Municipal Solid Waste Management in the Top 25 Most Populated Countries: A Review on the Application of LCA to Select Appropriate System in Reducing Greenhouse Gas Emissions

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REVIEW

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ABSTRACT

Population growth effectuates the continuous increase of municipal solid waste (MSW) generation. As it becomes a source of greenhouse gas (GHG) emissions calls for a strategic effort to manage MSW is needed to secure environmental sustainability. The life cycle assessment (LCA) tool has been proven as an effective method to assist policymakers in finding or evaluating various treatments for municipal solid waste management (MSWM) by quantifying the environmental impacts. This study reviewed the application of LCA to select preferred MSWM strategies in reducing GHG emissions in the top 25 most inhabited countries, which have about 74% of the total population worldwide. Systematic assessment has been conducted for 74 manuscripts from 2010–2021, resulting in a summary of the goal/purpose of study, functional unit (FU), LCA software, and considered MSWM options. The study found that per ton of MSW and amount of MSW in the study area were almost equally used, and SimaPro was utilized by 14 LCA studies, while 35 didn't mention the software preference. Among the various treatments, incineration with energy conversion was claimed to be the most environmentally friendly option. Meanwhile, most developed scenarios included landfill but an agreement to equip with a gas collection system was observed to minimize GHG emissions. Concurrence on applying the waste hierarchy approach to get emissions benefits was also detected. Based on income classification, all countries belonging to High Income (HI) and Upper Middle Income (UMI) have produced LCA manuscripts, while no LCA finding in 3 out of 10 Lower Middle Income (LMI) and 2 Lower Income (LI) countries. Although most listed countries have published the LCA studies, better distribution of the study area is still needed. Therefore active support from the government mainly in providing a standardized data collection system, financial backup for research activity and building consciousness among related.

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INTRODUCTION

Climate change, a major environmental problem caused by greenhouse gas (GHG) emissions, requires escalating global action to lessen the harsh impact on the environment and society. Among the various anthropogenic emission sources, which in total produced 33.1 billion metric tons of $CO_{2\text{-eq}}$ emissions in 2020, the waste management sector was reported to contribute GHG emissions as high as 1.6 billion metric tons of $CO_{2\text{-eq}}$, or 5% from the open dumping practice (Kurniawan et al., 2010; Fu et al., 2021). Although much less compared to other sources, especially agriculture, forestry and land-use (AFOLU) (18.4%) and energy (electricity, heat and transport) (73.2%) sectors, waste management is considered a crucial one. This is because it also produces methane (CH_4) and nitrous oxide (N_2O) gases, which have global warming potential as high as 21 and 310 times than carbon dioxide (CO_2), respectively (Eggleston, et al., 2006). It was reported that municipal solid waste management (MSWM), mainly from landfill areas, contributes about 3% to 4% of methane production of the yearly global GHG emissions (Kurniawan et al., 2021). Another study divulged that about 8 to 50 teragram of methane is emitted from landfills, making it accountable for 20% of total methane production worldwide per year (Lombardi et al., 2006). As for nitrous oxide, data from 2018 revealed that the waste sector was in the 4th position following agriculture, fuel combustion and industry, respectively, contributing as much as 142.38 million tons of $CO_{2\text{-eq}}$ (ourworldindata.org).

The scale of the emissions problem from MSWM is directly related to the amount of MSW and its composition. The more enormous solid waste will stimulate higher GHG emissions, while the composition will determine the resulting GHG type. Organic materials, especially biodegradable ones, will potentially emit methane and nitrous oxide along their decomposition process. During the anaerobic process, methane and carbon dioxide are two major expected final products while nitrous oxide will occur in the transformation of nitrogen elements. The involvement of thermal-based technology to treat inorganic or combustible material will produce carbon dioxide. The magnitude of MSW generation depends mainly on the size of the population then, followed by economic status and culture or lifestyle. Based on population growth prediction, the current MSW generation of 2.01 billion tons per year is estimated to rise to 3.4 billion tons in 2050 (Kaza et al., 2018). While the scale of the MSWM problem increases due to continuous population growth, it was reported that about 3 billion people in the globe still have no access to proper disposal facilities (Wilson et al., 2015). Concerning climate change, the unbalance condition between the amount of MSW production and its management will block the mitigation effort.

Considering the main factor that affects waste generation, countries with higher inhabitants will face the MSW problem more seriously than the lower group. This challenge will escalate and be localized when the urbanization rate inflates. Therefore, a proper management system to control municipal solid waste (MSW) from its source to its final disposal is crucial to eliminate or reduce GHG emissions. Moreover, the need for effective MSWM is essential not only for climate change mitigation but also to support the achievement of other Sustainable Development Goals (SDGs), especially Goal number 3 (Good Health and Well-Being), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production). The development of MSWM may differ from country to country due to several factors such as geographical conditions, culture, environmental issues, and economic perspectives. In order to formulate the preferable system, Life Cycle Assessment (LCA) – a systematic assessment tool for production processes or services, has been widely used for MSWM. As a standard yet effective tool, LCA can estimate the environmental impacts of various MSWM alternatives, thus enabling decision-makers to collate different systems and pick out the best management scheme with its optimum environmental performance (Slagstad and BrattebØ, 2013; Khandelwal et al., 2019). The application of LCA in MSWM has been reviewed by several studies with various perspectives, for example review for adjusting the LCA method (Tsalidis and Korevaar, 2020; Viau et al., 2020), for comparing waste to energy technology (Astrup et al., 2015; Mater et al., 2019) and for identifying the best MSWM option (Iqbal et al., 2020; Zhang et al., 2021). Besides those angles, some studies reviewed the implementation of LCA on MSWM based on area or region, such as Asia (Yadav and Samadder, 2018) and Latin America (Margallo et al., 2019). This study seeks the implementation of LCA on MSWM with a focus on reducing GHG emissions in the top 25 most populated countries. The analysis covers several elements such as area of study, LCA components and manuscripts distribution based on region and income level classification followed by a critical assessment of the findings. The results describe a developed strategy to tackle climate change from the waste sector in the selected countries. Moreover, the present study will assist policymakers and LCA practitioners in comprehending the current LCA practice in the MSWM area before research development based on each condition.

METHODOLOGY

This review study was started by searching scientific papers with these criteria: (i) the manuscripts published in the year of 2010 until 2021; (ii) areas of study were located in the top 25 most populated countries; (iii) the object of the study did not include industrial, electronic, hazardous waste; (iv) LCA was used as the primary tool for the assessment; (v) published study included at least two scenarios with GHG emissions expression (or one of among environmental impacts expression).

The search of scientific papers with those above criteria was done through an online search engine with "municipal solid waste" and "life cycle assessment" as specific keywords. Additional keywords representing the supplement criteria (respective countries, greenhouse gas emission, global warming potential) were set to narrow the result. