



Investigation of greenhouse gas emissions from municipal solid waste management practices using an economic input-output life cycle analysis approach

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ABSTRACT

The urban solid waste management is gaining attention due to ecological, economic, and demographic factors, emphasizing the importance of sustainable practices and infrastructure development. There are two main objectives of this work: developing an effective framework to predict the environmental impacts of alternative packaging waste collection rates and estimating the associated environmental emissions, energy consumption, and the materials required for goods and services for the case of Avcılar Municipality in Istanbul City, Türkiye. To achieve these objectives, an Economic Input-Output Life Cycle Assessment model was implemented to assess the impacts of all associated industrial sectors. The results showed that as the amount of packaging waste collection increases, the top two sectors that are responsible for the most emissions are Oil and Gasoline Production and Electricity Production and Supply sectors. In addition, the economic analysis results of the study show that as the packaging waste collection rate increases, the unit packaging waste collection cost decreases. The findings of this study provide valuable insights into the environmental emissions of packaging waste management strategies. Moreover, this study highlights the importance of packaging waste management in reducing overall greenhouse gas emissions and promoting more sustainable waste management practices. Policymakers and waste management stakeholders can utilize this framework to identify strategies that minimize environmental impacts and carbon footprints, thereby fostering a transition towards more sustainable waste management options.

1. Introduction

Long before concerns about water and air pollution, the effective management of solid waste has posed a significant challenge to human civilization. The fact that 54% of the world's population lives in cities as of 2018 and this percentage will increase to 68% by 2050 shows that the importance of the urban solid waste problem will increase (UNDESA, 2019). Urban solid waste, which is produced anytime and anywhere without being bound by any timeline, must go through multi-layered and sometimes chaotic stages such as collection, separation, transfer, and disposal. Because of this aspect of urban solid waste, the establishment of urban solid waste management systems is essential (S. Kumar, 2016).

Globally, 5% of greenhouse gas emissions are generated in waste disposal (transportation excluded), making solid waste management an important subject to be considered in reducing impact (Kaza et al.,

2018). Packages are the materials that cover the products, protect them from contamination, and impact on various raw materials. Most of the purchased materials (from grocery items to electronics, from kitchenware to sofa covers) come with their packaging. Considering the weight, economic value, and recyclability of packaging waste among solid wastes, recycling of packaging waste stands out as the focal point of solid waste management systems. Packaging waste management is a system in which every step, from the production of packaging wastes through their disposal, is carefully examined, followed, and improved with the use of developing technologies. The initial Solid Waste Control strategy was introduced in Türkiye in 1991 (Ozeler et al., 2006), followed by the implementation of the first regulations pertaining to packaging waste in 2004. Subsequently, in 2007, 2011, and 2021, amendments were made to the Packaging Waste Control Regulation. In 2019, the Zero Waste Regulation was enacted (Ministry of Environment Urbanisation and Climate Change, 2021). As per the 2021 Packaging Waste Control

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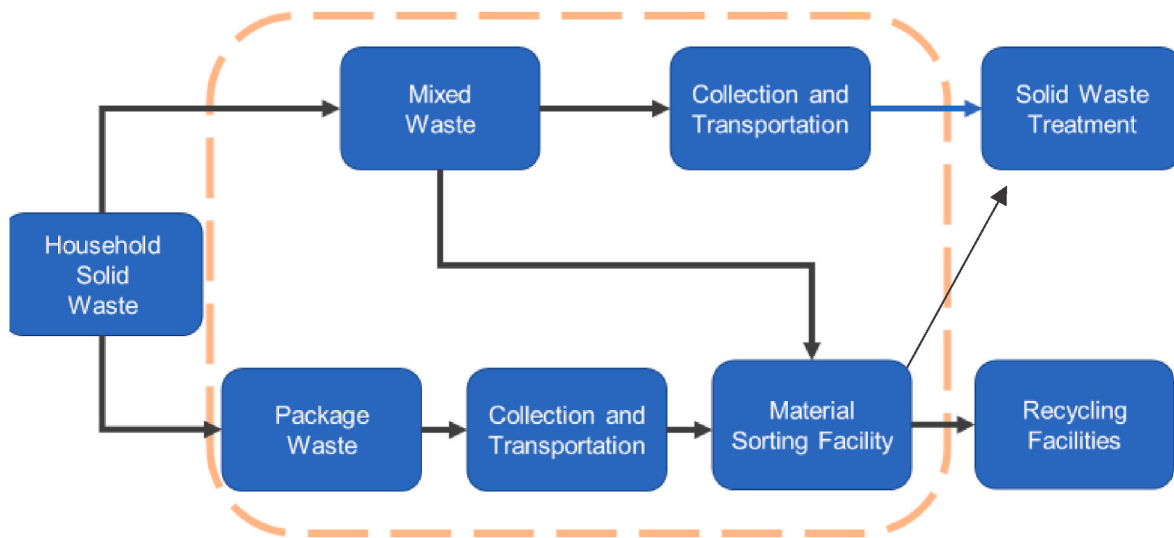


