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Environmental Life Cycle Assessment of Industrial Hazardous Waste Incineration: The Case of Kocaeli, Türkiye

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Abstract This study evaluates the environmental performance of a hazardous waste incinerator with integrated electricity generation using a life cycle assessment (LCA) approach. The aim is to quantify the environmental impacts of hazardous waste incineration with energy recovery and to assess improvement options based on circular economy principles. Three systems were examined: the current situation (CS), a scenario including the beneficial reuse of incineration bottom ash (S1), and a carbon capture and utilization scenario involving CO_2-based methanol production (S2). The assessment followed a consequential LCA framework with system expansion to address multifunctionality by crediting avoided environmental impacts. The system boundary was defined as gate-to-grave, covering operational inputs, emissions to air and water, electricity generation, and final disposal of residues. Electricity produced from the Waste-to-Energy (WtE) plant was credited through substitution of the average Turkish electricity mix. The functional unit was set as 1 ton of waste entering the facility. Foreground data were obtained from a large-scale operating hazardous waste incinerator, while background processes were modelled using the Ecoinvent 3.7 database within SimaPro 9.2 Results show that electricity consumption is the major contributor to environmental burdens in the CS, with a climate change impact of 921 kg CO_2-eq per ton of waste. This impact decreased to 856 kg CO_2-eq/ton in S1 and to 51 kg CO_2-eq/ton in S2. Although S2 achieved the lowest impacts in most categories due to CO_2 capture and conversion, it exhibited higher particulate matter formation and freshwater ecotoxicity linked to steam use. S1 performed best in freshwater ecotoxicity through bottom ash reuse and metal recovery. Overall, the findings demonstrate that circular economy strategies and CO_2 capture technologies can significantly enhance the environmental sustainability of hazardous waste management.

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1 Introduction

Hazardous waste management poses a significant challenge in today's industrialized world, with concerns ranging from public health risks to environmental degradation (Hong et al., 2017). Among the various methods employed for hazardous waste disposal, incineration has emerged as a prominent approach due to its ability to efficiently reduce waste volume and mitigate some hazardous constituents (Li et al., 2015). However, the incineration process also generates significant amounts of air emissions, solid residues, and wastewater, which require careful management to minimize environmental and health impacts (Cristelo et al., 2020; Makarichi et al., 2018). For this reason, the environmental impacts associated with hazardous waste incineration have prompted widespread scrutiny and necessitated the exploration of sustainable practices to minimize adverse effects. In an era where sustainable solutions are crucial, hazardous waste incinerators are considered important actors that can solve two critical problems at the same time: the disposal of hazardous waste and the generation of electricity.

Due to increasing energy demand and environmental concerns, efficient energy production from municipal solid waste and hazardous waste is termed Waste to Energy (WtE), which has been considered as a good option for the transition to a circular economy in recent years (Ungureanu et al., 2021). Waste-to-energy incineration represents a viable and sustainable alternative to conventional waste management approaches like landfilling, composting, and recycling (Bertone et al., 2024).

It is crucial to minimize the need for waste disposal for hazardous materials, ensure the safe final disposal for persistent organic materials, and achieve circular economy's (CE) goals of energy and material recycling (Brunner & Morf, 2025). One notable aspect of hazardous waste incineration is its potential for energy recovery, particularly through the generation of electricity from waste heat. This dual functionality not only addresses waste disposal but also contributes to energy production, aligning with broader efforts to promote renewable energy sources and reduce reliance on fossil fuels. Additionally, the integration of carbon capture technologies holds promise for mitigating greenhouse gas emissions associated with incineration, thereby enhancing the environmental performance of these facilities (Brunner & Morf, 2025; Wienchol et al., 2020). Carbon capture and utilization technologies have emerged as a potential solution to mitigate the environmental impact of hazardous waste incineration by capturing and repurposing carbon dioxide emissions (Bisinella et al., 2021; Sarvestani et al., 2024). Carbon capture processes consist of pre-combustion, post-combustion, and oxy-fuel combustion. Currently, post-combustion technology is regarded as the most developed approach for carbon capture, as it has the least impact on existing systems and is consequently the most widely employed (Wienchol et al., 2020).

An additional environmental challenge associated with waste-to-energy facilities, beyond greenhouse gas generation, is the management of the residual materials produced after the incineration process. The available options for managing these incineration residues (incineration bottom ash—IBA) include landfilling, resource recovery, or reuse of the IBA (Bansal et al., 2024). Beyond emissions reduction, the reuse of bottom ash generated during incineration presents an opportunity to close the material loop and minimize resource depletion. By incorporating bottom ash into construction materials or other applications, hazardous waste incinerators can reduce the demand for virgin resources and mitigate the environmental impacts associated with traditional waste disposal methods such as landfilling.

Life Cycle Assessment (LCA) has become a key methodological tool for evaluating the environmental impacts of waste management systems, including incineration-based WtE facilities (ISO 14040, 2006). Some research efforts have been directed towards assessing the energy efficiency (Lee et al., 2024; Lim et al., 2024) and carbon footprint of incineration facilities (Chang et al., 2025; Rouhi et al., 2024; Zhang et al., 2024), as well as the effectiveness of carbon capture technologies in reducing CO_2 emissions (Bisinella et al., 2021, 2022; Christensen & Bisinella, 2021; Wang et al., 2021; Xu et al., 2025). Furthermore, investigations into the reuse of bottom ash have highlighted its potential to substitute virgin materials in various applications, thus reducing the

environmental burden associated with waste disposal (Heberlein et al., 2024; Olea et al., 2024; Wang et al., 2024). Some studies have investigated the utilization of unbound incineration bottom ash in pavement layers within the context of life cycle assessment frameworks (Allegrini et al., 2015; Bansal et al., 2024. In the study by Allegrini et al. (2015), the importance of incorporating impacts related to leaching and data quality into LCA was assessed when evaluating management strategies for solid residues. Recent studies have predominantly focused on the incineration of municipal solid waste with energy recovery, with particular attention to overall environmental performance (Hsu et al., 2024; Setyono et al., 2025; Sun et al., 2024). In contrast, assessments addressing the incineration of hazardous waste with energy recovery remain relatively limited, especially those based on facility-specific operational data (Hong et al., 2017; Li et al., 2015). In addition, existing life cycle assessment studies employ a wide range of methodological choices, including differences in system boundaries, environmental impact assessment methods, background databases, and approaches to uncertainty and sensitivity analysis. Consequently, reported quantitative environmental impact results exhibit considerable variability, which makes it difficult to address quantitative environmental burdens within a common methodological reference framework. In this context, the present study aims to contribute new perspectives to the literature by presenting a comprehensive life cycle assessment of a hazardous waste incineration plant incorporating energy recovery, supported by facility-specific data and sensitivity analysis.

In this article, we have employed a life cycle assessment approach to comprehensively evaluate the environmental impacts of a hazardous waste incinerator with integrated electricity generation. Furthermore, in addition to the baseline configuration, we have developed two improvement scenarios: (S1) hazardous waste incineration integrated with beneficial reuse of incineration bottom ash (IBA), and (S2) hazardous waste incineration integrated with CO_2 capture and utilization (methanol production). By comparatively assessing these scenarios within a consistent methodological framework, we have aimed to provide insights into sustainable waste management practices and inform decision-making towards a more environmentally responsible approach to hazardous waste treatment.

