Oo, PZ, Prapaspongsa, T, Strezov, V, Huda, N, Oshita, K, Takaoka, M, Ren, J, Halog, A and Gheewala, SH

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Sustainable Production and Consumption 52 (2024) 498–510

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

The role of global waste management and circular economy towards carbon neutrality

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A R T I C L E I N F O

Editor: Prof. Carmen Teodosiu

Keywords:
Solid waste management
Circular economy
Life cycle assessment
Greenhouse gas emissions
Carbon neutrality
Global waste targets

A B S T R A C T

Solid waste management is a cross-cutting issue that significantly influences multiple aspects of sustainable development globally. The waste sector is a major anthropogenic source of global greenhouse gas (GHG) emissions. Most global GHG assessments of waste management rely on generic data due to limitations in available data. This research used reflective inventory data for municipal solid waste (MSW) treatment systems related to the income levels of countries, resulting in more context-specific and comprehensive assessments of GHG emissions. This study aims to assess life cycle GHG emissions from the global MSW management sector for the years 2023, 2030, and 2050 and then analyses the global and regional waste management goals set by the United Nations Environment Programme (UNEP) and the European Union (EU) to identify hotspots in the MSW management systems and critical factors that influence GHG emissions from the waste sector. The study was conducted in accordance with the standards outlined in ISO 14067:2018. The results show that the average global GHG emissions from 1 tonne of MSW in 2023 based on the existing MSW management practices was approximately 89.7 kg CO_{2e}. The major contributor was the open dumping of MSW, contributing almost 70 % of GHG emissions. The global MSW management sector emitted a total of 173.2 Mt CO_{2e} GHG emissions in 2023. If no improvements are made to existing systems, GHG emissions from the waste sector are projected to increase to 203.4 Mt CO_{2e} by 2030, and to 289.5 Mt CO_{2e} by 2050. Achieving waste management goals can reduce GHG emissions by approximately 1 % to more than 160 %. The implementation of the circular economy in the waste sector has the potential to achieve net zero emissions from the global MSW management sector by 2030 and 2050. This study provides achievable MSW management targets for the world and highlights key factors to achieve carbon neutrality from the waste sector. Prioritising policies such as upgrading open dumps, standardising household-level waste separation procedures, minimising food waste, establishing national recycling targets, and promoting circular economy through a zero-waste approach could substantially reduce GHG emissions from the waste sector. These findings are important for the adoption of circular economy principles in MSW management systems to effectively support the pursuit of carbon neutrality goals.

Abbreviations

GHG	Greenhouse gas
SDGs	Sustainable Development Goals
MSW	Municipal solid waste
UNEP	United Nations Environment Programme

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https://doi.org/10.1016/j.spc.2024.11.021
Received 28 September 2024; Received in revised form 14 November 2024; Accepted 15 November 2024
Available online 17 November 2024

EU	European Union
BAU	Business-as-usual
CES	Circular economy scenario
HICs	High-income countries
UMCs	Upper-middle-income countries
LMCs	Lower-middle-income countries
LICs	Low-income countries

1. Introduction

The waste sector is a major anthropogenic source of global greenhouse gas (GHG) emissions, ranking as the fourth highest contributor to global GHG emissions (Gautam and Agrawal, 2021). The waste sector is responsible for 5 % of global GHG emissions. Basic system improvements could reduce these emissions by more than 25 % (Kaza et al., 2018). For instance, about 200 million tonnes of GHG emissions could be eliminated annually in Europe starting from 2030 by improving waste management practices (Hogg and Ballinger, 2015). Solid waste management is a cross-cutting issue that affects various areas of sustainable development around the world. It is also a critical component for achieving Sustainable Development Goals (SDGs) and their related targets, all of which have a direct link to solid waste management (United Nations Environment Programme, 2023). Solid waste management has therefore become a dominant part of the solution for a country to succeed in its SDGs and reach net zero emissions.

The circular economy is a comprehensive and sustainable development strategy that has been widely adopted across the globe. It is an economic and industrial model that considers the use of natural resources in the most efficient way (Ellen MacArthur Foundation, 2015). Approximately 96 billion tonnes of primary materials were extracted and consumed globally in 2019, but only 9 % were recycled (United Nations Environment Programme, 2024). Production with new materials derived from nature and disposed of after use causes considerable waste and has negative consequences due to limited natural resources. It is also commercially unfeasible. Reclamation of valuable materials and energy recovery from existing waste treatment processes are therefore required by a comprehensive consideration of the circular economy in waste management. The circular economy has been highlighted as an increasingly important mitigation approach that can help deliver human well-being by minimising waste of energy and resources (Intergovernmental Panel on Climate Change, 2022). The recovery of energy and materials from municipal solid waste (MSW) offers several benefits, including the reduction of primary material extraction, the provision of local renewable energy, and the decrease of MSW in landfills, which also leads to the reduction of GHGs by reducing methane emissions from landfills.

GHG emissions from specific waste types and treatment methods have been assessed across various regions and countries worldwide (Matsuoka et al., 2023; Paes et al., 2020; Weitz et al., 2002). A comprehensive evaluation of life cycle GHG emissions from the MSW management sector remains limited at the global level due to variations in waste composition, management practices, infrastructure, and economic conditions across countries, as well as the scarcity of representative data. Most global GHG assessments for the waste sector primarily focus on direct emissions generated by MSW management activities (Gómez-Sanabria et al., 2022; Hoy et al., 2023). These assessments generally lack a full account of upstream and downstream GHG emissions, which is necessary for comprehensive environmental policy and climate strategies. The Global Waste Management Outlook 2024 provided an initial estimate of life cycle GHG emissions from the global MSW management sector (United Nations Environment Programme, 2024). However, this report relied on generic datasets due to limitations in comprehensive data availability. Applying more representative inventory data based on country income levels will enable a more context-specific GHG emissions assessment within the global MSW sector and development of strategies for reducing GHG emissions across diverse economic and infrastructural contexts.

The major GHG emitting sectors are increasingly focused on achieving net zero emissions by establishing detailed roadmaps and transition pathways, for instance, a roadmap for the global energy sector (International Energy Agency, 2021), net-zero transitions for the oil and gas industry (International Energy Agency, 2023), zero emissions for the global transport sector (Speizer et al., 2024), and a pathway to decarbonise the shipping sector (International Renewable Energy Agency, 2021). The United Nations Environment Programme (UNEP) has established global and regional waste management goals for sustainable development (United Nations Environment Programme, 2015, 2017, 2018, 2019), while the European Union (EU) has set waste targets as part of their transition towards a circular economy (McQuibban, 2020). However, a comprehensive evaluation of life cycle GHG emissions from the global MSW management sector is still needed to identify critical factors across its life cycle stages and potentials for carbon neutrality in the waste management sector.

A global assessment to effectively identify the potential for carbon neutrality in the waste sector, along with achievable targets, is essential to accelerate net zero transitions. To fill these gaps, this study aims to assess life cycle GHG emissions from the global MSW management sector for the years 2023, 2030, and 2050 using reflective inventory data for MSW treatment systems related to the income levels of countries. The global and regional management goals set by UNEP and the EU are analysed to identify critical factors influencing GHG emissions and the potential for carbon neutrality in the MSW management sector. This study provides the achievable MSW management targets by the adoption of circular economy principles in MSW management systems to the government, policymakers, and environmental organisations to support the pursuit of carbon neutrality goals in the global waste sector.

2. Literature review

Climate change is a major threat to the environment and societies. It is caused by the accumulation of heat-trapping GHGs. In 2023, average global temperature reached a historic high, surpassing all previous records since 1850. Predictions indicate that 2024 will surpass this record (National Oceanic and Atmospheric Administration, 2024). Each nation has therefore committed to reducing GHG emissions through the establishment of Nationally Determined Contributions (NDCs), which outline the pathway towards achieving a net-zero emissions society in alignment with the goals of the Paris Agreement. Solid waste management is not only crucial to environmental quality and human health but is also one of the main sources of anthropogenic GHG emissions. Methane emissions from the decomposition of organic waste in landfills, carbon dioxide emissions from waste incineration, and methane and nitrous oxide emissions from biological treatment, account for majority of the GHG emissions from MSW management (Huang et al., 2022; Liu et al., 2022). The Global Methane Pledge prioritises the rapid reduction of methane emissions from the waste sector due to its high mitigation potential for limiting global warming to 1.5 °C while offering significant co-benefits (United Nations Environment Programme, 2022).