Fig. 1. The economic input-output life cycle assessment study system boundary.

Regulation, the recycling targets for all packaging waste materials are set at 55% by 2025 and 65% by 2030. A comparison study based on European cities showed that municipal solid waste management is a multi-dimensional issue due to the variability and differentiation in waste management practices, including differentiated taxation, recycling targets, and lack of valorization of recycled waste, as well as differences in recycling network design, collection practices, and overall sustainable performance of municipal solid waste recycling (Bing et al., 2016). A material flow analysis of the Dutch post-consumer plastic packaging recycling network shows the impact of different packaging waste types and quantities on the circular economy (Brouwer et al., 2018). A very comprehensive study proposes a complex assessment approach using mathematical programming models and a multi-objective strategy to evaluate waste management systems for economic and environmental sustainability, focusing on main fractions of municipal solid waste (plastic, paper, glass, and mixed waste), resulting in the establishment of suitable numbers and locations for waste treatment and pre-treatment facilities in the case study of the Czech treatment infrastructure (Pluskal et al., 2021). These studies show that it is important to conduct local studies to investigate and compare the emissions that occur while reaching the specified recycling rates and to know the environmental burdens caused by not collecting packaging wastes at the specified rates.

Life cycle assessment (LCA) can be a useful tool to estimate the overall environmental impact of any human-made product or system. In this context, Craighill and Powell (1996) compared the relative environmental impacts of a recycling system with a waste disposal system using a life cycle assessment. The study showed that the recycling system generally performed better than the waste disposal system in terms of contribution to global warming, acidification effects, and the nutrification of surface water. Winkler and Bilitewski (2007) conducted a model-based comparison of the waste management system of Dresden, Germany, with six different models developed in Europe and America. The life cycle inventory results were analyzed in detail, revealing high variations among the LCA results calculated by the models. The authors concluded that the static, linear modeling approach employed by all analyzed models is unsuitable for reflecting actual conditions, and more advanced modeling techniques are needed to improve the accuracy of LCA results. Wenisch et al. (2004) conducted a study focused on the treatment of household waste in France, which included material recycling, incineration of household waste, treatment of flue gases, energy recovery, recycling of bottom ash, treatment of fly ash, and final disposal of waste. The study demonstrated that the life cycle approach is a useful tool for the study of technical and environmental aspects of an energy

and waste management system. Larsen et al. (2010) investigated alternative collection systems for recyclables and five scenarios were assessed by means of a life cycle assessment and an assessment of the municipality's costs. The study showed enhancing recycling and avoiding incineration was recommendable in general because the environmental performance was improved in several impact categories. The LCA approach is used for various purposes. A comparison study showed that LCA offers high potential to facilitate the decision-making process of clean composting processes (Bong et al., 2017). Another study developed a waste management planning approach using life cycle assessment and material flow analysis, showing the benefits of efficient household source separation, biological treatment of organic waste, and thermal treatment of unsorted waste to minimize landfill volumes and greenhouse gas emissions (Arená and Di Gregorio, 2014). The proposed study focuses on analyzing solid wastes from Avcılar Municipality in Istanbul City, Türkiye, which has a population of approximately 500,000, using the Economic Input-Output Life Cycle Analysis (EIO-LCA) method (Hendrickson et al., 1998) to assess the environmental impacts of existing and alternative waste management practices. The main goal of this study is to provide an economic and environmental perspective by determining the greenhouse gas emissions and the distributions of packaging waste management for the case of Avcılar Municipality in Istanbul City while developing an effective framework to predict the environmental impacts of alternative packaging waste collection rates and estimate the environmental emissions, energy consumption, and the required materials consumptions associated with the goods and services.

The economic input-output method analyzes and defines the relationship between the output levels of a sector and other sectors (Leontief, 1970). Equation (1) is used in order to express the demand of the final producer on a sectoral basis.

$$X = [I + A + Ax + Ax^2 + \dots] Y = IY + AY + A^2Y \dots \quad \text{Equation 1}$$

In the equation, I is the identity matrix, A is the matrix representing exchanges between sectors, and Y is the end consumer demand. An analysis of the equation reveals the interdependencies among sectors. Specifically, the absolute need matrix is represented by the A matrix. The following representation can be obtained by using matrix mathematics for the infinite series in Equation (2) which has been shown to follow the effect of purchasing in one sector in hundreds of other sectors.

$$X = [I - A]^{-1} Y \quad \text{Equation 2}$$

Thus, the economic model required to meet the final demand in a sector is calculated by including all relevant sectors. After the final

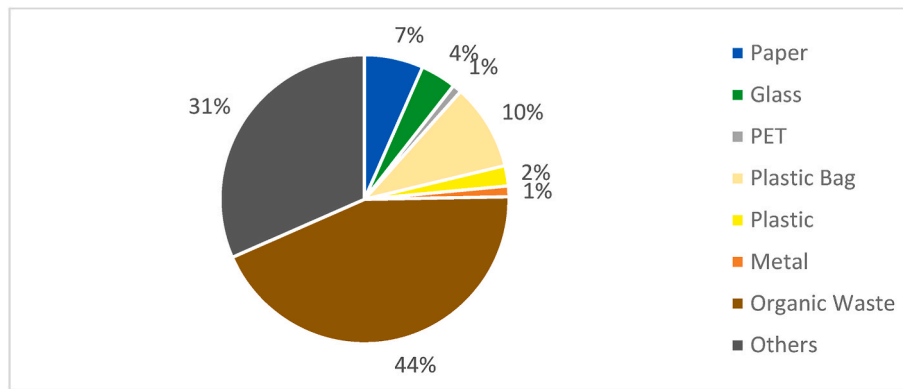


Fig. 2. Avcilar municipality summer-winter mix waste characterization (%) average values.

demand and the demands within the sector are revealed, the sum of the environmental impact is expressed with the vector E. In order to calculate the total environmental impacts of the E vector, the value of the environmental impacts occurring per unit cost on a sectoral basis is needed. This value is expressed as R. The equation required to find the value of E is given with Equation (3). The R-value represents the environmental impact corresponding to a unit cost on a sectoral basis (Hendrickson et al., 1998).

$$E = RX = [I - A]^{-1}Y \quad \text{Equation 3}$$

2. Methods

In this study, field-based monitoring was carried out for 9 months at the facilities belonging to a recycling company, which is the licensed company of Avcilar Municipality in Istanbul. In order to observe the change in the economic data on which the EIO-LCA method is based, and to create more stable scenarios, the reflection of the change in the amount of collected packaging waste to the economic data was monitored. Four hypothetical scenarios were formulated based on field data, literature information, and regulations, in addition to the existing system for collecting recyclable rates. Scenario 0 involves no collection of packaging waste, while Scenarios I, II, and III entail the collection of 30%, 60%, and 100% of the total packaging waste generated in the district, respectively. Further elaboration on these scenarios will be presented below. The economic input-output life cycle analysis system boundary is illustrated in Fig. 1.

While the study examines different scenarios of waste collection, it does not explore the potential for using residual municipal waste for energy generation or the benefits of Waste-to-Energy facilities in reducing emissions because that is not the case in the Avcilar district.