2 Materials and Method

2.1 Site Description

The waste-to-energy (WtE) plant selected within the scope of this study has a burning capacity of 5400 kg/h (Ata, 2022). The working principle of the plant is based on the elimination by burning of plastic wastes sourced from industry, including used oils, drug and cosmetic waste, petrochemical waste, PVC, solvents, paint waste, glue and adhesives, as well as dangerous wastes such as purifying mud and clinical wastes (Ata, 2022). These wastes are disposed of by feeding them through various feed inlets to incinerators, and the heat generated during incineration is converted into electrical energy (Ata, 2022). Design parameters of the plant are presented in Supplementary Material (Table S1).

The studied WtE plant consists of six main sections: (1) Temporary storage areas, (2) burning, (3) steam and energy production system, (4) purification of waste gas and emission measurement system, (5) wastewater purification system, (6) ash and slag accumulation system. Temporary storage areas consist of bunkers, special liquid area, drum storage area, and tank farm. After the waste accepted to the facility within the framework of waste management regulations are weighed and recorded, they are analyzed and sent to the relevant temporary storage area. In accordance with the prepared daily burning schedules, they are burned in a rotary kiln at a temperature range of 1000 °C to 1200 °C and for an average staying time of 95 to 120 min; whereas in the last burning room, the temperature range is 1050 °C to 1250 °C, with a minimum staying time of 2.5 s (Ata, 2022). The waste gas of 1050 °C – 1250 °C, coming from the last burning room, enters the boiler of wasted heat for cooling purposes and exits at 180 °C – 200 °C. Maximum 27.1 ton/h steam (at a temperature of 350 °C and 40 bar pressure) is produced in the waste heat boiler. The steam produced is sent to the Turbine-Generator Unit, and a maximum of 5.2 MW of electricity is produced. Once the electric energy produced meets the plant's needs (which average 1.2 MW), the rest is sold to the national system (Ata, 2022). After leaving the heat boiler, the waste gas is subjected to a series of treatment processes and released into the atmosphere. At the plant, the gas, which drops to 180 °C—200 °C at the outlet of the waste heat boiler,

passes through the electrostatic filter, and is exposed to an electrical field, and the particulate matter in the gas is retained at the collection electrode, providing 99% efficient treatment. The waste gas from the electrostatic filter outlet enters the venturi scrubber. HCl, HF, and heavy metals in the waste gas are captured in the venturi scrubber. Then, the gas from the venturi scrubber enters the lime spray scrubber. In this section, SO_2 and heavy metals are removed from waste gas subjected to neutralization, oxidation, and absorption processes. In the lime spray scrubber, the pH is kept at 5.5—6, and 10% milk of lime is fed (Ata, 2022). Subsequently, the flue gas passes through an activated carbon unit for the removal of dioxins and furans. Finally, the gas at 50–58 °C, which has been physically and chemically cleaned, is released into the atmosphere through the plant stack (https://www.izaydas.com.tr/files/documents/tanitim2018en.pdf). Washing water from the venturi scrubber, filtrate from filtration, and wastewater generated due to use in the system's operational processes are treated in the physical–chemical treatment unit. While the water treated in this unit is discharged to the canal, the sludge, after being dried, is sent to the hazardous waste storage area (Ata, 2022). Bottom ash resulting from incineration in the rotary kiln is sent to the hazardous waste landfill. Fly ash is sent to the physicochemical treatment unit for pre-treatment. As a result of this process, fly ash that meets storage criteria is converted into filter press cake and sent to a hazardous waste landfill (Ata, 2022).

2.2 Life Cycle Assessment (LCA)

There are four phases in an LCA study: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (ISO 14040). An extensive guideline is available on how to perform a waste LCA (Christensen et al., 2020; Manfredi & Pant, 2011).

2.2.1 Goal, Scope, and Functional Unit

The goal of this LCA study is to estimate the potential environmental impacts of hazardous waste disposal by incineration (with energy recovery) and to investigate future scenarios for the hazardous waste incineration plant by applying circular economy principles, aiming to reduce the environmental impact of waste and conserve natural resources. For this purpose, two scenarios were built in addition to the current situation (CS) of the studied hazardous waste incineration plant: (S1) Bottom ash reuse scenario and (S2) CO_2-based methanol production scenario.

Waste incineration plants, also referred to as Waste to Energy (WtE) plants, require various inputs (reagents, electricity, water, fuel, etc.) and provide energy (electricity, steam, hot water). Additionally, incineration produces different residues which require treatment. Hence, consumption of inputs and treatment of residues should be included within the system boundaries (Manfredi & Pant, 2011). The system boundary was set as 'gate to grave', i.e. from the entry to the incineration plant until the final disposal of all solid residues; as is common in LCA studies dealing with waste management (Paulu et al., 2022). It includes operational inflows (reagents, electricity, fuel, water, etc.), environmental outflows (emissions to air and water), and produced electricity from wastes (as environmental credit) as shown in Figure S1 (Supplementary Material). Consequential LCA studies need to expand the system boundaries to include effects of decisions, which include first order effects (i.e., direct substitution) as well as second and third order effects (Materazzi et al., 2024). For this purpose, consequential modelling was used in this study as the inventory modelling approach, and the multi-functionality issues in the system were resolved by system expansion (Bisinella et al., 2021). System expansion with crediting of the avoided environmental impacts is the most widely applied allocation approach in waste management studies (Materazzi et al., 2024). The electricity produced from the WtE plant was assumed to substitute the average Turkish electricity consumption mix. Waste collection and infrastructure were ignored in the LCA study because the focus was on the operational stage of hazardous waste incineration. Furthermore, waste collection is the same for all scenarios. The functional unit (FU) was chosen as 1 ton of input waste received at the gate of the WtE plant, which is also used, most frequently in the literature (Cleary, 2009; Dastjerdi, et al., 2021; Liao et al., 2025; Özer & Yay, 2021).

2.2.2 Life Cycle Inventory and Scenario Building

The inventory data for the foreground systems include the Waste-to-Energy (WtE) plant specification and

operating conditions. They were obtained from a specific plant, which operates a large-scale incinerator. On the other hand, background data were supplemented with the Ecoinvent 3.7 database embedded in SimaPro (v.9.2) LCA software. This was referred to as the current situation (CS) in this LCA study. The current situation (CS) includes the entry of waste into the incineration plant, energy consumption (electricity and heat), electricity production from waste, water consumption, chemical substance consumption, and disposal of all solid, liquid, and gaseous waste associated with the incineration process. In addition to CS, two more scenarios based on environmental sustainability and circular economy practices were built as follows:

- (S1) Bottom ash reuse scenario: In this scenario, it was assumed that all bottom ash resulting from rotary kiln incineration, were utilized as aggregate in road construction instead of being sent to the hazardous waste landfill. On the other hand, metals replaced fixed amounts of steel and aluminum (Arena et al., 2015). For this purpose, a bottom ash treatment model was developed and added to the Current Scenario (CS) in SimaPro (v.9.2). The data that used for modelling of "bottom ash treatment" was obtained from Ecoinvent 3.7 and Biganzoli et al. (2019). The metal components (steel, aluminum, and copper cake) recovered from bottom ash treatment were included in the LCA as avoided burdens. The details of the bottom ash treatment model can be seen in Table 1.
- (S2) Carbon capture and utilization scenario: In this scenario, it was assumed that CO_2 was captured by a post-combustion capture system and used to produce CO_2-based methanol instead of traditional methanol production in order to achieve carbon neutrality. To this end, the CO_2-capture process, hydrogen production process (via electrolysis), and methanol synthesis process were modelled and added to the Current Scenario (CS). For CO_2 capture, an amine-based post-combustion capture system was considered for the Waste-to-Energy Plant. The amine-based capture is the best-documented procedure and widely used technology that involves the absorption of CO_2 from the flue gas using an aqueous amine solution, typically monoethanolamine (Bisinella et al., 2021; Rafiq et al., 2024). Methanol is produced from CO_2 (captured) and H_2 by a catalytic process ($CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$) as stated in (Christensen & Bisinella, 2021). It was assumed that hydrogen was produced via electrolysis. Foreground inventory data of CO_2 capture system, hydrogen production, and methanol synthesis were derived from the various studies in the literature (Christensen & Bisinella, 2021; Michailos et al., 2018; Rafiq et al., 2024). The details of these models can be seen in Table 1. Aside from CO_2, emissions of SO_2 and NO_x from the power plant with post-combustion capture differ from those from the power plant without carbon capture and storage (CCS), because these emissions can react with the MEA (monoethanolamine) solvent in the absorber of the CCS unit. In addition, in the wet scrubber, partial particulates and HCl in the flue gas are removed as well. However, the degradation of MEA solvent promotes the formation of additional NH3, and MEA emission is directly released because part of the MEA solvent leaves the stripper through evaporation, or entraining as droplets (Tang & You, 2018). These additional removals resulting from the use of carbon capture unit were calculated and given in Table 1. All input and output data related to the CS, S1, and S2 were presented in Table 1.

2.2.3 Impact Assessment and Data Interpretation

In this study, potential environmental impacts of the Waste-to-Energy plant (CS) and two scenarios (S1 and S2) were assessed with the EF 3.0 method, taking into account 16 impact categories. The EF 3.0 method, developed by the European Commission to be used in the context of the Environmental Footprint (EF) initiative, is the most up-to-date European method (SimaPro, 2022). It contains normalization and weighting factors, in addition to a characterization step.

In the last phase, which is called an interpretation, life cycle impacts were evaluated in accordance with the goal and scope of the study. In addition, hot spot analyses, contribution analyses, and sensitivity analysis were performed at this phase, and the results were interpreted comparatively. Energy recovery and input waste composition are among the key parameters determining the

Table 1 Input and output data for LCA modelling for three scenarios (The values based on functional unit)

Parametre	CS	S1	S2	Unit
Input:				
Amount of waste	1000	1000	1000	kg
Lower heating value of waste	1.22E + 04	1.22E + 04	1.22E + 04	MJ
Energy recovery (electricity)	−4.24E + 02	−4.24E + 02	−4.24E + 02	kWh
Material use:				
Lime	1.69E + 01	1.69E + 01	1.69E + 01	kg
Tap water	1.53E + 00	1.53E + 00	1.53E + 00	m3
Sodium hydroxide	2.30E-01	2.30E-01	2.30E-01	kg
Iron (III) chloride	8.00E-02	8.00E-02	8.00E-02	kg
Acrylonitrile	3.70E-03	3.70E-03	3.70E-03	kg
Nitrogen (liquid)	8.00E-01	8.00E-01	8.00E-01	kg
Energy use:				
Electricity (medium voltage)	2.49E + 02			kWh
Heat, from natural gas	8.42E + 02			MJ
Bottom ash management:				
Electricity consumption	-			
Tap water	-	9.58E + 01**	-	kg
Polyacrylamide	-	6.28E-03**	-	kg
Aluminum sulfate	-	4.07E-02**	-	kg
Transport	-	5.99E + 00**	-	tkm
Gravel	-	−2.60E + 02**	-	kg
Steel	-	−7.66E + 00**	-	kg
Aluminum (primary)	-	−1.29E + 00**	-	kg
Copper cake	-	−5.60E-01**	-	kg
Wastewater	-	3.89E-02**	-	m3
Carbon capture and utilization:	-	-	0.685	kg
CO_2 capture unit:	-	-	0.74	kg
Tap water	-	-	622	kg
Activated carbon	-	-	0.0518	kg
Monoethanolamine (MEA)	-	-	1.11	kg
NaOH	-	-	0.0888	kg
Electricity	-	-	266	MJ
Heat, from steam	-	-	2.74E + 03	MJ
Methanol synthesis (CO_2-based) process			510	kg
Tap water			2.29E + 03	kg
Copper oxide	-	-	0.0316	kg
Zinc oxide	-	-	0.0148	kg
Aluminum oxide	-	-	0.00612	kg
Hydrogen (via *electrolysis)*	-	-	102	kg
Electricity, medium voltage	-	-	36	MJ
Methanol production (NGTM-avoided impact)	-	-	−510	kg
Output:				
Emissions to air:				
Carbon monoxide	4.33E-02	4.33E-02	4.33E-02	kg
Nitrogen oxides	5.88E-01	5.88E-01	*5.73E-01	kg
Sulfur dioxide	7.97E-03	7.97E-03	*3.99E-05	kg

Table 1 (continued)

Parametre	CS	S1	S2	Unit
TOC, Total Organic Carbon	1.28E-03	1.28E-03	1.28E-03	kg
Hydrogen fluoride	6.28E-06	6.28E-06	6.28E-06	kg
Hydrogen chloride	2.15E-03	2.15E-03	*1.08E-04	kg
Particulates	2.68E-03	2.68E-03	*1.34E-03	kg
Carbon dioxide, fossil	8.70E+02***	8.70E+02***	1.00E-02	kg
Wastewater discharged:	0.5	0.5	0.5	m3
Mercury (Hg)	1.65E-04	1.65E-04	1.65E-04	g
Cadmium (Cd)	3.07E-01	3.07E-01	3.07E-01	g
Thallium (Tl)	3.50E-02	3.50E-02	3.50E-02	g
Antimony (Sb)	1.80E-01	1.80E-01	1.80E-01	g
Arsenic (As)	4.25E-03	4.25E-03	4.25E-03	g
Lead (Pb)	1.04E-01	1.04E-01	1.04E-01	g
Chromium (Cr)	9.90E-02	9.90E-02	9.90E-02	g
Cobalt (Co)	2.50E-02	2.50E-02	2.50E-02	g
Copper (Cu)	2.83E-01	2.83E-01	2.83E-01	g
Manganese (Mn)	2.52E-01	2.52E-01	2.52E-01	g
Nickel (Ni)	2.45E-02	2.45E-02	2.45E-02	g
Vanadium (V)	2.90E-02	2.90E-02	2.90E-02	g
Dioxin/Furan	2.10E-03	2.10E-03	2.10E-03	g
Suspended solid	3.80E+01	3.80E+01	3.80E+01	g
Solid waste to treatment:				
Bottom ash (to sanitary landfill)	2.99E+02	-	2.99E+02	kg
Fly ash and filter press cake (to sanitary landfill)	3.98E+01	3.98E+01	3.98E+01	kg

*a further reduction in NOx, SO2, HCl, and particulates (Tang & You, 2018)

**Scenario built by Biganzoli et al. (2019): "natural gravel in the realization of a road embankment layer"

***Obtained from the literature: Zhao et al. (2009)

environmental performance of waste incineration technologies (Key factors influencing the environmental performance of pyrolysis, gasification and incineration Waste-to-Energy technologies). Therefore, sensitivity analysis was performed for these two critical parameters, which are thought to significantly affect the LCA results. For this purpose, a total of six sensitivity analysis scenarios were created by varying the amounts of electricity production and natural gas consumption at different rates. It was assumed that natural gas consumption would increase due to the decrease in the calorific value of the inlet waste composition. The sensitivity scenarios that are created for the CS are summarized in Table 2.