The total GHG emissions from the waste sector in China increased more than threefold from 2006 to 2019. With landfills identified as the primary source, implementing effective strategies to divert waste from landfills significantly mitigated GHG emissions in the waste sector (Bian et al., 2022b). In 2022, the waste sector in the United States accounted for approximately 3 % of national GHG emissions (Environmental Protection Agency, 2024). According to previous research in the United States, increasing recycling rates decreased the amount of solid waste to be managed and led to more effective reduction of GHG emissions from the waste sector (Lee et al., 2016). A study conducted in Shanghai stated that the source segregation of MSW significantly reduces GHG emissions from MSW treatment systems by preventing organic waste from entering landfills, an essential step for GHG mitigation, while highlighting anaerobic digestion as a more effective long-term strategy for emission reductions compared to incineration (Liao et al., 2022). A study in China found that GHG emission reductions increased linearly with higher recycling efficiency, suggesting that increasing recovery efficiency could bring the waste sector to near carbon neutrality. The study also identified effective strategies for reducing GHG emissions from MSW management, such as optimising the separation of food waste, increasing the recycling efficiency of recyclable materials, and minimising biogas leakage from anaerobic digestion (Bian et al., 2022a).

In Malaysia, more than 80 % of MSW is still disposed of in landfills. However, an integrated approach targeting a recycling rate of 40 % and an incineration rate of 31.9 % by 2050 could result in an estimated 64 % reduction in GHG emissions from MSW management (Devadoss et al., 2021a). A strategy in Pakistan that involves recycling 23 % of MSW, anaerobic digestion of 10 %, and disposal of 67 % in sanitary landfills with energy recovery could reduce GHG emissions by 36 % (Devadoss et al., 2021b). China initiated a national zero-waste pilot program in 11 cities to achieve zero-waste goals, and following its success, expanded the program to 113 cities under the Five-Year Plan (Qi et al., 2024). The potential for GHG reductions in MSW management varies between countries and is not directly transferable due to differences in system structures, waste management practices, and the composition of waste fractions.

Implementing circular economy practices in MSW management to mitigate GHG emissions presents challenges in many regions, particularly in LICs. For instance, LICs face challenges in the transition of traditional, linear approach of waste management methods, to a circular economy of waste management due to the absence of robust national strategies and plans (Debrah et al., 2022). The absence of comprehensive strategic plans for MSW management, inadequate waste collection and segregation systems and insufficient budgets for proper waste collection, storage, treatment, and disposal, are significant barriers for moving towards circular solid waste management practices (Kumar et al., 2017). Some HICs also face challenges in waste management during the transition to a circular economy due to overcapacity in waste management facilities, poor implementation of the waste hierarchy, and unclear roles and responsibilities among authorities. These issues result in high landfilling rates, the loss of valuable resources, and financial burdens on municipalities and the government (Luttenberger, 2020).

Many countries have extensively analysed GHG emissions from the MSW sector and its GHG emission mitigation potential at the national and regional levels to achieve carbon neutral goals (Fernández-Braña et al., 2020; Gama et al., 2023; Li et al., 2024). For most developing countries, information about GHG estimations from the waste sector is still sparse because of limited resources and expertise, which could affect the development of effective mitigation strategies for GHG reduction. A context-specific and comprehensive estimation of global GHG emissions in 2030 and 2050 is therefore an essential requirement for developing efficient strategies to reduce GHG emissions and achieve carbon neutrality from the waste sector. A global assessment using reflective inventory data categorised by income level would be beneficial, especially for developing countries, in their efforts to reach carbon neutrality goals using circular economy principals to manage MSW.

3. Methodology

The study quantified the life cycle GHG emissions from the global waste sector, following the guidelines of ISO 14067:2018 (International Organization for Standardization, 2018).

3.1. Goal and scope of the study

The goal of the study was to evaluate the life cycle GHG emissions from MSW management on a global scale for the years 2023, 2030, and 2050. This assessment was conducted using current MSW treatment methods and proposed MSW management targets, incorporating circular economy principles to achieve carbon neutrality within the waste sector.

The system boundary of this study includes the entire life cycle of MSW management systems, starting with waste collection and transport, sorting, and waste management using globally applied methods such as incineration, anaerobic digestion, composting, recycling, landfilling, and open dumping. Also, the study additionally considers the use of by-products generated during the MSW management process, as shown in Fig. 1. The biogas generated from anaerobic digestion of the organic fraction of MSW was considered a substitute for electricity generation. The compost derived from composting the organic fraction of MSW was considered a substitute for the production of inorganic nitrogen, phosphorus, and potassium (NPK) fertiliser. The energy recovered from the incineration of MSW was also considered a substitute for electricity generation. Landfill gas (LFG) collected from sanitary landfills was regarded as a substitute for electricity generation. The recovered materials from the recyclable fractions of MSW were considered substitutes for virgin material production with substitution ratios.

The units of assessment applied in this study were 1 tonne of MSW (wet weight) managed by different waste treatment methods around the world in 2023 and the total amount of MSW managed by different waste treatment methods around the world in 2023, 2030, and 2050.

3.2. Scenario description

The scenarios considered in this study are presented in Table 1. Business-as-usual (BAU) scenarios were established by considering the current and projected waste composition and share of treatment methods in 217 countries for the years 2023, 2030 and 2050. Improvement scenarios were defined according to the proposed global waste management goals (United Nations Environment Programme, 2015) and regional waste management goals for the years 2030 and 2050 (McQuibban, 2020; United Nations Environment Programme, 2018). The goals aim to ensure universal access to safe, adequate, and affordable waste collection services and seek to halve per capita global food waste at the consumer level to reduce food losses. The goals focus on achieving sustainable and environmentally sound waste management, eliminating uncontrolled dumping, and diverting waste to improve reuse, recycling, and recovery rates.

Business-as-usual scenarios (BAU 2023, BAU 2030, and BAU 2050) reflected the current and projected amounts of MSW generation in years 2023, 2030 and 2050. BAU scenarios assumed that the proportion of MSW managed by different treatment methods and collection coverage in each country will remain constant, with no improvements. In scenarios S1.1 and S1.2, waste collection coverage was increased from BAU level to a proposed global waste management goal of 100 % (United Nations Environment Programme, 2015), while an alternative scenario considered an increase to 80 %. Countries that have already achieved 80 % collection coverage were assessed based on their BAU collection coverage. The increased amount of collected MSW was proportionally allocated to BAU waste treatments.

In scenarios S2.1 and S2.2, the amount of food waste was reduced from BAU level to a proposed global waste management goal of 50 % (United Nations Environment Programme, 2015), while an alternative scenario considered a reduction to 40 %. In recycling scenario S3.1, the amount of recycling was increased from BAU level to a proposed regional waste management target of 60 % for Europe (McQuibban, 2020), and a proposed global waste management goal of 50 % for the rest of the world (United Nations Environment Programme, 2015). As an alternative scenario, S3.2 increased recycling from BAU levels to 50 % for Europe and 40 % for the rest of the world.

