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Research Article

Life cycle assessment of energy production from municipal solid waste: İstanbul case

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ABSTRACT

Several methods are used during waste management: landfill, incineration, composting, anaerobic digestion, pyrolysis, and recycling etc. In particular, the use of biogas formed through anaerobic digestion in energy production and the energy obtained through the incineration process is very effective in turning the negative effects of wastes into positive ones. In this study, the effects of three different waste management scenarios were examined from a life cycle perspective. According to the results, scenario1 (landfill and incineration), scenario2 (landfill, incineration, and anaerobic digestion), and scenario3 (landfill, anaerobic digestion, and recycle) produced emissions of 3233.1, 328.8, and -848.9 kg of CO_2eq, respectively. Accordingly, and in accordance with the results of the previous studies, it is observed that the landfill application gave the worst environmental result, the incineration and anaerobic digestion applications reduce the environmental effects, and the recycling application provides environmental benefits. It is concluded that the best environmental practice is plastic and metal recycling.

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INTRODUCTION

Urbanization has many potential benefits, including increased access to jobs, education, healthcare, and other services. However, it can also lead to overcrowding, traffic congestion, pollution, and other challenges. Excessive consumption, meanwhile, can drive economic growth and innovation, but can also lead to resource depletion, environmental degradation, and social inequality. Excessive consumption refers to the trend of increased demand for goods and services, often driven by factors such as population growth, economic development, and technological advancements. This trend has been on the rise in recent years, as global populations continue to grow and economies continue to expand. Industrialization, increasing population growth, and economic development can contribute to the generation of large amounts of municipal solid waste (MSW) - which refers to the waste produced by households, commercial and institutional establishments, and other non-industrial sources. As economies grow, the demand for goods and services increases, resulting in the production of more waste. In addition, urbanization and population growth can further exacerbate this problem, as more people live in urban areas where waste generation is typically higher. Industrialization can also lead to the generation of hazardous waste from manufacturing and other industrial processes, which can be difficult and expensive to dispose of safely [1, 2]. The increase in people's welfare

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level and quality of life causes an increase in solid waste production per capita. Owing to the increasing population and rapid industrialization, municipal solid waste management (MSWM) has become a significant problem faced by countries. The municipal solid waste consists of both biodegradable and non-biodegradable parts of organic and inorganic materials [3]. Biodegradable waste refers to organic materials that can break down naturally over time, such as food scraps, yard waste, and paper products. Non-biodegradable waste, on the other hand, includes materials that do not break down naturally, such as plastics, metals, and glass. To eliminate these problems, it is urgent to improve environmentally friendly methods in MSW management. Therefore, landfill, anaerobic digestion, and incineration methods have acquired importance to minimize MSW.

The landfill is the most common method of waste management worldwide and has served as final waste recipients for municipal waste, industrial residues, recycling waste and wastewater sludge [4]. A landfill is a site where MSW and other types of waste are disposed of in the ground. Landfills are a common method of waste disposal and are typically managed by municipal or regional waste management authorities. The wastes accepted to the landfills during the operation phase are stored at a security level that will not damage the structural strength of the site and will not cause slips and collapses on interior and exterior slopes. It must be ensured that the stability of the ground is such that it will not damage the impermeability layer [5, 6].

Anaerobic digestion is a process in which complex organic materials are decomposed under anaerobic conditions and fermented into volatile fatty acids (VFA) by acid bacteria. VFA is then consumed by methanogenic bacteria and converted to methane gas This process produces biogas, a mixture of methane (CH4) and carbon dioxide (CO_2), as well as a nutrient-rich digestate that can be used as a fertilizer [7]. The end product of anaerobic digestion contains biogas (50–75% CH4, 50–25% CO_2 and the remainder are impurities) and an organic residue [8, 9].

The incineration method has become an effective method of dealing with MSW due to its bulking and weight reduction effects [10]. Incineration is a waste management method that involves the combustion of MSW at high temperatures, typically between 800–1000 degrees Celsius, to produce energy and reduce the volume of waste that must be disposed of in landfills. Incineration has the advantage of significantly reducing the volume of MSW that must be disposed of, which can help to extend the lifespan of landfills. In addition, incineration can also generate renewable energy, reducing the reliance on fossil fuels. Even so, since heavy metals and organic pollutants in the ashes resulting from incineration pose a serious threat to the ecosystem and biological community including human health, they should be carefully examined and investigated [11].