Table 2 Description of the sensitivity analysis scenarios

Sensitivity Scenario		Description
Electricity generation (SA1)	SA1-a	No electricity generation
	SA1-b	Electricity production increases by 10%
	SA1-c	Electricity production increases by 30%
Calorific value of input waste (SA2)	SA2-a	Calorific value of input waste decreases by 10%
	SA2-b	Calorific value of input waste decreases by 20%
	SA2-c	Calorific value of input waste decreases by 30%

3 Results and Discussion

The impact assessment results for CS, S1, and S2 were presented comparatively in this section. In Section 3.1, the interpretation of results was given and explained for the current situation (CS). In Section 3.2, life cycle assessment results for CS, S1, and S2 were discussed comparatively.

3.1 Environmental Profile of Current Situation (CS) for the Studied Waste-to-Energy Plant

The environmental profile of the WtE plant studied is presented in Fig. 1. While negative values indicate an environmental saving, positive values indicate the presence of an environmental burden (Sukma et al., 2022). Figure 1 shows the characterization results of mid-point impact categories. The contribution of characterization was divided into seven life cycle stages: chemical substance consumption, electricity consumption, electricity generation, natural gas consumption, water consumption, residual management, and direct emissions. When considering the environmental burden of hazardous waste incineration, electrical energy consumption ranks first in all impact categories. Its contribution ranges from 7% (for land use) to 60% (marine eutrophication). The environmental burden of natural gas consumption on ozone depletion (77.5%) and fossil resource use (52.1%) is noteworthy. Direct emissions (especially CO_2-fossil) and water consumption are other mid-point impact categories that negatively affect the environmental profile of hazardous waste incineration. The climate change impact is evaluated at 921 kg CO_2-eq/t.waste, and it constitutes approximately 90% of the overall environmental burden of the plant. While electricity generation improved climate change impact by 9.4%, direct emissions related to incineration (CO_2-fossil) had a negative impact of 94.4%. The incineration of waste directly releases significant amounts of

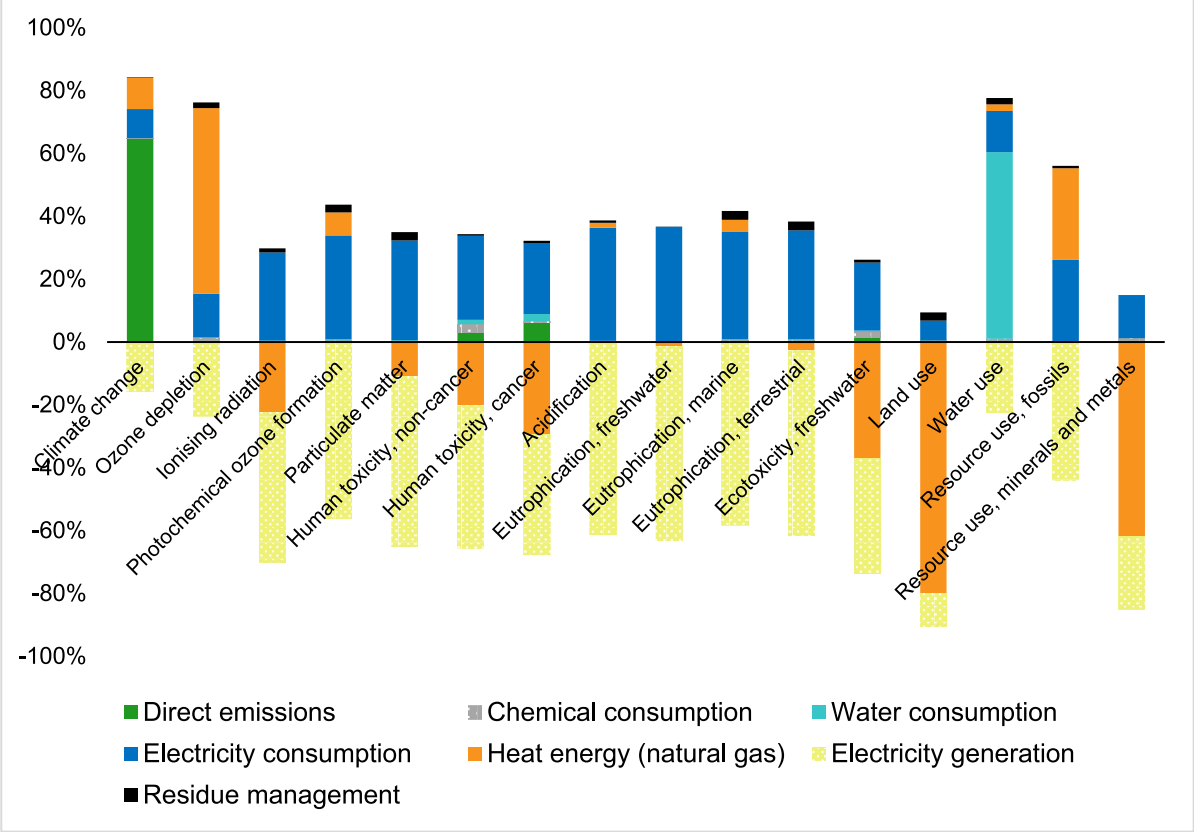

Fig. 1 Characterization results for the Current Situation (CS)

greenhouse gases into the atmosphere as stated in the literature (Salvador & Doong, 2024). The residues (bottom ashes) formed after incineration are disposed of in a sanitary landfill. It is determined that residue management contributes approximately 11% to eutrophication (marine and terrestrial) and photochemical ozone formation.

When the environmental savings of hazardous waste incineration were evaluated, these savings related to electricity generation and heat energy (natural gas consumption) are quite significant as seen in Fig. 1. Electricity generation from hazardous waste incineration makes a significant contribution to almost all mid-point impacts; especially acidification, eutrophication (freshwater, marine, and terrestrial), and photochemical ozone formation (approximately 100%).

In terms of human toxicity-related impacts in our study, it was determined that this impact is mainly related to heat and electrical energy (consumption and generation). On the other hand, direct emissions contribute 13% and 8% to the human toxicity (cancer) and human toxicity (non-cancer) impact categories, respectively. All of these direct emissions that cause human toxicity (cancer) and human toxicity (non-cancer) are mainly waterborne emissions. The wastewater generated from the incineration process is treated in the on-site physical–chemical wastewater treatment plant within the facility and then released into the municipal sewage network. Therefore, wastewater from the incineration plant contains relatively low concentrations of heavy metals, and the pollutants in the wastewater make only a minimal contribution to human toxicity, consistent with the findings of Li et al. (2015). The water-borne emissions that contribute to the human toxicity-related impacts was shown in Supplementary Material (Figure S2). While chromium accounts for 90.9% of these emissions, cadmium, nickel and arsenic account for the rest within the human toxicity (cancer) impact category. Considering how chemical substances affect the human toxicity (non-cancer) impact category, cadmium is seen to account for 86% of this impact category, while the rest are arsenic (7%), antimony (4%), and thallium (3%).

3.2 Comparison of the Environmental Impact of Scenarios

The comparative life cycle impact assessment results of the scenarios are given in Table 3.

Table 3 shows that S2 has the lowest environmental burden as compared to CS and S1 in almost all impact categories, except for the impact categories of particulate matter, human toxicity (cancer and non-cancer), and freshwater ecotoxicity. The levels of particulate matter and freshwater ecotoxicity were found to be highest in S2. The main reason for

Table 3 The results of the life cycle impact assessment of CS, S1, and S2. (FU: 1 ton hazardous waste)

Impact category	Unit	CS	S1	S2
Climate change	kg CO_2 eq	9.21E+02	8.56E+02	5.08E+01
Ozone depletion	kg CFC11 eq	2.14E-05	1.85E-05	−2.10E-04
Ionising radiation	kBq U-235 eq	−5.98E+00	−6.70E+00	−1.28E+01
Photochemical ozone formation	kg NMVOC eq	−9.33E-02	−3.72E-01	−8.74E-01
Particulate matter	disease incidence	−3.69E-06	−8.32E-06	2.76E-06
Human toxicity, non-cancer	CTUh	−9.10E-07	−3.11E-06	−1.50E-06
Human toxicity, cancer	CTUh	−3.36E-08	−2.55E-07	−6.47E-08
Acidification	mol H+eq	−4.54E-01	−7.96E-01	−1.41E+00
Eutrophication, freshwater	kg P eq	−9.81E-03	−1.30E-02	−2.36E-02
Eutrophication, marine	kg N eq	−3.38E-02	−1.04E-01	−1.57E-01
Eutrophication, terrestrial	mol N eq	−5.15E-01	−1.26E+00	−2.01E+00
Ecotoxicity, freshwater	CTUe	−1.51E+03	−3.93E+03	−4.83E+02
Land use	Pt	−3.34E+03	−3.61E+03	−5.36E+03
Water use	m3 depriv	6.15E+01	4.48E+01	−3.37E+02
Resource use, fossils	MJ	8.27E+02	1.72E+02	−1.15E+04
Resource use, minerals and metals	kg Sb eq	−2.46E-03	−2.30E-03	−3.23E-03

the increase in the particulate matter and freshwater ecotoxicity impact category is steam usage, according to the process contribution analysis. A high amount of steam is used in the MEA process to capture CO_2. Christensen and Bisinella (2021) have also stated that carbon capture induces an energy penalty, since the MEA process uses part of the steam originally used for electricity production. The results of processes and chemical substances that contribute to particulate matter in S2 can be seen from Fig. 2(a) and (b). In the S2 scenario, CO_2-based methanol production is modeled as a substitute for natural gas-based methanol production. This situation provides environmental savings in the usage of natural gas and oxygen used in natural gas-based methanol production according to the process contribution analysis. Environmental gain in electricity consumption is related both to the prevention of natural gas-based methanol production and to energy production during waste incineration. When the chemical substances are examined, the chemical contents that are dominant in the particulate matter impact category are generally $PM_{2.5}$ and SO_2 (Fig. 2(b)).

Considering the processes that contribute to freshwater ecotoxicity, deionized water is the second most affected process after steam production (Fig. 3). Deionized water is used in the production of hydrogen required in both CO_2-based and natural gas-based methanol production processes. However, while the potential impact of deionized water used in CO_2-based methanol production on freshwater ecotoxicity is 1382 CTUe, the potential impact of deionized water used in natural gas-based methanol production on freshwater ecotoxicity is 2642 CTUe. Therefore, when the results are evaluated using the approach that natural gas-based methanol production will be avoided by applying the S2 scenario, it is seen that net deionized water consumption will provide considerable environmental savings on freshwater ecotoxicity (Fig. 3). However, S1 preceded CS and S2 in terms of freshwater ecotoxicity (Fig. 4). The main reason for this finding is the environmental savings from the management of incineration bottom ash. Therefore, it is possible to say that instead of sending bottom ash to a sanitary landfill, recovering the valuable metals (steel, aluminum, and copper) in it and reusing its inert part as filling material (instead of gravel) in road pavement has a positive environmental contribution to freshwater ecotoxicity.

Life cycle impacts after normalization and weighting steps are shown in Fig. 5. This figure was created by taking into account the most dominant impact categories after normalizing all data following the characterization step. Therefore, it is important as it indicates that the most dominant impact category for CS and S1 is climate change because of the direct

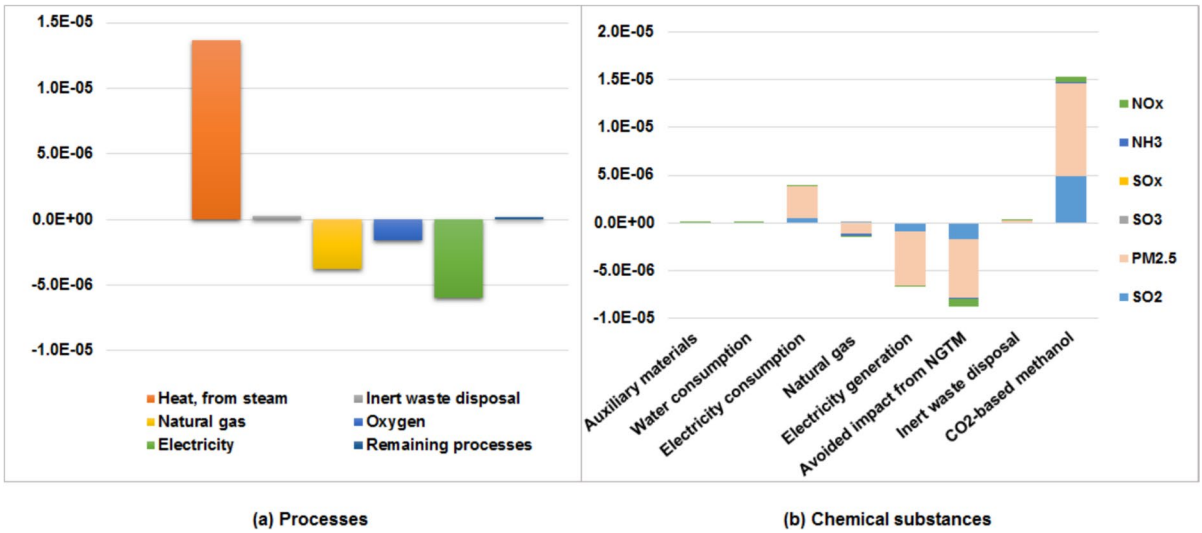

Fig. 2 Contribution analysis of the particulate matter impact category under Scenario S2 (Unit: disease inc.; NGTM: Natural gas to methanol production)