In the other recovery scenario (S4.1), the electricity generation efficiency from incineration was increased from BAU level to 26 %, which is the average electrical efficiency for large new incineration facilities (Istrate et al., 2023). For the landfill scenario (S5.1), the landfill gas collection efficiency was increased from BAU level to 85 %, as it is the highest efficiency from optimistic landfill conditions (Anshassi et al.,

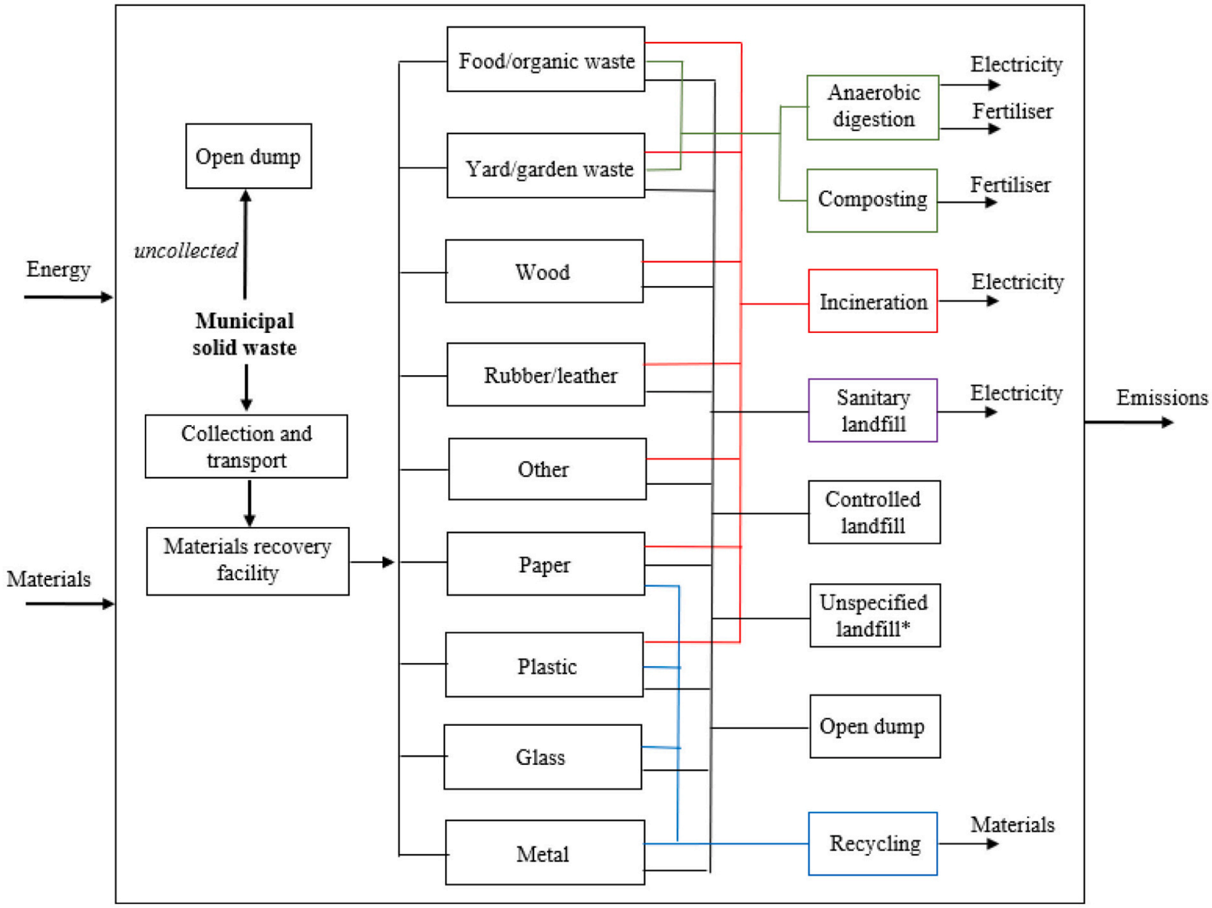


Fig. 1. System boundary of MSW management system with different management systems.

2022). In the controlled disposal scenarios (S6.1 and S6.2), the amount of uncontrolled dumping was decreased from BAU level to a proposed global waste management goal of 0 % (United Nations Environment Programme, 2015). 30 % was considered as an alternative scenario, then proportionally diverted to sanitary landfills and controlled landfills. Countries that have already achieved a lower uncontrolled dumping rate of 30 % were assessed based on their BAU uncontrolled dumping rate.

3.3. Life cycle inventory (LCI)

Life cycle inventory data for global MSW management on a national scale, such as the total MSW generation per year, distance for waste collection and transport, composition of MSW, and the share of treatment methods in 217 countries, were collected from the World Bank database (Kaza et al., 2018), as presented in Electronic Supplementary Material (ESM1). The typical components of MSW in this study were food and organic waste, glass waste, metal waste, paper and cardboard waste, plastic waste, rubber and leather waste, wood waste, yard and garden green waste, and other waste.

MSW treatment methods were the globally applied methods including anaerobic digestion, composting, incineration, recycling, landfilling, and open dumping. The landfill category was categorised into three types: sanitary landfills equipped with landfill gas collection systems, controlled landfills, and unspecified landfills with incomplete or unknown management practice information. The LCI was categorised based on the World Bank's World Development Indicator's Gross Domestic Product (GDP) per capita of the countries into four groups: high-income countries (HICs), upper-middle-income countries (UMCs), lower-middle-income countries (LMCs), and low-income countries (LICs). For the countries for which country-level data for the composition of MSW and treatment methods are not available, the data gap was filled by applying the average data according to GDP. Unidentified fractions of MSW stream and leakage to waterways were considered open dumping.

The LCI for MSW treatment, including the energy and materials needed for MSW treatment, the energy and materials that will be recovered, and the energy and material recovery efficiencies, were gathered through a comprehensive literature review using specific keywords in the Scopus database from 2015 to 2024 in order to collect the most recent data for the LCI of MSW treatment. Weighted average LCI data with MSW generation rate was then calculated for each income level category, as indicated in ESM1. The LCI and MSW data were modelled in order to obtain representative country-level MSW datasets. The moving grate furnace was considered for MSW incineration, as approximately 90 % of existing incineration facilities in Europe use this technology (European Commission; Joint Research Centre, 2019). Windrow composting was considered for MSW composting due to its widespread global use in processing high volumes of organic waste, attributed to its cost-effective and relatively straightforward operational requirements (Tchobanoglous and Kreith, 2002). Metal wastes were considered as a combination of ferrous and nonferrous fractions. Specifically, 75 % of metal wastes were accounted for as the ferrous fraction, categorised as steel containers, and 24 % nonferrous fractions, categorised as aluminium cans, with the remaining 1 % attributed to other metals (Kuusiola et al., 2012).

The background data for electricity generation for each country was

Table 1
Description of scenarios.

Approach	Scenario	Description
Business-as-usual	BAU 2023	Scenario reflects current amount of MSW in 2023.
	BAU 2030	Scenario reflects projected amount of MSW in 2030.
	BAU 2050	Scenario reflects projected amount of MSW in 2050.
Waste management goals	S1.1*	Waste collection was increased from BAU level to 100 %.
	S1.2	Waste collection was increased from BAU level to 80 %[a].
	S2.1*	Food waste was decreased from BAU level to 50 %.
	S2.2	Food waste was decreased from BAU level to 40 %.
Recycling	S3.1*	Recycling was increased from BAU level to 60 % for Europe and 50 % for ROW.
	S3.2	Recycling was increased from BAU level to 50 % for Europe and 40 % for ROW.
Other recovery (energy)	S4	Efficiency of electricity generation was increased from BAU level to 26%[b].
Landfill	S5	Landfill gas collection efficiency was increased from BAU level to 85%[c].
Controlled disposal	S6.1*	Uncontrolled dumping was decreased from BAU level to 0 %.
	S6.2	Uncontrolled dumping was decreased from BAU level to 30%[d].
Circular economy scenario	CES	Waste collection was increased from BAU to 80 %, food waste was decreased from BAU to 40 %, recycling was increased from BAU to 35 % for Europe and 15 % for ROW, uncontrolled dumping was decreased from BAU to 30%[a,d].

ROW = Rest of the world.
* Global and regional waste management goals to be achieved by 2030 and 2050.
[a] Countries that have already achieved 80 % collection coverage were assessed based on their BAU collection coverage.
[b] Average electrical efficiency for large new incineration facilities (Istrate et al., 2023).
[c] Highest efficiency from optimistic landfill conditions (Anshassi et al., 2022).
[d] Countries that have already achieved a lower uncontrolled dumping rate of 30 % are assessed based on their BAU uncontrolled dumping rate.

sourced from the ecoinvent database v3.8 (Moreno et al., 2021) as indicated in ESM2. The regional electricity generation data was applied if country-level electricity generation data was not available. The recovered electricity from MSW management processes was considered a substitute for the corresponding national grid electricity generation mix. The data on the production of input materials and recovered materials from MSW management was also collected from the ecoinvent database v3.8. MSW collection service by 21 metric tonne lorry was considered to collect and transport waste to the sorting stations. For the incineration of MSW, the chemical composition of the MSW fractions was collected to estimate their energy content (Yadav and Samadder, 2018; Zhou et al., 2014). The energy content of each MSW fraction was assessed using high heating value (HHV) and low heating value (LHV) to estimate the electricity generation potential from the various MSW fractions as indicated in ESM1. The recycling of materials (paper, plastic, glass, and metals) and substitution ratios were collected from the literature as indicated in ESM1.

3.4. Greenhouse gas emissions assessment

GHG emissions from the MSW management sector, including waste collection and transport, sorting, different MSW treatment methods and open dumping, were assessed according to the IPCC Guidelines (Intergovernmental Panel on Climate Change, 2019). GHG emissions in kg CO_{2e} from 1 tonne of MSW management were quantified by multiplying GHG emissions from waste collection and transport, sorting, different MSW treatment methods, and open dumping with characterisation factors. The characterisation factors were obtained from the Global Warming Potential (GWP) climate change factors with a timeframe of 100 years developed by the Intergovernmental Panel on Climate Change (Forster et al., 2021). Total GHG emissions for each country were quantified by multiplying GHG emissions per tonne of MSW management (in kg CO_{2e}) with the total MSW generation rate within the respective country.

The results from the assessment were analysed to identify key hotspots and primary contributors, identify significant issues, and were compared with other studies. Data were then modelled against each country's GHG emissions and MSW management scenarios to assess the current state of GHG emissions within the MSW management sector and to identify potential GHG reduction opportunities based on the income level of the country. Sensitivity analysis was performed to investigate the robustness of the assessment results and their sensitivity to input parameters under specified assumptions. The sensitivity analysis considered parameters that could potentially influence the assessment results, as detailed in Table 2.

4. Results and discussion

4.1. Global status of greenhouse gas emissions from municipal solid waste management sector

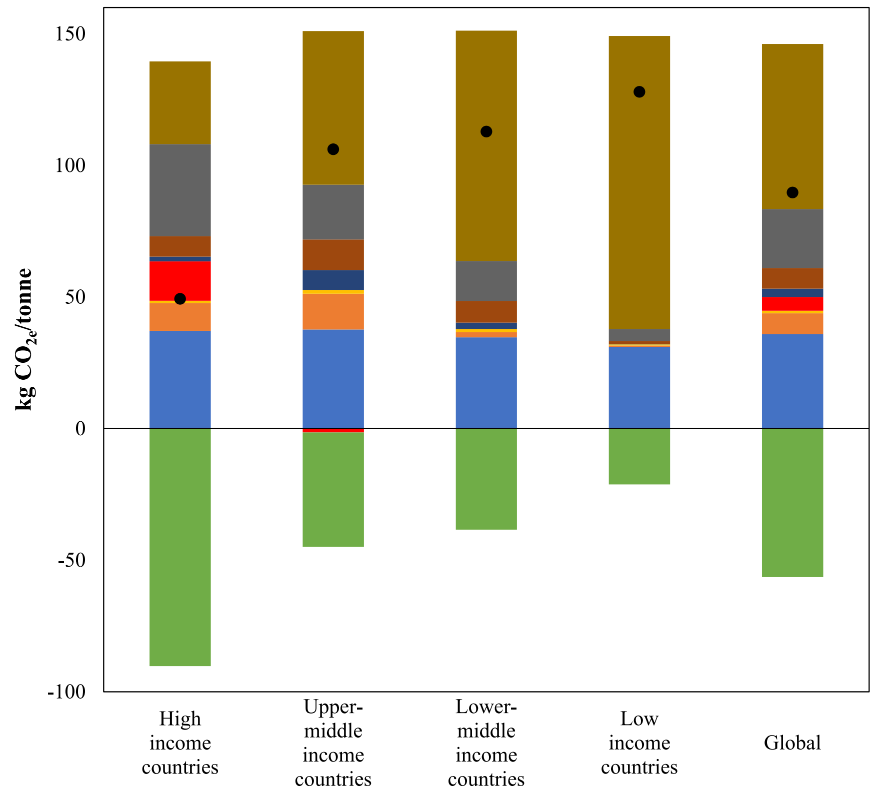
Results of the assessment revealed that the average global GHG emissions from 1 tonne of MSW management in 2023 based on the existing MSW management systems is approximately 89.7 kg CO_{2e}, ranging from 49.3 kg CO_{2e} in HICs, 106.1 kg CO_{2e} in UMCs, 112.9 kg CO_{2e} in LMCs and 128.0 kg CO_{2e} in LICs as shown in Fig. 2. The results indicate that the average GHG emissions from managing 1 tonne of MSW in HICs are lower than the average global GHG emissions. However, for other income levels, the average GHG emission is higher. The major contributor of global GHG emissions from MSW management is the open dumping of MSW, which contributes to almost 70 % of GHG emissions. Collection and transport, unspecified landfills, sorting of MSW, controlled landfills, sanitary landfill and composting follow in descending order.

Recycling the recoverable fractions of MSW has substantial environmental benefits, as it can substitute the intensive energy for the production of virgin materials. Anaerobic digestion and incineration of MSW have the potential to offer environmental benefits from MSW

Table 2
Sensitivity analysis.

Sensitivity analysis	Description
SS1.1	The analyse was conducted using the chemical composition of MSW fractions from China.
SS1.2	The analyse was conducted using the chemical composition of MSW fractions from Denmark.
SS2.1	The analyse was conducted using the maximum waste collection and transport distances from the collected LCI in different regions of the globe.
SS2.2	The analyse was conducted using the minimum waste collection and transport distances from the collected LCI in different regions of the globe.
SS3.1	The analyse was conducted using projected future global renewable electricity generation mix data in 2030 from the World Energy Outlook 2023 report.
SS3.2	The analyse was conducted using projected future global renewable electricity generation mix data in 2050 from the World Energy Outlook 2023 report.
SS4	This analysis was conducted using characterisation factors from the Global Temperature Potential (GTP) method for climate change, as defined by the Intergovernmental Panel on Climate Change (IPCC), with a timeframe of 100 years.

Details in ESM1.



	High income countries	Upper-middle income countries	Lower-middle income countries	Low income countries	Global
Open dump	31.4	58.4	87.5	111.3	62.7
Unspecified landfill	35.0	20.8	15.2	4.6	22.4
Controlled landfill	7.8	11.6	8.3	1.1	7.9
Sanitary landfill	1.8	7.6	2.5	0.2	3.2
Recycling	-90.2	-43.5	-38.3	-21.2	-56.4
Incineration	14.9	-1.4	-0.1	0.0	5.2
Composting	0.9	1.4	1.1	0.4	1.0
Anaerobic digestion	0.0	0.0	0.0	0.0	0.0
Sorting	10.5	13.6	2.0	0.5	7.9
Collection and transport	37.2	37.6	34.7	31.1	35.8
Net emissions (2023)	49.3	106.1	112.9	128.0	89.7

Fig. 2. Average GHG emissions from 1 tonne of MSW management across different income levels around the world in 2023.

management. However, the energy recovery efficiency influences the environmental benefits of MSW incineration, whereas the extent of the benefits from anaerobic digestion is quite low due to its limited applications globally. HICs gain the highest benefits from engaging in recycling practices, followed by UMCs, LMCs and LICs.

The majority of GHG emissions per tonne of MSW management in LMCs and LICs come from open dumping of MSW. In particular, open dumping is responsible for over 70 % of the total GHG emissions associated with MSW management in LMCs and more than 80 % in LICs. On average, over 80 % of MSW in LICs is managed through open dumping, representing the highest proportion among all income-level categories. This practice is significantly more common than in other income groups, leading to the uncontrolled decomposition of organic waste in open dumps. This decomposition generates substantial quantities of methane, a potent GHG with a global warming potential substantially higher than that of carbon dioxide.

MSW collection and transport is the second largest source of GHG emissions from the global MSW management sector. The collection and transport distances vary according to the geographical locations and urbanisation of the countries, with the average collection and transport distance across income levels ranging from 15.5 km to 35 km (Kaza et al., 2018). For HICs, the major source of GHG emissions from MSW management is the collection and transport of MSW. This is primarily due to the longer collection distances and broader collection coverage associated with MSW management systems in HICs compared to other income-level categories. The extensive MSW collection services across large urban and rural areas result in higher fuel consumption and, consequently, increased GHG emissions from the transport vehicles. This highlights the need for more efficient MSW collection strategies and the potential for reducing GHG emissions through improved logistics and alternative fuel sources. The use of artificial intelligence (AI) has the potential to improve the efficiency of MSW collection routes, reducing transport distances and increasing collection efficiency by over 36 % in both areas (Fang et al., 2023). These optimisations not only lead to substantial gains in operational efficiency, such as reduced fuel consumption and lower operational costs, but also contribute to a significant reduction in GHG emissions.

GHG emissions from unspecified landfills represent the third largest source of GHG emissions within the global MSW management sector. To achieve carbon neutrality in the waste sector, upgrading these landfills by incorporating LFG collection and energy recovery systems is the most effective solution for mitigating GHG emissions. The financial feasibility and technological readiness of such upgrades in HICs and UMCs offer an opportunity to address this environmental challenge and reduce the overall climate impact from the waste sector.

GHG emissions are also generated during the process of waste sorting, making it a notable contributor to overall GHG emissions in the management of MSW globally. These emissions are significantly influenced by the energy consumption required for sorting operations as well as the sources of electricity generation employed within a country. GHG emissions from the electricity used for waste sorting vary depending on the energy mix of the country, with higher GHG emissions associated with electricity generated from fossil fuels compared to electricity produced from renewable sources. GHG emissions from waste sorting are therefore closely tied to both the electricity consumption of the sorting processes and the energy mix of the local energy supply. HICs and UMCs are responsible for the higher GHG emissions in waste sorting due to their greater energy consumption, as they use more advanced technologies and machinery compared to other income level countries. However, the application of advanced technologies such as AI-based robotics system for automatic waste sorting achieved an average purity of 90 % across the sorting of up to 13 different materials (Wilts et al., 2021), which could improve the reclamation of recyclable materials and lead to greater environmental benefits.

Anaerobic digestion is one of the MSW management methods that can reduce GHG emissions in the waste sector and provide environmental benefits. However, the benefits remain relatively limited on a global scale. According to current MSW management data, Iran has the largest proportion of anaerobic digestion treatment and achieves the highest environmental benefits from this treatment method. Approximately 0.3 % of the MSW generated is treated by anaerobic digestion, resulting in an estimated reduction of 0.2 kg CO_{2e} per tonne of MSW as indicated in ESM2. This demonstrates the potential of anaerobic digestion to reduce GHG emissions from the waste sector, although its impact is currently constrained by its limited application.

The recycling of glass, metal, paper, and plastics from MSW provides substantial environmental benefits, in terms of reducing GHG emissions. However, these benefits are predominantly observed in HICs, where a higher proportion of recycling treatment is implemented. For instance, Singapore achieves the most significant GHG reduction of 349 kg CO_{2e} per tonne of MSW treated, due to its higher recycling rate and the greater metal content within its waste stream. This highlights the critical role of recycling treatment and MSW composition in maximising the environmental advantages of recycling practices.

4.2. Future status of greenhouse gas emissions from the global municipal solid waste management sector

The global MSW management sector emitted a total of 173.2 Mt CO_{2e} GHG emissions in 2023, as shown in Fig. 3. According to projections, GHG emissions from the MSW sector will increase to 203.4 Mt CO_{2e} by 2030 and further rise to 289.5 Mt CO_{2e} by 2050. This indicates that global GHG emissions from MSW management are expected to grow by over 17 % by 2030 and 67 % by 2050 without any future improvements or mitigation measures. This highlights the immediate necessity for improved MSW management systems to reduce GHG emissions. In 2030, UMCs and LMCs will account for the largest amount of GHG emissions, specifically 77.3 Mt CO_{2e} and 98.3E Mt CO_{2e} respectively. These figures have the potential to rise to 93.0 Mt CO_{2e} and 146.3E Mt CO_{2e} by 2050. HICs benefit significantly from the recycling of paper, plastics, glass, and the metal fractions of MSW. As a result, GHG emissions from the waste sector in HICs are projected to be 7.9 Mt CO_{2e} in 2030 and 11.4 Mt CO_{2e} in 2050, which is substantially lower than the emissions from UMCs and LMCs. In contrast, the GHG emissions from the waste sector in LICs are projected to reach 19.9 Mt CO_{2e} in 2030 and 38.9 Mt CO_{2e} in 2050.

Previous studies assessed the GHG emissions of waste sector at the global level, as presented in Table 3. The scope of the studies by Kaza et al. (2018) and Chen et al. (2020) aligns with this assessment, utilising the most comprehensive MSW data from the World Bank database. However, the projected GHG emissions from MSW management for the year 2050 in this assessment are not directly comparable to these studies, as they focused particularly on direct GHG emissions from MSW management and did not consider the environmental benefits derived from energy and material recovery. Another study assessed GHG emissions from MSW management across 13 global regions using the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model, to evaluate potential future GHG emissions and other air pollutants (Gómez-Sanabria et al., 2022). The GAINS model primarily relies on the potential of direct GHG emissions and does not account for emissions savings from energy and material recovery. Our findings indicate that recycling recoverable fractions of MSW, such as glass, metal, paper, and plastic waste, leads to significant electricity and energy savings. For instance, recycling 1 tonne of glass waste can save 94.49 kWh of electricity and 757.38 GJ of energy in HICs and 63.56 kWh of electricity and 794.56 GJ of energy in other income-level countries. Previous studies on direct GHG emissions from MSW management have

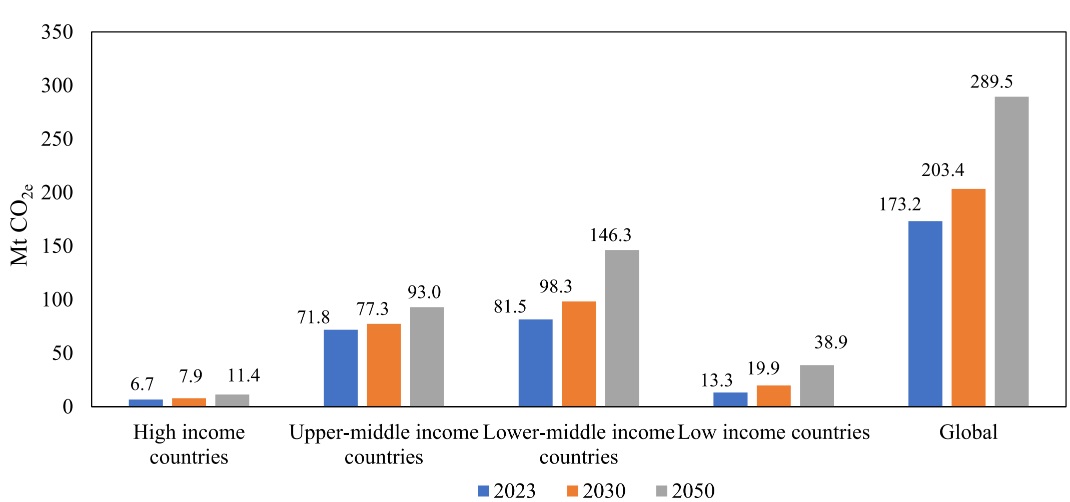


Fig. 3. Projected annual global GHG emissions from MSW management sector based on income levels in 2023, 2030 and 2050 without improvement.

Table 3
Previous studies assessing GHG emissions of the waste sector at the global level.

Study	Scope of study	GHG emissions	
		2030	2050
Kaza et al. (2018)	217 countries	–	2.6 Gt CO_{2e}
Chen et al. (2020)	217 countries	–	2.4 Gt CO_{2e}
Gómez-Sanabria et al. (2022)	13 regions (e.g. EU 28, North America, Middle East, Oceania, Africa, China, India, Russia)	~1.2[a] Gt CO_{2e}	1.6 to 1.8[b] Gt CO_{2e}
Hoy et al. (2023)	43 highest MSW generating countries (approximately 86 % of global MSW generation)	13 Gt CO_{2we}	32 Gt CO_{2we}
This study	217 countries	203.4 Mt CO_{2e}	289.5 Mt CO_{2e}
	EU 27	−34 kg CO_{2e}/tonne of MSW	
Albizzati et al. (2024)	EU 27	−49 kg CO_{2e}/tonne of MSW	

[a] 36 to 37 Mt CH_4 and 193 to 209 Mt CO_2 were converted into Gt CO_{2e}.
[b] 49 to 55 Mt CH_4 and 242 to 308 Mt CO_2 were converted into Gt CO_{2e}.

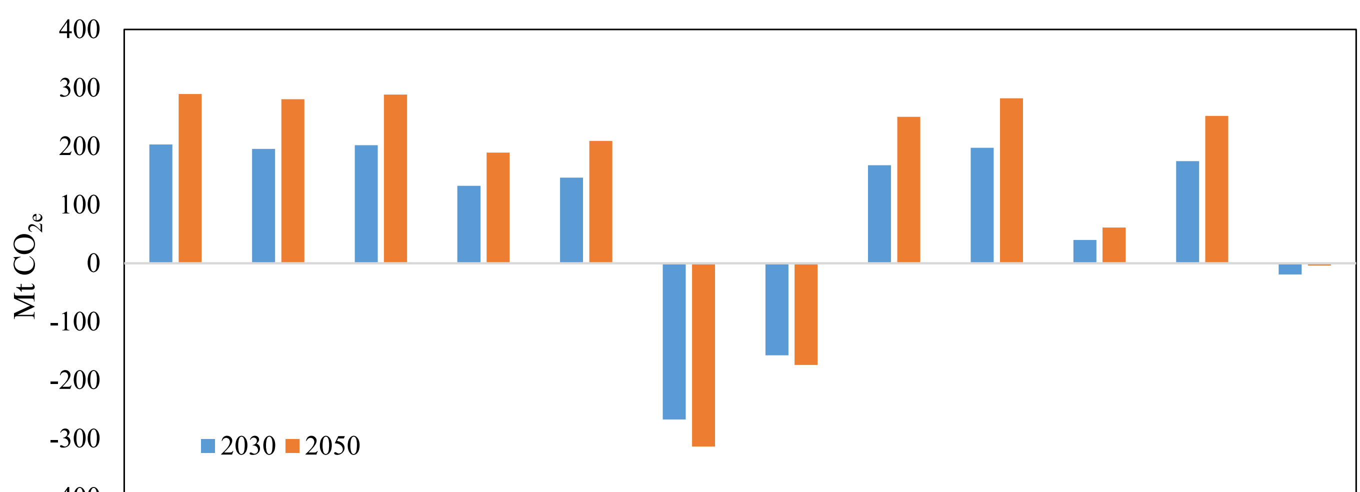
not accounted for these savings, resulting in higher GHG emissions from the waste sector.

A global study evaluated GHG emissions from the 43 highest MSW generating countries, representing approximately 86 % of global MSW generation, to assess the potential contribution of the waste sector to the climate targets of the Paris Agreement and the Global Methane Pledge (Hoy et al., 2023). However, GHG emissions were reported using an alternative approach, specifically the CO_2 warming equivalents (CO_{2we}) metric, which emphasises short-lived climate pollutants such as methane to capture immediate warming impacts. This methodological difference restricts direct comparability with the findings of this study. Variations in estimated GHG emissions were attributed to differences in MSW data, including MSW composition, share of treatment methods and projected generation rates by nation, as well as LCI for MSW treatment methods. The use of diverse data sources and methodological variations in GHG emissions estimates leads to challenges in the quantitative comparison of GHG emissions across studies. In contrast, a recent study examined the life cycle GHG emissions associated with MSW management within the EU27 in 2020. The weighted average GHG emissions from 1 tonne of MSW management in the EU27 were −49 kg CO_{2e} (Albizzati et al., 2024), which is the same order of magnitude and comparable to the findings of this study, −34 kg CO_{2e} for the EU27 in 2023.

4.3. Potential reductions of GHG emissions from the global MSW management sector in 2030 and 2050

The reduction potential of global GHG emissions from the MSW management sector was assessed through the implementation of global and regional waste management goals set by the UNEP, as well as through improvement scenarios and a circular economy scenario as shown in Fig. 4. Achieving 100 % waste collection globally by 2030 and 2050 (S1.1) could potentially reduce GHG emissions from MSW management by over 3 %. This reduction is attributed to the prevention of open dumping of uncollected MSW, with the collected MSW being proportionally allocated to BAU waste treatment methods. In contrast, achieving waste collection rates of 80 % by 2030 and 2050 (S1.2) would result in projected GHG reduction rates by less than 1 %, as the environmental benefits derived from achieving an 80 % waste collection rate were only beneficial for the LMCs and LICs. MSW collection rates in BAU are almost 90 % in HICs and nearly 80 % in UMCs, while collection rates in LMCs stand at over 50 % and approximately 25 % in LICs. When considering MSW collection and transport, the separate collection of food waste offers several environmental benefits, including conversion of the collected food waste into compost or used to produce alternative animal feeds, such as black soldier fly larvae (United Nations Environment Programme, 2023).

Implementing a 50 % food waste reduction scenario (S2.1) has the potential to reduce GHG emissions by nearly 35 % by both 2030 and 2050. Similarly, a 40 % food waste reduction scenario (S2.2) could result in GHG emission reductions exceeding 27 % by 2030 and 2050, respectively. In many developed countries, distributing surplus food from suppliers to the community through charity is an effective strategy to prevent food waste problems, effectively address zero hunger (SDG 2), and reduce food losses (SDG 12.3) (Karki et al., 2021). The recycling scenarios demonstrate the potential for achieving carbon neutrality in the MSW management sector. Recycling scenario (S3.1) could lead to a reduction of over 200 % in GHG emissions by both 2030 and 2050 through the increased recycling rates. Similarly, recycling scenario (S3.2) could reduce GHG emissions over 160 % by 2030 and 2050. However, increasing the proportion of recycling from the BAU levels to 50 % or 60 % in Europe and to 40 % or 50 % in other countries presents a



	BAU	S1.1	S1.2	S2.1	S2.2	S3.1	S3.2	S4	S5	S6.1	S6.2	SCES
2030	203.4	195.5	202.0	132.4	146.6	-267.2	-157.4	167.9	197.7	39.9	174.6	-19.0
2050	289.5	280.8	288.8	189.2	209.3	-313.5	-174.0	250.5	282.2	61.0	252.2	-3.8

Fig. 4. Total GHG emissions from global MSW management sector in 2030 and 2050 based on the BAU and improvement scenarios.

significant challenge, as the current recycling rates are approximately 20 % in Europe and 6 % in other countries. Recycling scenarios offer significant environmental benefits by reducing the need for virgin material production and mitigating associated GHG emissions. However, the recycling process involves significant energy use and costs, including collection, separation, sorting, and processing, as well as capital investment in specialised equipment. LICs typically face barriers related to insufficient capital investment in specialised recycling equipment, which limit their capacity to manage and process recyclable materials efficiently. Despite these limitations, recycling processes offer significant potential for creating employment and supporting community development.

The other recovery scenario (S4.1), in which electricity recovery efficiency from incineration is increased, has the potential to reduce GHG emissions by more than 17 % by 2030 and 13 % by 2050. This scenario is based on an average electrical recovery efficiency of 26 % of LHV for large, new incineration facilities (Istrate et al., 2023). The implementation of source separation could reduce the water content in MSW, resulting in a 99 % increase in LHV (Zhang et al., 2023) and potentially leading to higher electricity recovery. Scenario S5.1, which considers the increased collection of LFG from sanitary landfills, has the potential to reduce GHG emissions by approximately 3 % by both 2030 and 2050. This scenario assumes an LFG collection rate of 85 %, based on reported collection efficiencies in developed countries, which range from 79.5 % to as high as 88.4 % (Di Trapani et al., 2013). Controlled disposal scenarios represent the second-highest potential for reducing GHG emissions within the MSW management sector. By eliminating uncontrolled dumping and diverting waste fractions to sanitary landfills and controlled landfills, scenario S6.1 has the potential to achieve a GHG emissions reduction of approximately 80 % by both 2030 and 2050. On the other hand, if the uncontrolled dumping is decreased from the BAU level to 30 % (Scenario S6.2), GHG emissions could be reduced by more than 13 % by 2030 and 2050.