2.1. Waste collection scenarios

2.1.1. Existing collection system

In this scenario, packaging waste and mixed waste are collected separately. In order to collect packaging waste separately, there is waste collection equipment at points such as containers on the sidewalks, mobile waste collection centers, factories, markets, and public institutions. The packaging waste collection and sorting company has two vehicles working in the region. The company brings the collected packaging wastes to the collection and sorting facility, where packaging wastes are separated according to their material. There are 12 workers at the facility to separate packaging waste. On behalf of planning and other administrative works, two environmental engineers and one occupational health and safety specialist work in the company. There is one regional control engineer to assist with packaging waste collected from the region. The company has one crane and one driver of this crane to organize the packaging waste in the facility. At the same time, one

workplace physician also works in the company. In the existing system, there are also curbside containers for mixed waste. While a licensed company of Avcilar Municipality collects the packaging waste in the district, vehicles belonging to the Avcilar Municipality collect the mixed waste. Mixed collected wastes are sent to the sanitary landfill of Istanbul Metropolitan Municipality. A total of 449 workers, including drivers, district staff, and street sweepers, are involved in the collection of mixed waste in the South and North region of Avcilar Municipality. Information on vehicles in the South region is shown in Table A1 and information on vehicles in the North region is shown in Table A2 in Appendix.

The characterization study of Avcilar Municipality was carried out in 2017 within the Istanbul Metropolitan Municipality. Fig. 2 shows the mixed waste characterization study of Avcilar Municipality. The ratio of packaging wastes in mixed waste collected in containers is 24.7% on average. The largest amount of waste is organic waste with an average of 50%. The largest amount of the remaining waste belongs to other flammable materials.

The others category represents a diverse group of materials that may have different disposal requirements such as textiles, electronics, or fines. Fines, which are typically smaller than 10 mm, are detected after the waste is sieved (Dahlen and Anders, 2008). The fine fraction can make up ten percent of the overall amount of waste and cause errors in overall mixed waste.

2.1.2. Scenario 0

In this scenario, packaging wastes are not collected separately, therefore, mix waste sent to the sanitary landfill together with all other wastes. In this case, there are no costs (facility, worker, rent, electricity, etc.) for the separate collection of packaging waste. In this scenario, it is assumed that the separately collected packaging wastes will be collected as mixed waste, and 100 tons/month of waste is included in the mixed waste collection data.

2.1.3. Scenario I

In this scenario, it is assumed that 30% of the packaging waste in the waste containers in the Avcilar district will be collected. For the scenario where packaging waste is collected at a rate of 30%, it is calculated that 30 tons of mixed waste will be reduced per day.

2.1.4. Scenario II

In this scenario, it is assumed that 60% of the packaging waste sent to the sanitary landfill in the Avcilar district will be collected. For the scenario where packaging waste is collected at a rate of 60%, it is calculated that 60 tons of mixed waste will be reduced per day.

2.1.5. Scenario III

In this scenario, it is assumed that 100% of the packaging waste sent to the sanitary landfill in the Avcilar district will be collected. For the

Table 1
Economic data for existing system, scenario 0, scenario I, scenario II, and scenario III.

Sectors	Existing System	Scenario 0	Scenario I	Scenario II	Scenario III
Mix Waste Collection	\$8,889,663	\$9,029,314	\$8,699,489	\$8,393,335	\$7,982,400
Waste Package Collection	\$685,020	–	\$956,375	\$1,617,921	\$2,652,759
Total	\$9,574,683	\$9,029,314	\$9,655,864	\$10,011,256	\$10,635,159