Life cycle assessment (LCA) is an innovative approach that can be used in many different areas and is frequently used in the accurate and comprehensive assessment of the cumulative and holistic environmental impacts of MSWM processes. LCA can help to identify the environmental trade-offs associated with different waste management strategies and can provide insight into opportunities for reducing the environmental impact of waste management [12]. LCA typically considers a range of environmental impacts, including greenhouse gas emissions, energy consumption, water use, and waste generation. LCA evaluates all sub-processes of a product system from cradle to grave and provides a calculation of the environmental loads caused by these processes. LCA consists of five phases: goal definition, scope definition, inventory analysis, impact assessment, and interpretation. Sometimes, the goal and scope definition can be reviewed in a single topic [13]. This phase is considered very important as it will directly affect the work to be carried out in other stages. Then, an inventory is created by collecting the data to be used in the study, and then the impact assessment is carried out by making the necessary calculations. Finally, the obtained outputs are interpreted and the final result is reached [14].

Babu et al. [15] reported that a literature review conducted on LCA studies of landfills in Europe identified waste composition, climatic conditions, and landfill management as the most significant factors that influence the environmental impacts of landfill sites. Comparative analyses of landfilling against other MSWM options by Dong et al. [16] showed that landfilling was associated with greater global warming potential (GWP) than other waste management options, primarily due to increased methane and carbon dioxide emissions. LCA has been extensively utilized in forecasting MSW technology. Babu et al. [15] undertook an LCA comparison among four distinct MSWM scenarios for India, encompassing open dumping, storage sans gas recovery, storage with gas recovery, and bioreactor storage. Their findings favoured bioreactor storage over other options. In a similar vein, delineated the environmental impacts associated with six alternative scenarios in India. They observed that Incineration, composting, anaerobic digestion, recycling, landfilling, and landfilling with biogas collection yielded the highest reductions in environmental impacts, especially with a recycling rate of approximately 90% [16]. Rana et al. [17] scrutinized the impacts of diverse MSW disposal methods in India via LCA and determined that MSW Incineration (MSWI) exhibited the most promising outcomes for mitigating environmental impact and reducing greenhouse gas emissions. These studies collectively underscore that each city possesses its own unique dynamics, leading to disparate outcomes in LCA MSW analyses. The results of a similar study conducted in India presented that integration of material recovery, composting, and sanitary landfill provides the most environmentally friendly solution [18, 19].

Although all three disposal methods used in this study have their advantages, landfill is considered environmentally risky when used alone (where no biogas production process is available), and incineration is generally considered better for global warming than landfill [20]. Anaerobic digestion, on the other hand, is considered to be very beneficial in terms of the environment as a disposal method that supports biogas and therefore energy production [5, 21–23].

This study aims to examine the environmental effects of different MSWMs (incineration, anaerobic digestion, and recycling) that allow energy production, together with landfill. The application of LCA scenarios for MSWM management in Türkiye involves evaluating the environmental impacts of different waste management options throughout their entire life cycle. The scenarios include various MSWM options, scenario1 (landfill and incineration), scenario2 (landfill, incineration, and anaerobic digestion), and scenario3 (landfill, anaerobic digestion, and recycling). Thus, the dimensions of environmental gain, especially through the production of biogas from organic waste, will be examined from the perspective of LCA.

The main objective of the study is to reveal the waste-to-energy potential of a city like Istanbul, which generates a large amount of waste. For this purpose, different scenarios were developed, but all of them favoured methods (incineration, anaerobic digestion, and recycling) that can either generate energy or save energy. In addition to these methods, the landfill was included in the scenarios as a control for the utilisation of waste that cannot be utilised for energy. In this context, it is aimed to draw attention to the potential in large cities by revealing the extent of energy that can be obtained from waste.

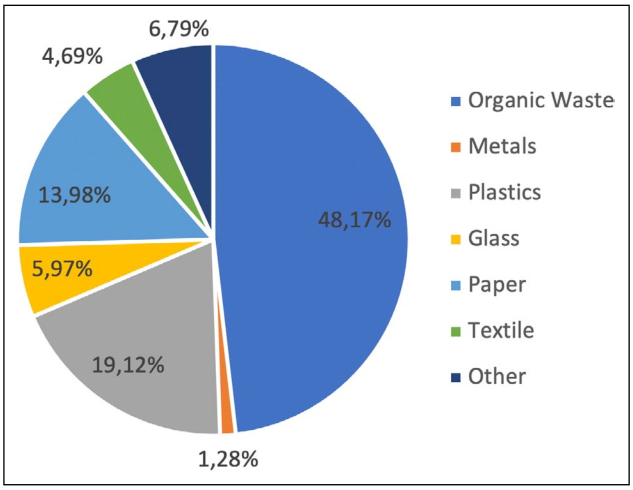

Figure 1. İstanbul 2020 waste composition.

Table 1. Energy production of disposal methods

Scenarios	Disposal method	Electric energy	Heat energy
Scenario1	Incineration	181.01 kWh	1678.78 MJ
Scenario2	Anaerobic digestion	1153.19 kWh	516.77 MJ
	Incineration	181.01 kWh	1678.78 MJ
Scenario3	Anaerobic digestion	1153.19 kWh	516.77 MJ

MATERIALS AND METHODS

LCA is widely used for calculating the environmental impacts of waste management methods and it provides numerous benefits for especially observing the differences between MSW scenarios, which include various methods. In the study, SimaPro 9.3.0.2 package program and ReCiPe 2016 method in this program were used for LCA calculations [24]. On account of calculating the results of the waste management processes, the previously calculated input-output data for each waste disposal method is defined in the system in the Processes title. After, the wastes are defined in the program under the Product Stages title. Then, the information of which disposal method will be used in the treatment of which waste is defined, and finally, the desired LCA method is selected, and the results are reached. The main reason for the choice of SimaPro software in the study is the familiarity of the authors with this software, but also the diversity of the content of the Ecoinvent database that SimaPro utilises.

Scenario Setting

The scenarios are determined to measure the combinations of the impacts of the landfill and energy production from anaerobic digestion and incineration processes. These scenarios were selected in accordance with the previous literature and were optimized to reach the most different results. The potential outputs were also considered.

Scenario-1 (S1): Situation where all combustible waste is incinerated, and ash and residual waste is stored in a landfill. This approach is often referred to as "waste-to-energy" (WTE) or "energy-from-waste" (EFW).

Scenario-2 (S2): The situation in which all organic waste is treated with anaerobic digestion, all combustible waste is incinerated and the remaining waste is stored in a landfill.

Scenario-3 (S3): The situation in which all organic waste is treated with anaerobic digestion, all recyclable waste is recycled, and the remaining waste is stored in a landfill.

Data Collection

The waste composition used in the study was obtained from the wastes collected in Istanbul in 2020 and is presented in Figure 1. The data were taken from the Provincial Environmental Status Report published by the Istanbul Provincial Directorate of Environment.

In all three scenarios, the input (water as rain, oxygen (O_2), diesel fuel)-output (wastewater as equal to precipitation, CO_2, water, sulphur dioxide (SO_2), nitrogen oxides (NO_x) data of the relevant disposal methods were introduced to the program. Information on the amount of energy produced from the disposal methods, which is the main purpose of the study, is presented in Table 1. Thus, the life cycle inventory, which is one of the main components of an LCA study, was completed. The inventory consists of waste composition, input and output data, and the energy produced as a result of the relevant disposal method.

Functional Unit

A functional unit is a measure of the performance of a product or service that is used as a reference point in an LCA. The functional unit is a key component of the LCA because it defines the basis for comparing different products or services in terms of their environmental impacts. 1 t of waste was chosen as the functional unit. This means that the environmental impacts of managing 1 tonne of waste will be assessed and compared across different waste management options. By using a common functional unit, it is possible to compare the environmental impacts of different waste management options on an equal footing. It is assumed that the incineration process does not involve any energy recovery.

System Information

Considering the ongoing efforts of national and international organizations to reduce greenhouse gas emissions and the declarations taken by all states that are party to the United Nations Framework Convention on Climate Change (UNFCCC), decision-makers are turning to different disposal methods and increasingly assessing the GWP. Waste management is important because of its environmental effects. Landfill leachate is produced by excess rainwater that percolates through layers of waste from the landfill. The resulting liquid is a complex mixture of organic and inorganic compounds, including nutrients, heavy metals, pathogens, and other pollutants [25]. Once a landfill is closed, it will continue to produce contaminated leachate, which can last 30–50 years. In general, leachate contains large amounts of organic matter and may also contain heavy metals that pose a major threat to the surrounding soil, groundwater and even the surface. When precipitation occurs, the rain comes into contact with solid waste and as a result, forms leachate. The leachate may contain large amounts of organic content, heavy metals and inorganic salts, so precipitation can have a direct impact on the quality and quantity of leachate produced by a landfill. When rainwater percolates through the layers of waste in a landfill, it can dissolve and mobilize organic and inorganic pollutants, including heavy metals and salts, and carry them along with the leachate. This can lead to an increase in the concentration of these pollutants in the leachate, potentially leading to greater environmental impacts if the leachate is not properly managed. Istanbul, which hosts the Asian and European continents, has a transitional climate between the Black Sea and the Mediterranean and is one of the cities that receive the most precipitation in the Marmara Region. The lowest temperature in the city is -11, the highest temperature is +40 degrees throughout the year, and the average relative humidity is 75%. Although all months of the year are humid in Istanbul, the period when the city has the highest humidity is determined as December-January with a rate of 80–85%. Although snowfalls are not frequent due to the high humidity, there is little snowfall in the period between December and March. Landfill Gas (LFG) is a natural by-product of the anaerobic decomposition of organic substances. LFG includes roughly 50 to 55 per cent methane and 45 to 50 per cent carbon dioxide and contains less than 1 per cent non-methane organic compounds (NMOCs) and traces of inorganic matter [26].