Scenarios S3.1 and S3.2 are the only scenarios with the potential to achieve significant environmental benefits by the MSW management sector. However, increasing the recycling proportion from the BAU level to more than 2.5 times in European countries and 6 times in other countries is difficult to achieve. Additionally, achieving a 100 % waste collection target globally presents considerable challenges for many countries. Circular economy scenario (CES) was therefore developed that assumes waste collection is increased from BAU to 80 %, food waste is decreased from BAU to 40 %, recycling is increased from BAU to 35 % for Europe and 15 % for ROW, and uncontrolled dumping is decreased from BAU to 30 % and diverted to sanitary landfills and controlled landfills. The implementation of the CES, which includes achievable targets for MSW management targets for all countries, has the potential to achieve net zero emissions from the global MSW management sector by 2030 and 2050.

4.4. Sensitivity analysis

The sensitivity scenarios were developed to evaluate the influences of major input parameters on the assessment results, as shown in Fig. 5. The key assumptions considered in the scenarios include variations in chemical composition of MSW fractions, MSW collection and transport distances, the projected future global renewable electricity generation mix, and Global Temperature Change Potential over 100 years (GTP100) factors. These factors were selected based on their potential to influence the assessment results, considering their potential impact on the overall results. The chemical composition of MSW fractions from China (Yang et al., 2018) and Denmark (Clavreul et al., 2014) were applied in SS1.1 and SS1.2 to assess the variations of GHG emissions representative of developing country and developed country.

The analysis of different chemical composition datasets of MSW fractions revealed that GHG emissions associated with MSW management increased by approximately 8 % for the China dataset and 3 % for the Denmark dataset. This increase is attributed to the influence of the energy content of MSW on electricity recovery from incineration of MSW. The energy content of MSW in both the China and Denmark datasets is slightly lower than the data used in this assessment, resulting in lower environmental benefits from electricity recovery during MSW incineration.

The analysis of the maximum and minimum MSW collection and transport distances, based on the collected data from different regions of the globe, demonstrates a significant sensitivity of GHG emissions to variations in collection and transport distances. The results specifically indicate that GHG emissions increase by approximately 31 % when maximum transport distances are applied, while a reduction of around 32 % is observed when minimum distances are considered. These findings highlight the influence of MSW collection and transport distances on the overall GHG emissions from MSW management. MSW collection and transport distances represent the second largest source of GHG emissions in the waste sector. Optimising these distances is therefore crucial for reducing the GHG emissions of the waste sector.

The analysis of the projected future global renewable electricity generation mix indicates that incorporating renewable electricity into

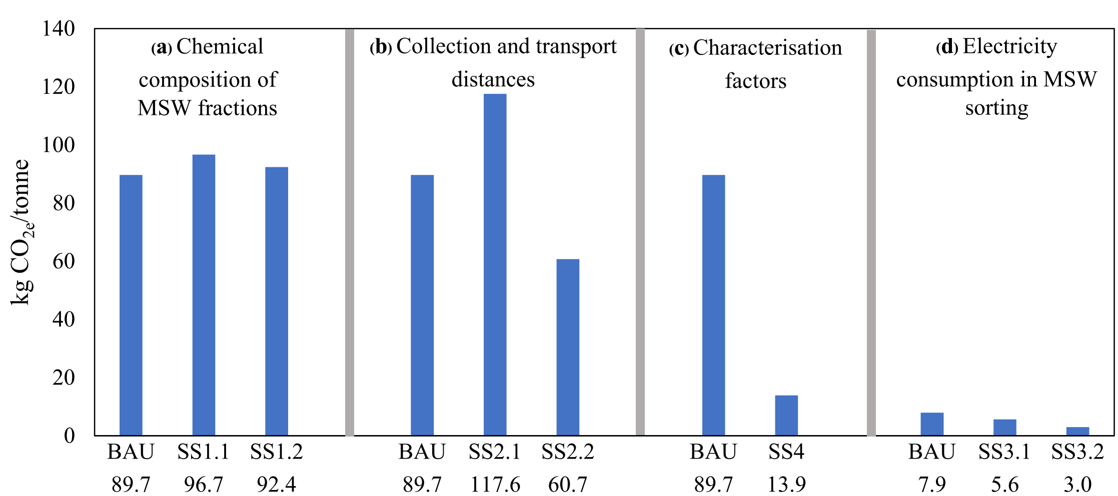


Fig. 5. GHG emissions of MSW management sector based on the BAU and sensitivity scenarios **(a)** chemical composition of MSW fractions from different datasets (SS1.1 and SS1.2), **(b)** maximum and minimum waste collection and transport distances in different regions (SS2.1 and SS2.2), **(c)** characterisation factors from the Global Temperature Potential method (SS4), and **(d)** GHG emissions from electricity consumption in MSW sorting with BAU, future global renewable electricity generation mix data in 2030 and 2050 (SS3.1 and SS3.2).

MSW management processes has the potential to reduce GHG emissions from energy application in the waste sector. The findings indicate that the use of the future global renewable electricity generation mix in 2030 and 2050 could decrease GHG emissions by approximately 30 % by 2030 and by more than 60 % by 2050 in the electricity application of MSW management activities. This highlights the critical role of renewable electricity to achieve climate goals, reduce GHG emissions from waste management practices and maximise environmental benefits.

The analysis of using characterisation factors from the Global Temperature Potential method for climate change with a time frame of 100 years (GTP 100) indicates that the characterisation factors could significantly influence the results of the GHG emissions from the waste sector. The use of GTP 100 characterisation factors results in an approximate reduction of 85 % in GHG emissions compared to using the GWP 100 characterisation factors. This difference arises because the characterisation factor for biogenic methane in GWP 100 is nearly six times greater than that in GTP 100. The sensitivity analysis identifies the critical parameters that require a high level of accuracy and helps waste sector experts and scholars clarify which parameters have the greatest potential to impact the outcome, particularly in terms of increasing or decreasing GHG emissions from MSW management.

4.5. Limitations of the study

Technological advancements present opportunities to enhance the efficiency of MSW treatment technologies, potentially reducing their operational emission factors beyond current IPCC guidelines. Innovative approaches, such as using recycling residues as fossil fuel alternatives for electricity generation within treatment facilities, are expected to enhance the contributions of the global MSW sector towards the goals of the Paris Agreement and the Global Methane Pledge. However, it is essential to recognise that these evolving factors may influence the accuracy of projected emissions in future scenarios.

This study focused on the global warming impact of GHG emissions from MSW systems. It recommends further investigation into human toxicity potential and the effectiveness of mitigation strategies to reduce these impacts. Pollutants released from waste incineration, including highly toxic and carcinogenic dioxins and furans, highlight the need for a more comprehensive global emissions assessment. Future assessments should therefore incorporate country-specific pollutants such as particulate matter (PM), sulphur oxides (SOx), nitrogen oxides (NOx), and heavy metals to improve the evaluation and management of associated environmental and health risks.

4.6. Policy recommendation

4.6.1. Landfill management

The assessment shows that open dumping of MSW is a predominant source of GHG emissions within the global waste sector due to the uncontrolled decomposition of organic fractions of MSW. The transition from open dumping to more controlled MSW management options and food waste reduction are necessary to mitigate GHG emissions from open dumping of MSW. Among countries that mentioned the waste sector in their NDCs, improved landfilling was the most frequently cited mitigation action within the waste sector (Powell et al., 2018) due to its significant potential for reducing GHG emissions. The Government and local municipalities should therefore prioritise upgrading open dumps to controlled or sanitary landfills where feasible that incorporate LFG collection and energy recovery systems.

In LICs, upgrading open dumps to semi-aerobic landfills offers a cost-effective approach, achieving a 40 % reduction compared to emissions from open dumping (Muchangos and Tokai, 2020). Simultaneously, landfill diversion strategies should be implemented to reduce the amount of MSW directed to landfills. HICs could improve landfill management by introducing taxes or fees on conventional landfill practices and allocating funds to research and development of advanced landfill technologies. In terms of GHG emissions, energy recovery from waste incineration may be more advantageous in cases where the recovery rate of LFG is not high (Anshassi et al., 2022). From the perspective of the energy structure and security of each country, energy recovery from residual waste may be a realistic option for the transition period until a Net-Zero society can be reached.