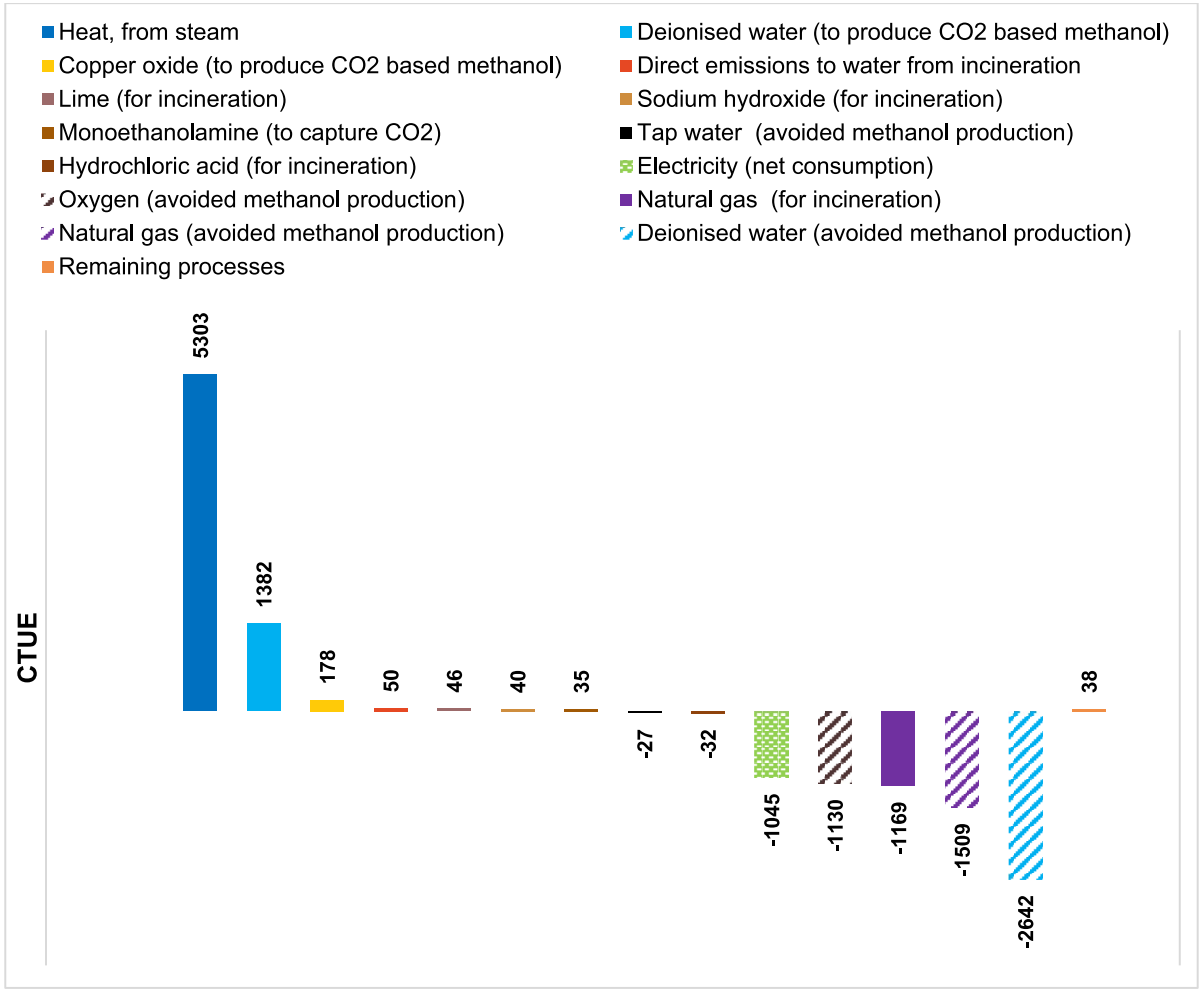

Fig. 3 Contribution of individual processes to freshwater ecotoxicity impacts in S2

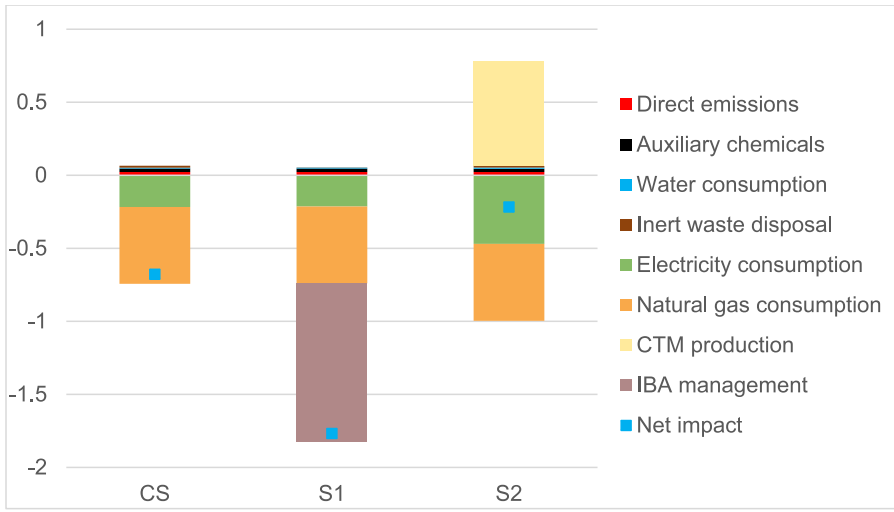

Fig. 4 Comparison of process contributions to freshwater ecotoxicity impacts under three scenarios