The production of LFG is a natural result of the decomposition of organic waste materials in landfills. As waste materials break down, they release gases, including methane and carbon dioxide, into the surrounding air. In landfills, however, these gases are trapped by the layers of waste above and around them, leading to the build-up of LFG.

Figure 2. Flowchart for the method.

As a microbial ecosystem, the anaerobic digestion process has different stages of digestion, starting with the breakdown of complex organic compounds and ending with the generation of biogas as the final product. Anaerobic digestion is a good option for stabilizing sludge and is the most energy-efficient and environmentally useful technique for bioenergy production. The sludge produced after anaerobic digestion is mostly inert, less in volume and less hazardous than untreated sludge.

Municipal solid waste incineration is standard practice to reduce waste disposal. This is because incineration technology provides a more efficient way of reducing the amount of municipal solid waste that needs to be landfilled. The incineration of municipal solid waste can reduce its mass by 70% and volume by 90% [27], as well as electricity and heat recovery [10]. The primary goal of incineration is to reduce the volume and weight of waste and to minimize the need for landfill space.

Although incineration can reduce the volume of waste and generate energy, it has been a controversial method of waste disposal due to the potential environmental and health risks associated with emissions from incineration facilities. Incineration can release pollutants such as dioxins, furans, and heavy metals, which can have harmful effects on human health and the environment.

A flowchart for the method implemented in the study is presented below as Figure 2.

RESULTS AND DISCUSSIONS

Results

The incineration of waste necessitates the use of chemical inputs for flue gas treatment, including hydrochloric acid, lime, and ammonia, as well as diesel and electricity to power the incinerator. Following incineration and the cleaning of flue gas, the secondary waste in the form of slag and fly ash is recovered and necessitates treatment. In S1, the incineration of combustible waste in a WTE facility can generate electricity and/or heat, which can be used to power homes and businesses. In addition, the ash generated from the incineration process can be landfilled, reducing the volume of waste that must be disposed of in a landfill. However, there are also concerns associated with this approach. Incineration facilities can emit air pollutants, including dioxins and other harmful chemicals,