4.6.2. Source separation

Government should standardise waste separation procedures at the household level as part of the integrated waste management system as it directly impacts waste management efficiency, environmental sustainability, and resource recovery. Well-designed policies based on local situations can enhance source separation practices and increase recycling rates, reducing landfill use and mitigating GHG emissions. Successful source separation depends not only on technical and financial factors but also on an informed and motivated public. Public awareness campaigns, coupled with accessible information on benefits of waste separation, are essential for effective source separation practices. Additionally, integrating advanced digital technologies such as robotics in waste sorting facilities can further enhance sorting efficiency in HICs.

4.6.3. Food waste reduction

Food waste constitutes a significant portion of MSW, particularly in LICs, where waste management infrastructure is limited and open dumping is the prevalent disposal method, resulting in substantial GHG emissions. Reducing food waste not only mitigates GHG emissions effectively but also conserves valuable resources. Minimising food waste at the source can be achieved through responsible consumption practices, improved supply chain management, and the redistribution of surplus food to individuals or communities in need. For unavoidable food waste, implementing source separation and separate collection for composting and anaerobic digestion offers diversion of landfill disposal. Other closed-loop recycling methods, such as insect bioconversion of food waste into protein-rich biomass and nutrient-dense frass offer alternatives for reducing food waste while producing livestock feed and fertilisers. Additionally, the insect bioconversion industry has the potential to create jobs and encourage local enterprise, while contributing to GHG emissions reduction (Rehman et al., 2023).

4.6.4. Recycling initiatives

The recycling scenarios offer substantial environmental benefits by substituting virgin material production. Governments should therefore implement national recycling targets to increase recycling rates in the MSW management sector. In Europe, setting ambitious recycling targets has proven effective in driving higher recycling rates. At the same time, establishing standards for recycled materials is essential to build supply chain confidence, ensuring that recycled materials are safe to use and meet specified quality requirements. In HICs, economic policies such as deposit-return schemes and extended producer responsibility (EPR) programs, can further enhance recycling rates by providing incentives that encourage active participation from consumers and producers. Deposit-return schemes for products like bottles and cans encourage consumers to return these items in exchange or for a refund, which can boost recycling rates while curbing the prevalence of improper littering (Zorpas, 2024). In LICs, limited financial resources and inadequate infrastructure are significant barriers to increasing the recycling rate in the MSW management sector. International aid, cooperation, and assistance can support the transition to circular economy systems in LICs. Partnerships with international organisations, such as the World Bank, along with international funding and donor contributions, can support infrastructure development and capacity-building. Private sector involvement, including public-private partnerships (PPPs), brings investment and innovation, enhancing the efficiency and sustainability of the MSW management sector.

4.6.5. Waste reduction and prevention

Recycling is in a lower position in the waste hierarchy and the less preferred options for sustainability compared to waste reduction, repair, and reuse, which extend material life and prevent further waste generation. The government should focus on waste reduction and prevention policies that involve prioritising efficient product use and manufacturing, extending the lifespan of products, and promoting a circular economy through a zero-waste approach. Effective waste minimisation and prevention require adequate economic incentives and active public participation to reduce MSW generation and to shape the waste management behaviours and decisions of waste producers. Financial incentives, such as volume-based waste user fees instead of flat fees per household, can drive reductions in MSW generation in HICs. Zero-waste strategies support a circular economy by maintaining products and materials in circulation for as long as possible, thereby reducing MSW, GHG emissions, and harmful chemicals to protect human health and the environment. Governments should therefore implement zero-waste strategies that maximise product lifespans and prevent waste through repair and refurbishment. Some activities may require regulatory support, such as the EU's Right to Repair, or subsidies to promote and sustain these practices. Prioritising policies that minimise waste generation and enhance product lifespans through reuse and recycling can significantly reduce the GHG emissions in the waste sector and the need for new resources.

5. Conclusions

The average global GHG emission from 1 tonne of MSW management in 2023 based on the existing MSW management systems was approximately 89.69 kg CO_{2e}, ranging from 49.27 kg CO_{2e} in HICs, 106.14 kg CO_{2e} in UMCs, 112.47 kg CO_{2e} in LMCs and 128.11 kg CO_{2e} in LICs. The major contributor of global GHG emissions from MSW management was the open dumping of MSW, which contributes almost 70 % of GHG emissions followed by collection and transport, unspecified landfills, sorting of MSW, controlled landfills, sanitary landfill and composting. Recycling the recoverable fractions of MSW had substantial environmental benefits. Anaerobic digestion and incineration of MSW have the potential to provide environmental benefits in the waste sector. However, the environmental benefits of incineration are dependent on energy recovery efficiency, while the benefits of anaerobic digestion are relatively limited due to its limited global application.

The global MSW management sector emitted a total of 173.2 Mt CO_{2e} GHG emissions in 2023. If no improvements are made to existing systems, GHG emissions from the MSW sector will increase to 203.4 Mt CO_{2e} by 2030 and rise to 289.5 Mt CO_{2e} by 2050. This highlights the necessity for improved MSW management systems to reduce GHG emissions to achieve the carbon neutrality goal from the waste sector. A circular economy scenario that considered MSW collection is increased from BAU to 80 %, a reduction in food waste by 40 % from BAU, an increase in recycling rates from BAU to 35 % for Europe and 15 % for the rest of the countries, uncontrolled dumping is also reduced from BAU to 30 %, with MSW diverted to sanitary and controlled landfills. The implementation of the circular economy, which includes achievable targets for MSW management for all countries in the world, has the potential to achieve net zero emissions from the global MSW management sector by 2030 and 2050.

The sensitivity analysis of different chemical composition datasets of MSW fractions revealed that GHG emissions from MSW management increased by approximately 8 % and 3 %, depending on the energy content of MSW fractions. MSW collection and transport distances also significantly affected GHG emissions, with a 31 % increase at maximum distances and a 32 % reduction at minimum distances, underscoring the need for optimisation. Application of the future global renewable electricity mix could reduce GHG emissions from electricity applications by 30 % by 2030 and over 60 % by 2050. Using the Global Temperature Potential (GTP 100) method could lower GHG emissions by 85 % compared to the Global Warming Potential (GWP 100) method. The sensitivity analysis identified the influence of major input parameters on the assessment results, as well as the critical parameters that require a high level of accuracy and helps policymakers and waste sector experts clarify which parameters have the greatest potential to reduce GHG emissions from MSW management.

The assessment shows that the transition from open dumping to more controlled MSW management options and food waste reduction are necessary to mitigate GHG emissions. The Government should standardise waste separation procedures at the household level as it directly impacts waste management efficiency and resource recovery. National recycling targets should be implemented to increase recycling rates within the MSW management sector. The government should focus on waste reduction and prevention policies that prioritise efficient product use and manufacturing, extending the lifespan of products, and promoting a circular economy through a zero-waste approach. The findings from this study benefit governments, municipalities, and environmental organisations in effectively supporting the pursuit of carbon neutrality goals within the global waste sector.

CRediT authorship contribution statement

Phyo Zaw Oo: Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Trakarn Prapaspongsa:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Vladimir Strezov:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Nazmul Huda:** Writing – review & editing, Supervision. **Kazuyuki Oshita:** Writing – review & editing, Validation. **Masaki Takaoka:** Writing – review & editing. **Jun Ren:** Supervision. **Anthony Halog:** Writing – review & editing. **Shabbir H. Gheewala:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Macquarie - Mahidol University Seed Grant 2023 from Macquarie University and Mahidol University and the Scholarship for Cotutelle & Joint Ph.D. Program 2023 from Mahidol University. This work also received support from the Dual PhD Scholarship provided by the Faculty of Engineering and Technology, Liverpool John Moores University. The authors acknowledge the language editing contributions of Mr. Graham K. Rogers, Foreign Expert at the Faculty of Engineering, Mahidol University.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.11.021.

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