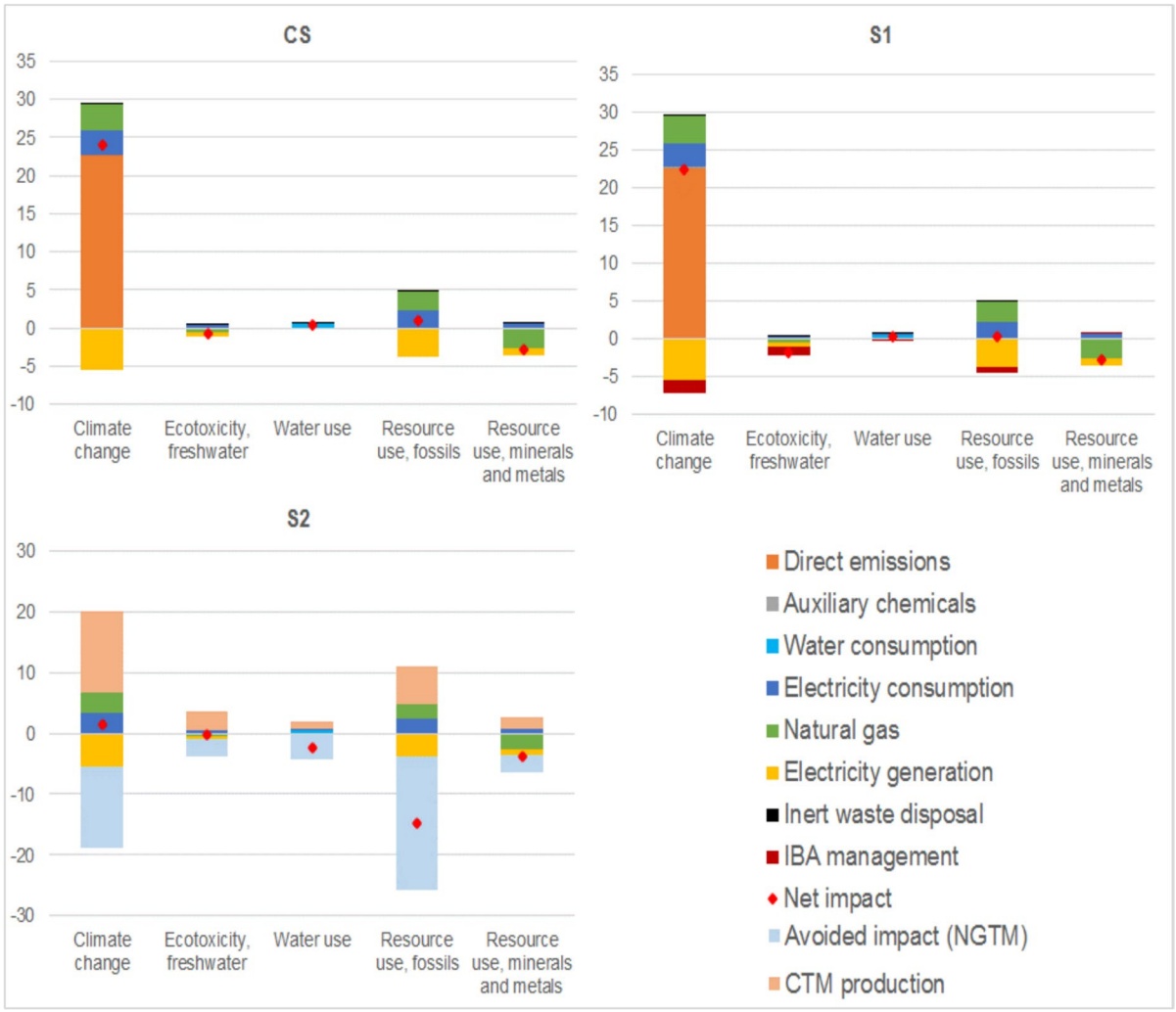

Fig. 5 Normalized results of the three scenarios for the most dominant impact categories (Unit: mPt. NGTM: Natural gas to methanol production, CTM: CO_2 to methanol production)

emissions from incineration. Climate change is one of the most significant impact categories in waste incineration plants as discussed by other authors (Lausselet et al., 2016; Li et al., 2015). Lausselet et al. (2016) reported that direct emissions from a WtE plant account for more than 90% of the WtE process, with fossil CO_2 being the primary driver. Hong et al. (2017) have determined the global warming potential impact of industrial hazardous waste incineration was 1.64 t CO_2eq/t, which is approximately two times higher than our results for CS and S1. However, in contrast to our findings, the study by Hong et al. (2017) reported a dominant contribution to environmental degradation from the carcinogen impact category. They stated that the chemical substances that have the dominant contribution to carcinogens are heavy metals and carbon dioxide emissions. In our study, most of the impact categories (ionising radiation, photochemical ozone formation, particulate matter, ecotoxicity, human toxicity, acidification, eutrophication, and land use) have negligible values. The main reason for this difference is the high amount of electrical energy generated from waste (424 kWh/t. waste) in the facility selected in our study. This result clearly demonstrates the contribution of waste-to-energy recovery to preventing

environmental degradation. Additionally, one of the important results of our study is that environmental gains can be achieved in the climate change impact category with the use of carbon capture and utilization technologies (Fig. 5).

When the contributions of the processes affecting climate change are investigated (Table S2 and Fig. 5), it is noticeable that direct emissions arising from the incineration process significantly decreased in the S2 scenario that used the CO_2 capture and utilization process. With this process, the impact of direct emissions, almost all of which are related to CO_2-fossil, was reduced to 1.32 mPt. Despite causing additional electricity consumption, the use of CO_2 capture and utilization systems (as in S2) is effective in reducing the climate change impact by 95%, compared to CS and S1. Consistent with our findings, the study by Bisinella et al. (2021) demonstrated that integrating carbon capture and storage technology into municipal solid waste incineration facilities can mitigate climate change impacts by approximately 700 kg of CO_2-equivalent per tonne of incinerated waste, despite the energy requirements of the capture process.

The other important finding in Table S2 is the environmental savings that are achieved in the climate change impact category thanks to the recovery of aggregates (as gravel) and scrap metals (steel, copper, and aluminum) because of the incineration bottom ash (IBA) management in S1. Instead of sending IBA to hazardous waste landfills, using it as aggregate (gravel) in road pavement after recovering the scrap metals in it provides an environmental benefit of 66 kg CO_2-eq/tonne.waste in the climate change impact category. Bisinella et al. (2021) have similarly noted that the management of incineration residues provides relatively modest savings due to the recovery of materials such as aggregates and scrap metals (-63 kg CO_2-eq per tonne), in accordance with our study.

Finally, a single score comparison was conducted between CS and two scenarios (S1 and S2), and the results were given in Fig. 6. Single scores of CS and S1 were evaluated as 19.9 and 14.1 mPt, respectively. Climate change impact constitutes a significant proportion of the overall environmental burden for CS and S1, as shown in Fig. 6. When S2 is considered, a significant decrease is observed in the climate change impact category because of the CO_2 capture. The utilization of captured CO_2 for methanol production provides significant environmental benefits in the fossil resource use impact category, while it adversely affects mineral and metal resource use. However, CCS increases environmental impacts in other categories, though not to the same order of magnitude as the savings achieved in the climate change category (Bisinella et al., 2022).

The environmental impacts of a modern waste-to-energy (WtE) plant in Belgium were assessed by Boakes et al. (2023) in the context of the use of recovered energy and the addition of carbon capture and storage. Similar to the findings of our investigation, the largest environmental benefit in the climate change impact category was attained when carbon capture and storage technology was incorporated. But the environmental burden of the other categories increased due to the additional energy consumption and material requirements. Existing studies have found that monoethanolamine-based carbon capture and storage technologies can mitigate the climate change impacts of waste-to-energy processes; however, they also increase the overall resource utilization of these systems due to the additional energy and material requirements (Lausselet et al., 2016; Tang & You, 2018; Boakes et al., 2023). Our results have also indicated that the implementation of carbon capture and utilization technologies has led to increases in the impact categories of particulate matter and freshwater ecotoxicity, owing to the substantial steam consumption required by these processes.

3.3 Sensitivity Analysis

The results of the sensitivity analysis are present in Table S4 (in Supplementary Material). The table shows the percentage changes in six different sensitivity analysis scenarios compared to the current scenario (CS). In the SA1-b and SA1-c scenarios, where electricity generation is increased (by 10% and 30% respectively), the negative percentage changes observed in most impact categories (ranging from 1.31% to 134.19%) indicate that environmental burdens are lower than in the current scenario. In contrast, in the SA1-a scenario, which assumes no electricity generation, higher environmental burdens are observed in all impact categories, as expected. When examining the SA2 scenarios, which are based on the assumption of changes in the calorific values of the