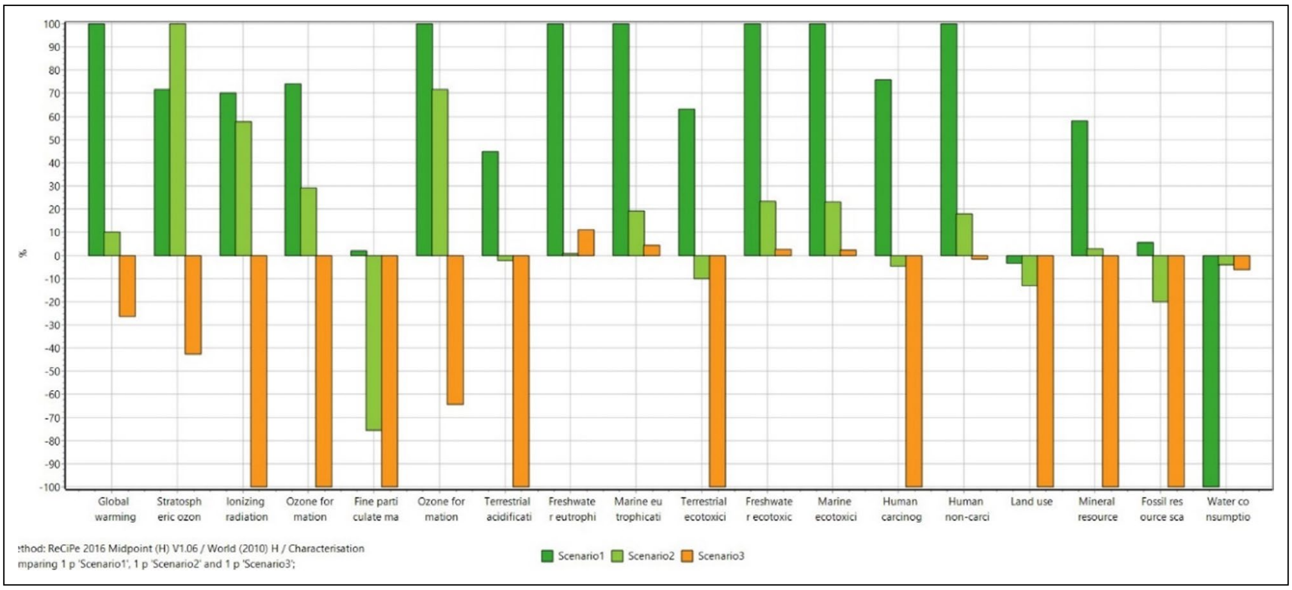

Figure 3. Comparison of the scenarios in midpoint categories.

which can have negative impacts on human health and the environment. In addition, while the ash generated from incineration is less voluminous than the original waste, it may contain concentrated levels of heavy metals and other contaminants, which can pose risks to human health and the environment if not properly managed.

In S2, anaerobic digestion is a biological process that involves the decomposition of organic material in the absence of oxygen, producing biogas and a nutrient-rich digestate. The biogas can be used to generate electricity and heat, while the digestate can be used as a fertilizer or soil amendment. The incineration of combustible waste can generate energy in the form of electricity or heat and can reduce the volume of waste that must be disposed of in a landfill. The remaining waste, which is not suitable for anaerobic digestion or incineration, is disposed of in a landfill. This waste may include non-combustible waste, hazardous waste, and other materials that cannot be effectively managed through other waste management strategies. While this waste management strategy has advantages, such as reducing the volume of waste that must be landfilled and generating renewable energy, it also has potential drawbacks. Incineration can emit air pollutants, such as dioxins and particulate matter, which can negatively impact human health and the environment. Landfills can also generate greenhouse gas emissions, including methane, which contributes to climate change.

In S3, anaerobic digestion is a biological process that involves the breakdown of organic material. The recoverable fraction of the biodegradable portion of MSW can be collected and subjected to anaerobic digestion, after which the digester can be employed as a substitute for chemical fertilizers in agricultural fields. The resulting biogas can be used in electricity generation since it can be directly incorporated into the grid. Although the use of biogas as heat with central heating or biofuel has not been considered in the present context due to the absence of appropriate infrastructure, additional research will be necessary to determine the most effective use of biogas within a regional context. In the absence of oxygen, producing biogas and a nutrient-rich digestate. The biogas can be used to generate electricity and heat, while the digestate can be used as a fertilizer or soil amendment. Recycling all recyclable waste can reduce the amount of waste that must be disposed of in a landfill, and can conserve natural resources by reducing the need for virgin materials. Recycling can also help to reduce greenhouse gas emissions associated with the extraction, processing, and transportation of raw materials. The remaining waste, which is not suitable for anaerobic digestion or recycling, is disposed of in a landfill. This waste may include non-recyclable materials, hazardous waste, and other materials that cannot be effectively managed through other waste management strategies. This scenario represents a waste management hierarchy known as "reduce, reuse, recycle" where the priority is to reduce waste generation, followed by the reuse of products and materials, and the recycling of as much waste as possible. While this waste management strategy has advantages, such as reducing the volume of waste that must be landfilled and conserving natural resources, it also has potential drawbacks. Landfills can generate greenhouse gas emissions, including methane, which contributes to climate change. In addition, the transport and processing of recyclable materials can generate greenhouse gas emissions and other environmental impacts.

Midpoint categories are typically used in LCA to help quantify the potential environmental impacts of a product or activity. The midpoint categories used in LCA depend on the specific impact categories of interest. It would be feasible to evaluate the impact of each safeguard subject by comparing the outcomes of scenarios based on the results of individual midpoint and endpoint categories.

