this study for CML-IA method.
- Since the performance of the scenarios dramatically changes with the assumptions, one can be misled about the results according to the variables taken into consideration. For this reason, the scientific basis of assumptions plays a crucial role in the evaluation process. As stated in this study, neither of the alternative scenarios performed better than the existing system. But even a slight change of the assumptions like participation rate or material type may result in an environmentally more beneficial outcome. To evaluate more realistic results, the study may be broaden with adding the factors like socioeconomic level, education, socio-demographic characteristics, collection frequency, collection materials.
- Almost all impact assessment indicators have negative values suggesting environmental benefits. By all manner of means, separation of packaging materials was always environmentally beneficial regardless of the collection system.
- When resource consumption data were analyzed without LCA methodology, curbside collection system performed better than door-to-door and drop-off collection systems. However, LCIA result showed that door-to-door collection system was more advantageous than curbside and drop-off systems. Additionally, fractionated collection systems were compared. Although, collection of waste in three and four fractions reduced the wastage amount, collection in two fractions performed better in all types of collection systems. Among the studied models, two fractionated door-to-door system (ES) and two fractionated curbside system (S5) were environmentally optimum models.
- Since each impact assessment indicator was analyzed individually, numerous parameters for decision-makers to take into consideration exist. In order to propose a rational solution, the scores must be aggregated to reach a cumulative value. According to four different single score evaluation methods, the existing system was proved to be the environmentally optimum solution.

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