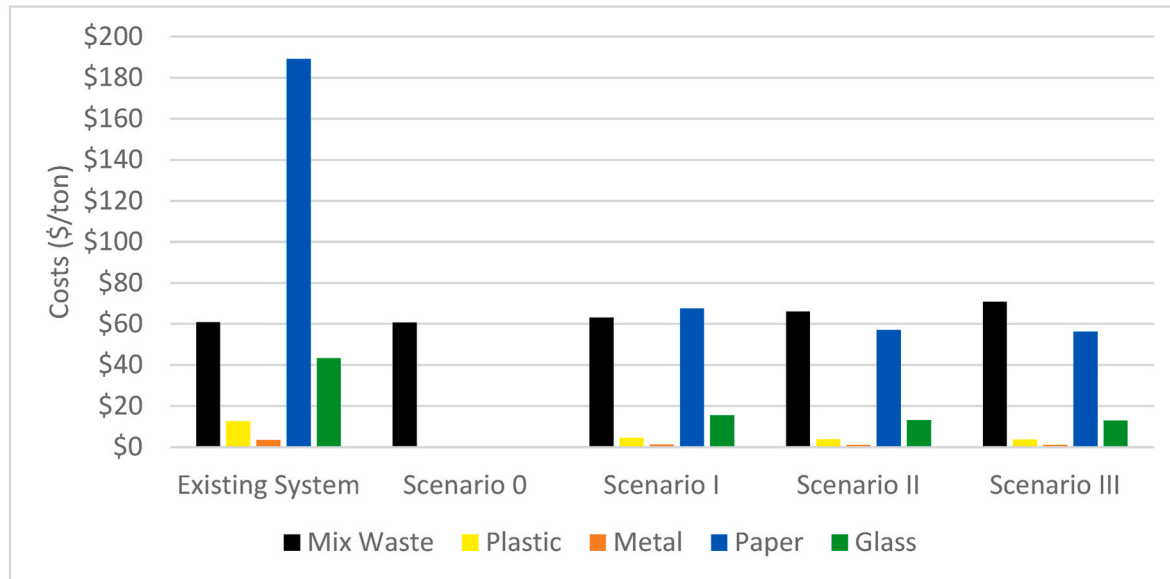


Fig. 3. Cost analysis comparison of different scenarios.

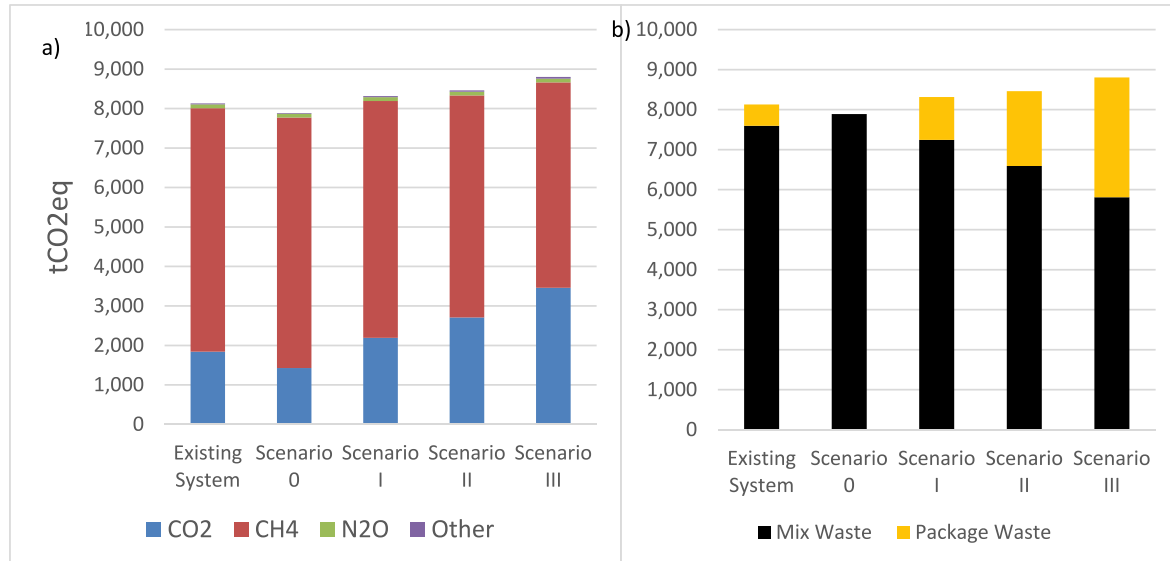


Fig. 4. Total GHG Emissions (ton CO₂eq) for a) Scenarios and Existing System b) Mix Waste and Package Waste.

scenario where packaging waste is collected at a rate of 100%, it is calculated that 100 tons of mixed waste will be reduced per day.

2.2. EIO-LCA methodology

This study uses the MATLAB version of the 2002 EIO-LCA model of the US economy (Weber et al., 2009). The collected sectoral economic data for mix waste collection and transportation and packaging waste collection and sorting for existing system are listed in Table A3 in Appendix.

In Scenario 0 Waste Management and Remediation Services and Employment Services were used as inputs of the Mix Waste Collection. In Scenario I, Scenario II, and Scenario III Waste Management and Remediation Services and Employment Services are used as inputs of the model for Mix Waste Collection. For Packaging Waste Collection, Ready-Mix Concrete Manufacturing, Metal Tank-Heavy Gauge Manufacturing, Other Plastic Product Manufacturing, General State and Local Government Services, Iron and Steel Mills, Employment Services, Packaging Machinery Manufacturing, Light Truck and Utility Vehicle Manufacturing, Automobile Manufacturing, and Real Estate sectors used

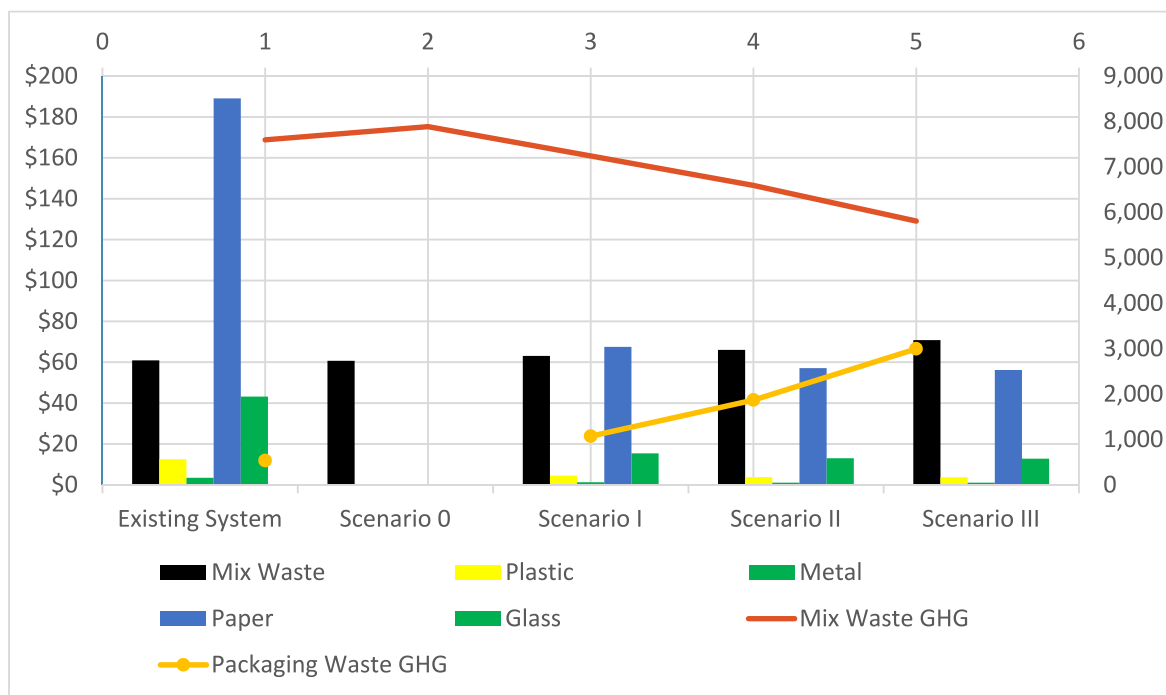


Fig. 5. Comparison of cost analysis (\$/ton) of scenarios and total GHG emissions (ton CO₂eq) by waste fractions.

Table 2

Top 5 sectors total greenhouse gas emissions for the existing system and alternative scenarios.

Existing System	Scenario I	Scenario II	Scenario III
General state and local government services	Oil and gas extraction	Oil and gas extraction	Oil and gas extraction
Light truck and utility vehicle manufacturing	Power generation and supply	Power generation and supply	Power generation and supply
Oil and gas extraction	General state and local government services	Spring and wire product manufacturing	Light truck and utility vehicle manufacturing
Iron and steel mills	Spring and wire product manufacturing	Light truck and utility vehicle manufacturing	Spring and wire product manufacturing
Ready-mix concrete manufacturing	Light truck and utility vehicle manufacturing	General state and local government services	General state and local government services

as inputs of the model. Total monetary values for Existing System, Scenario 0, Scenario I, Scenario II, and Scenario III are shown in Table 1.

3. Results and discussions

Fig. 3 shows the cost analysis comparison of different scenarios. For the existing system, the paper has the highest portion of the overall management cost. As the packaging waste collection rate increases, the cost of packaging waste collection decreases. When Scenario II and Scenario III are examined, it can be seen that mixed waste collection costs per ton exceed packaging collection costs.