Table 2. Environmental impacts of the scenarios

Impact categories	S1	S2	S3	Unit
GWP	3233.1	328.8	-848.9	kg CO_2eq
SOP	0.0007	0.001	-0.0004	kg CFC11 eq
IR	10.6	8.7	-15.1	kBq Co-60 eq
OF	1.8	0.7	-2.5	kg NO_xeq
FPMF	0.08	-2.9	-3.9	kg $PM_{2.5}$eq
TA	3.9	2.9	-2.6	kg SO_2eq
FEU	1.9	-0.1	-4.2	kg P eq
MEU	1.5	0.01	0.2	kg N eq
TE	0.5	0.1	0.02	kg 1,4-DCB
FEC	1008.7	-163.6	-1595.5	kg 1,4-DCB
MEC	287.1	67.0	7.8	kg 1,4-DCB
HCT	376.1	86.7	8.9	kg 1,4-DCB
HNCT	64.4	-4.1	-84.9	kg 1,4-DCB
LU	5927.1	1067.4	-101.03	m^2a crop eq
MSS	-7.3	-27.8	-212.8	kg Cu eq
FSS	2.5	0.1	-4.3	kg oil eq
WC	24.4	-90.6	-449.1	m^3

GWP: Global warming potential; SOP: Stratospheric ozone depletion; IR: Ionizing radiation; OF: Ozone formation; FPMF: Fine particular matter formation; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MSS: Mineral source scarcity FSS: Fossil source scarcity; WC: Water consumption.

Figure 3 and Table 2 present the results of the environmental impacts of all three scenarios visually and numerically, respectively. The sub-categories presented in Table 2 and Table 3 are referred to the following abbreviations: global warming potential (GWP), stratospheric ozone depletion (SOP), ionizing radiation (IR), ozone formation (OF), fine particular matter formation (FPMF), terrestrial acidification (TA), freshwater eutrophication (FEU), marine eutrophication (MEU), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FEC), marine ecotoxicity (MEC), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral source scarcity (MSS), fossil source scarcity (FSS), water consumption (WC). These midpoint categories are useful for comparing the environmental impacts of different waste management strategies and identifying areas where improvements can be made to reduce the overall environmental impact of MSW.

As seen in Figure 3, it is understood that S3 is a more environmentally friendly approach in all categories except the water consumption category. The reason for this is that the recycling process is also implemented. Recycling is a key element in sustainable waste management as it aims to reduce the amount of waste sent to landfill or incineration, conserve natural resources, and reduce the environmental impact of waste disposal. On the other hand, S2, in which anaerobic digestion and incineration methods are used in addition to landfill management, showed much better environmental performance than S1, which is based only on landfill and incineration methods. Anaerobic digestion and incineration are two waste management methods that are commonly used to treat organic waste. The potential environmental impacts of these methods can be assessed using midpoint categories, which help to quantify the environmental impact of the waste treatment process. Based on this information, it can be said that landfill is the most environmentally problematic method among the methods evaluated in this study. In S2, where the anaerobic digestion method is used together with incineration, a serious environmental performance increase is observed compared to S1, but it is also seen that the values cannot go down to negative levels, that is, a full environmental gain cannot be achieved. However, S3, where recycling is applied together with anaerobic digestion, is the scenario where negative values, that is, a complete environmental gain, are obtained. Based on Figure 3, it is evident that S2 and S3 result in the greatest adverse impact in the Human Health damage category. process is responsible for the S3 scenario being the most unfavourable in this study.

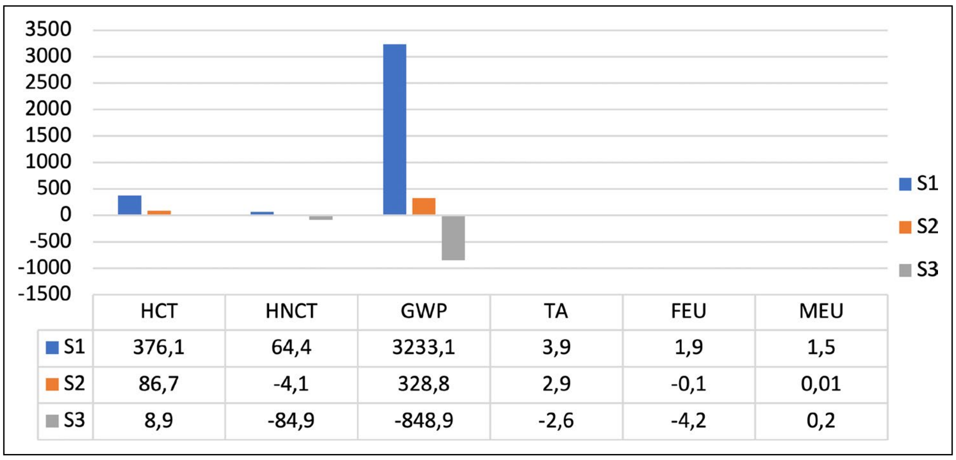

Figure 4. Comparison of some environmental impacts.