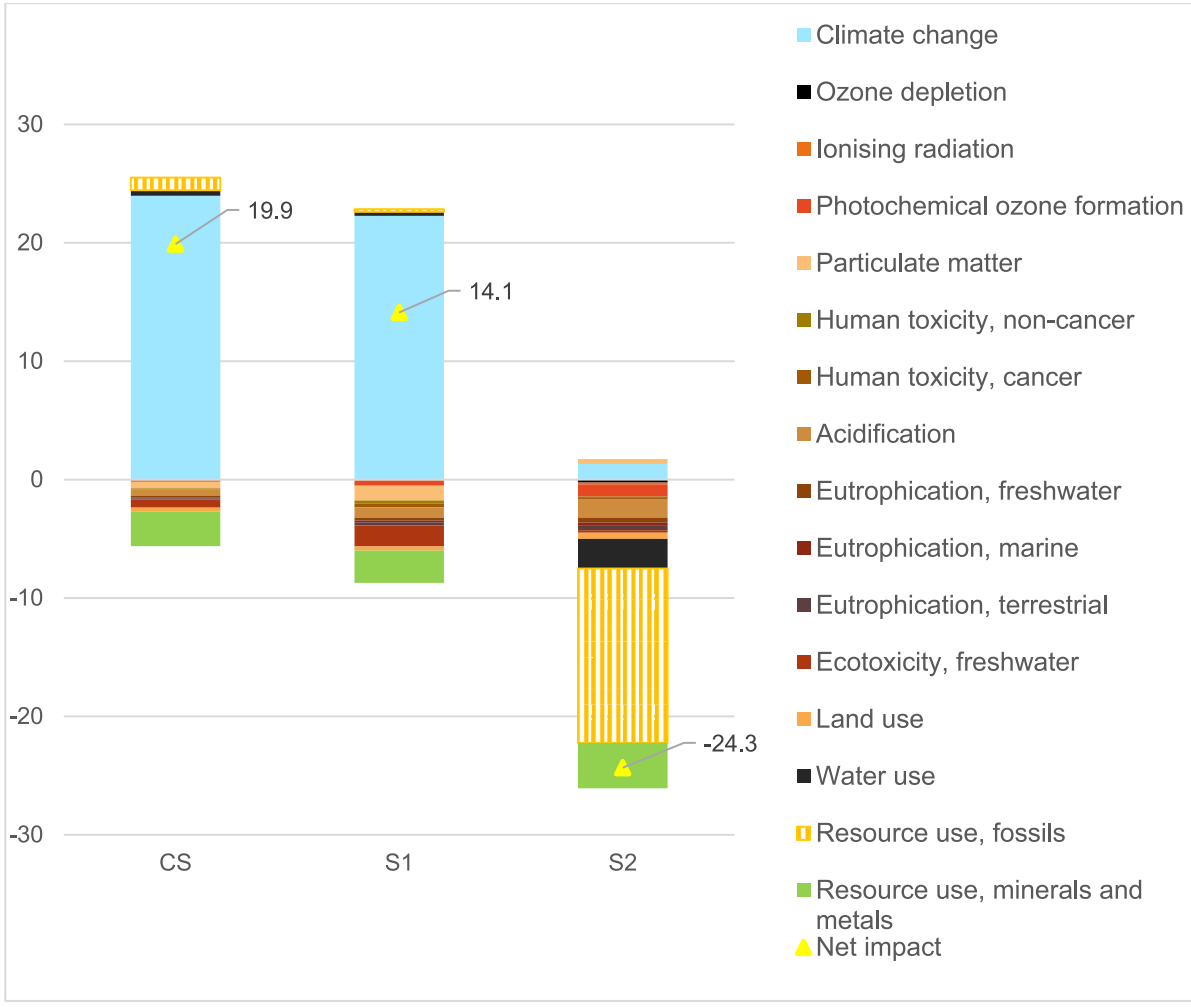

Fig. 6 Comparison of single score (mPt) results across scenarios

influent, it is noteworthy that these scenarios show significant positive increases, especially in the categories of fossil resource use and ozone depletion.

When the sensitivities of the impact categories are examined separately, it is possible to say that 3 impact categories in particular are significantly sensitive to changes in electricity production and the calorific value of the input waste: fossil resource use, ozone depletion, and photochemical ozone formation.

It is important for decision-making that scenario selection should be considered not only through individual impact categories but also through a multidimensional impact assessment approach. For this reason, single score results were determined, and the results are presented in Figure S3. When the sensitivity analysis scenarios are examined, it is seen that SA1-a (where there is no electricity generation) and SA2-c (where the waste calorific value is reduced by 30%) have the highest environmental load, as expected.

4 Conclusion

This study addresses the environmental life cycle assessment (LCA) of an existing hazardous waste incinerator in Türkiye. The study compares the current status (CS) and two scenarios that aim to increase sustainability in waste management: S1, which includes the reuse of bottom ash, and S2,

which examines carbon capture and utilization (for CO_2-based methanol production). Compared to S2, climate change impacts constitute a substantial component of the overall environmental burden in CS and S1.

According to the life cycle impact assessment results, S1 has a lower environmental burden (or more environmental savings) in many impact categories compared to the CS. It also outperformed both the CS and S2 scenarios in the freshwater ecotoxicity impact category. Reusing the inert portion of bottom ash from hazardous waste incinerators as a road filler material, after recovering the valuable metals, provides a positive environmental contribution to freshwater ecotoxicity. In addition, the S1 scenario has an environmental impact profile that is approximately 29% lower than that of CS.

The study showed that the use of CO_2 capture and utilization systems (as in S2) is effective in reducing the climate change impact by 95% compared to the CS and S1 scenarios (without capture). This result clearly demonstrates that carbon capture provides a significant environmental benefit in reducing the impact of hazardous waste incinerators on climate change. According to Tang and You (2018), the use of MEA-based absorption technology significantly mitigates the overall impact of direct emissions, primarily driven by substantial reductions in the climate change impact category. On the other hand, since the MEA absorption used in the carbon capture process requires a significant amount of energy (steam and electricity) and materials, it can increase the environmental burden in some impact categories other than climate change (particulate matter, human toxicity (cancer and non-cancer) and freshwater ecotoxicity). Therefore, conversion of captured carbon dioxide into value-added products such as methanol can offer additional environmental benefits by mitigating the impacts associated with conventional methanol production methods. This situation offers a significant environmental benefit, especially in the fossil resource use impact category. Indeed, the use of methanol in chemical processes resulted in a net climate change benefit (-870 kg CO_2-eq/tonne waste) for S2 compared to CS.

Based on the study's findings, capturing CO_2 and converting it into a value-added product is highly valuable for environmental sustainability. On the other hand, it is stated in the literature that post-combustion capture, although it is the most mature and known method today, causes a significant decrease in the efficiency of WtE plants. Therefore, it is important for future studies to focus on the investigation of carbon capture and storage technologies, such as oxy-fuel combustion capture, that better alternatives to MEA absorption to optimize resource use in the carbon capture process and to prevent efficiency decreases in WtE plants.

On the other hand, the fact that the leakage characteristics of the bottom ash formed in the selected hazardous waste incineration plant were not determined, which can be expressed as a limitation of this study. Although life cycle assessment studies provide comprehensive results about possible impacts and environmental benefits, a definitive recommendation for the reuse of bottom ash should be carried out primarily by determining the leakage characteristics, conducting leakage tests and integrating these results into LCA models and evaluating them.

Author Contributions All authors contributed to the study conception and design. Data collection was performed by Abdullah ATA and Şahan DEDE. Software analyses were performed by Abdullah ATA and Simge ÇANKAYA. The first draft of the manuscript was written by Simge ÇANKAYA and Beyhan PEKEY. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Publish Not applicable.

Competing Interests The authors declare no competing interests.

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