A comparison of the total GHG emissions of the scenarios is shown in Fig. 4 and a comparison of cost analysis of scenarios and total GHG emissions by waste fractions is shown in Fig. 5. As Fig. 4a shows, the total GHG emission increases in other scenarios, except for the scenario where packaging waste is not collected at all. It should be noted that the absence of packaging waste recycling within the scope of this study may have contributed to this outcome.

Table 2 shows that sectoral emissions vary according to the collection rates of packaging waste for the Existing System, Scenario I, Scenario II, and Scenario III, where packaging waste is collected. Scenario 0 is not included due to no packaging waste collected. The results indicate that when 1.6% of the packaging waste is collected, the total cost of mixed waste is 12 times higher than the cost of packaging waste, while the total GHG emission of mixed waste is 14 times higher than that of packaging waste collection. Conversely, when 100% of the packaging waste is collected, the total cost of mixed waste is 3 times higher than the cost of packaging waste, and the total GHG emission of mixed waste is 1.93 times higher than that of packaging waste collection. Additionally, the emission rate of certain sectors, such as Oil and Gas Extraction, Power Generation and Supply, Spring and Wire Product Manufacturing, and Light Truck and Utility Vehicle Manufacturing, increases as the collection rate of packaging waste increases, whereas the total emission rate of sectors with fixed expenses, such as Iron and Steel Mills, Ready-Mix Concrete Manufacturing, and General State and Local Government Services, decreases. Along with the increasing collection rate of packaging waste, the increase in operational expenditures also increased the emissions rate in the specified sectors such as Oil and Gas Extraction, Power Generation and Supply, and Spring and Wire Product Manufacturing. As the collection rate of packaging waste increased, the fixed costs increased much less than the operational costs therefore, the emission rates in the sectors formed by fixed costs have also decreased such as General State and Local Government Services, Iron and Steel Mills, and Ready-Mix Concrete Manufacturing.

The construction of Table 2 involves quantifying the GHG emissions for each sector under different waste collection rates. It considers the total GHG emissions associated with both mixed waste and packaging waste collections. By analyzing the ranking, policymakers can identify which scenarios are more environmentally sustainable and prioritize waste management strategies that lead to lower overall emissions. This information can be used to inform and guide the development of local waste management policies and practices that have a positive impact on climate change mitigation. Overall, Table 2 enhances the contribution by providing a quantitative and sector-specific assessment of GHG emissions under different waste management scenarios. It helps bridge the gap between waste management strategies and their environmental

implications, guiding stakeholders toward more sustainable and climate-friendly waste management practices.

The current paper addresses specific research gaps that have not been fully explored in existing studies of Life Cycle Assessment (LCA) in the context of solid waste management. Some of these research gaps include local context, focusing on packaging waste management, analyzing impacts of alternative collection rates, defining sector-specific contributions, and including economic analysis.

Several studies investigated multi-dimensional modeling approaches to integrate municipal solid waste management (Asefi and Lim, 2017). The outcome of this presented study can be used as an input to potential multi-dimensional models. It is recommended to investigate the role of Waste-to-Energy (WtE) facilities in reducing emissions for various case scenarios in the future, even if this study does not consider the possibility of utilizing residual municipal waste for energy generation. WtE facilities are made to turn non-recyclable waste into energy, such as heat and electricity, through a variety of procedures like incineration. The ability of WtE plants to reduce the volume of waste that would otherwise be transferred to landfills helps to minimize the environmental impact of landfilling, including the emission of greenhouse gases like methane (Ferdan et al., 2018). Additionally, WtE plants frequently use cutting-edge flue gas cleaning technology, which reduces air pollutants and particulate matter generated during the incineration process.

4. Conclusions

This study focuses on the environmental analysis of different packaging waste collection rates in Istanbul's Avcilar district, Türkiye. Using the EIO-LCA method, we assessed the environmental impact of packaging waste and mixed waste collection, transportation, and separation. Four scenarios were compared, revealing that CH₄ was the major greenhouse gas emitted during mixed waste and packaging waste collection and transportation. As the packaging collection rate increased, CO₂ became the dominant greenhouse gas during packaging

waste collection. Notably, the sectors contributing the most to greenhouse gas emissions varied with the collection rate of packaging waste. We predict that recycling measures for packaging waste will be strengthened in the next 5 years, necessitating a holistic approach to address emission sources and support reduction measures. The study highlights the need to consider emissions from packaging waste recycling when setting targets and regulations, ensuring sustainable practices in involved sectors. Our analysis shows that collecting and recycling three tons of packaging waste generates over half of the emissions from collecting and disposing of nine tons of mixed waste, emphasizing the importance of reducing emissions from packaging waste recycling to achieve sustainable recycling targets. Further measures should be taken to identify and mitigate emissions from recycling sectors to achieve comprehensive and sustainable recycling practices.