Table 3. Environmental impacts of the scenarios

Impact categories	Total	Landfill	Anaerobic digestion	Glass recycle	Metals recycle	Paper recycle	Plastics recycle	Unit
GWP	-848,9	175,4	-299,9	-75,3	-286,3	-19,4	-343,4	kg CO_2 eq
SOP	-0,0004	0.000004	0,0004	-0.00003	-0.00006	-0.00001	-0,0007	kg CFC11 eq
IR	-15,1	0,2	2,8	-2,4	-1,9	-1,8	-12,06	kBq Co-60 eq
OF	-2,5	0,02	-0,8	-0,2	-0,7	-0,2	-0,6	kg NO_x eq
FPMF	-3,9	0,007	-2,9	-0,2	-0,6	-0,07	-0,2	kg $PM_{2.5}$ eq
TA	-2,6	0,02	-0,8	-0,2	-0,8	-0,2	-0,7	kg SO_2 eq
FEU	-4,2	0,02	-1,6	-0,4	-1,3	-0,1	-0,8	kg P eq
MEU	0,2	0,7	-0,3	-0,02	-0,1	-0,03	-0,04	kg N eq
TE	0,02	0,06	-0,02	-0,001	-0,006	-0,001	-0,005	kg 1,4-DCB
FEC	-1595,5	31,5	-201,4	-211,2	-210,2	-153,1	-851,1	kg 1,4-DCB
MEC	7,8	30,9	-3,2	-2,08	-6,9	-1,09	-9,9	kg 1,4-DCB
HCT	8,9	40,6	-4,6	-2,8	-9,6	-1,5	-13,1	kg 1,4-DCB
HNCT	-84,9	2,4	-16,1	-2,6	-52,5	-2,2	-13,9	kg 1,4-DCB
LU	-101,0	645,5	-232,2	-51,2	-241,9	-33,9	-187,2	m^2a crop eq
MSS	-212,8	0,3	-15,1	-5,7	-3,3	-186,7	-2,4	kg Cu eq
FSS	-4,3	0,07	-0,07	-0,2	-3,06	-0,1	-0,9	kg oil eq
WC	-449,1	1,3	-88,1	-19,7	-58,9	-4,7	-278,9	m^3

GWP: Global warming potential; SOP: Stratospheric ozone depletion; IR: Ionizing radiation; OF: Ozone formation; FPMF: Fine particular matter formation; TA: Terrestrial acidification; FEU: Freshwater eutrophication; MEU: Marine eutrophication; TE: Terrestrial ecotoxicity; FEC: Freshwater ecotoxicity; MEC: Marine ecotoxicity; HCT: Human carcinogenic toxicity; HNCT: Human non-carcinogenic toxicity; LU: Land use; MSS: Mineral source scarcity FSS: Fossil source scarcity; WC: Water consumption.

LCA impact categories are a set of environmental indicators that are used to assess the potential environmental impacts of a product or service throughout its entire life cycle. These impact categories are typically based on the different environmental issues that can arise from a product or service and are used to provide a standardized method for comparing different products or services.

As can be seen from Table 3, the best positive contribution to the global warming category is the recycling of plastics. Recycling can help reduce greenhouse gas emissions by reducing the need for virgin materials and the energy required to extract, process, and transport them. It is followed by the recycling of metals by anaerobic digestion. When the table is examined as a whole, it can be seen that plastic recycling and metal recycling bring very beneficial results from an environmental point of view in most of the impact categories. In addition, paper recycling can also be considered a very useful process. In addition, the anaerobic digestion process has a remarkable effect on reducing the environmental burden.

Accordingly, considering a scenario where only recycling is not possible, operating the anaerobic digestion process for organic wastes, recycling recyclable wastes and addition to these, incineration can be interpreted as an environmentally beneficial application.

Figure 4 presents a summary of comparison for toxicity, global warming potential, acidification, and eutrophication.

DISCUSSION

The outcomes of an LCA analysis are often affected by the input parameters used in the assessment. Thus, the input-output (sources from nature, avoided products, energy output etc.) data was carefully calculated and added to the software. Besides, the appropriate methods were selected among various similar method, such as landfill, recycle, composting, and anaerobic digestion.