CRedit authorship contribution statement

Raşit Fırat Deniz: Conceptualization, Formal analysis. **Xiaoju Chen:** Conceptualization, Formal analysis. **Nur H. Orak:** Conceptualization, Formal analysis.

Declaration of competing interest

The authors declare that they have no actual or potential competing financial interests.

Data availability

Data will be made available on request.

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Appendix

Table A1

Vehicle and Shifts Used to Collect Mixed Waste in South Region

Name and Short Description	Number x Shift	Name and Short Description	Number x Shift
Container Washing and Disinfecting Vehicle	1	Mini Dump Garbage Truck	4
Compression Garbage Truck 21 + 1.5 m ³	2	Passenger Car	36
Compression Garbage Truck 13 + 1.5 m ³	8	Crawler Excavator, Backhoe Loader	2
7 + 1 m ³ Compression Garbage Truck	2	Hydraulic Compaction Garbage Truck 18 + 1 m ³	8
Vacuum Road Sweeper 8 m ³	2	13 + 1 m ³ Hydraulic Compressed Garbage Truck	2
7 Ton Water Truck	2	Crane System Pickup Truck for Transportation of Underground and Ground Garbage Collection Containers	1
Mobile Washing Vehicle	1	Multi-Purpose Garbage Truck with Minimum 18 m ³ Capacity Fully Automatic Robot Crane System	2
Dump Vehicle 10 m ³	2	Vacuum Road Sweeper with Minimum 8 m ³ Capacity	1
Dump Truck 6 m ³	6		

Table A2

Vehicle and Shifts Used to Collect Mixed Waste in North Region

Name and Short Description	Number x Shift	Name and Short Description	Number x Shift
Multi-Purpose Garbage Truck 18 m ³	2	Dump Truck with Minimum 6 m ³ Capacity	6
Compression Garbage Truck 15 + 1.5 m ³	6	Loader with Rubber Wheels	4
Compression Garbage Truck 13 m ³	6	Mini Dump Garbage Truck	4
Compression Garbage Truck 9 m ³	15	Mini Dump Garbage Taxi Hybrid	1
Galvanized Type Container Washing Garbage Truck	1	Shuttle	1
Road Washing and Sweeping Vehicle	1	Passenger Vehicle	4
7 m ³ Road Sweeper	2	Mobile Washing Vehicle	1
8 Ton Water Truck	2	Hydraulic Compaction Garbage Truck 18 + 1 m ³	6
Dump Vehicle 13 m ³	6	Hydraulic Compression Garbage Truck	2

Table A3
Mixed Waste and Packaging Waste Collection Sectoral Cost Data for the Existing System

NAICS Name	Service	Economic Input (USD)	NAICS Name	Service	Economic Input (USD)
Waste Management and Remediation Services	Mix Waste Collection and Transportation	\$2,745,022.64	Packaging machinery manufacturing	Second hand stacking machine for papers	\$40,792.54
Employment Services	All Employee Costs	\$6,144,640.40	Packaging machinery manufacturing	Second hand sorting tape machine	\$6993.01
Ready-mix concrete manufacturing	Concrete for facility's ground	\$24,475.52	Light Truck and Utility Vehicle Manufacturing	Package Collection Cars	\$132,284.38
Metal Tank, Heavy Gauge Manufacturing	Fix containers at the facility	\$1282.05	Automobile Manufacturing	Field Control Cars	\$15,734.27
Other Plastic Product Manufacturing	Fix containers at the facility	\$1282.05	Real Estate	Material Separation Facility	\$9090.91
General state and local government services	Licence etc.	\$212,645.69			
Iron and steel mills	Iron bars around facility	\$18,648.02			
Employment Services	Employee costs for iron bars	\$6993.01			

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Glossary

- EIO-LCA: Economic Input-Output Life Cycle Assessment
GHG: Greenhouse Gas
WtE: Waste-to-Energy