The main limitation of this study is the difficulty to reach the waste composition. Since municipalities do not keep proper records and large amounts of waste are generated, there may be a certain degree of error in the calculations.

Integrating different MSMWs may provide a better environmental performance as shown in [17, 18]. Landfill disposal has a significant impact on the GWP. Studies have found that storage emits -0.07 to 0.16 kg CO_2eq/kg and 0.25–0.45 kg CO_2eq/kg [28]. Landfill disposal can have a significant impact on the GWP due to the release of methane, a potent greenhouse gas, during the decomposition of organic waste in the landfill. CH4 has a much higher global warming potential than CO_2 over a 20-year time horizon, although it breaks down more quickly in the atmosphere. Recycling makes significant support to both direct and avoided impacts across all impact categories [29]. Anaerobic digestion is widely recommended as an ideal disposal method for organic wastes, as it is suitable for the circular economy due to the possibility of material and energy recovery. At the same time, composting can be a major source of greenhouse gases when not done with the appropriate ratio and content [12]. According to the LCA results of (Slorach et al. [29]), composting has been identified as the worst option for treating food waste in the United Kingdom. It has been observed that anaerobic digestion systems cause a significant negative impact in terms of the GWP effect [30] It has been observed that the performance of anaerobic digestion in categories such as marine eutrophication and terrestrial ecotoxicity is worse than in landfills [31] As a result of analysis with the LCA program, incineration outperformed landfill in terms of environmental impacts [32]. Anaerobic digestion detects more environmentally friendly. Scenarios 1 and 2 were found to have very close global warning potential. Scenario 2 found the least environmental impact in terms of the human toxicity potential of the waste management system. The impact of human toxicity includes global effects arising from global warming, regional consequences related to human toxicity, as well as local effects such as the creation of photochemical oxidation and urban air pollution. S3 also provides much better results for acidification and freshwater eutrophication. However, marine eutrophication potential seems much less in S2.

CONCLUSION

Waste management is an important issue that is considered one of the biggest problems in today's developed cities. As well as neutralizing the wastes collected from the urban environment by processing them with appropriate methods, obtaining a certain amount of environmental gain from these wastes is an approach that has been increasing in importance and application recently. In addition to saving energy and materials by recycling recyclable wastes, organic wastes are also processed to support energy production through biogas production. Incineration and anaerobic digestion methods are the two most preferred methods for energy production and serious energy gains can be achieved if these methods are used as integrated. In addition, as a result of the effective implementation of recycling processes, it is possible to obtain a negative effect in value but a positive effect in meaning. Anaerobic digestion can help to reduce greenhouse gas emissions by capturing and utilizing methane that would otherwise be released into the atmosphere during the decomposition of organic waste in landfills. On the other hand, an interpretation is needed from the perspective of LCA to calculate the holistic effects of these disposal methods. Thus, a full assessment of the environmental effects of the energy consumed during the treatment of wastes and the energy obtained as a result of the treatment of wastes will be made. In these processes, energy is not the only input and output, but different indirect components are also considered as input and output. In this study, four different waste management processes, namely landfill, incineration, anaerobic digestion, and recycling, were evaluated in different scenarios from the perspective of LCA. The results show that while landfill is the method with the highest environmental burden, great reductions in environmental impact occur with the implementation of incineration and anaerobic digestion processes. Since these two processes also provide energy production, a decrease in negative effects during the process has been observed. The recycling process, on the other hand, enabled environmental gains by making environmental impacts positive. As presented in Table 3, especially the recycling of plastics and metals is considered the process that reduces the burden on the environment the most. According to the values shown in Table 2, S1, S2, and S3 produced emissions of 3233.1, 328.8, and -848.9 kg of CO_2eq, respectively, and according to this data, recycling has a positive effect on the global warming potential by reducing the impact. According to the results, a combination of methods consisting of processing the organic components of urban wastes through anaerobic digestion and using the obtained biogas in energy production, recycling the recyclable wastes and generating energy by incinerating the remaining combustible wastes is suggested as the most environmentally friendly method. There is no other option but to send non-recyclable and non-incinerator wastes to a landfill, but in this case, the negative effects of a landfill will be minimized. This study aims to assess the environmental impact of different waste management options, helping decision-makers make informed choices about how to manage the MSW in a way that minimizes environmental damage. By adopting a hierarchical waste management system, prioritizing waste reduction, recycling and responsible waste-to-energy conversion, the environmental footprint of MSW can be significantly reduced. By implementing recommended measures and encouraging collaboration among stakeholders, we can turn MSW into a resource rather than a burden.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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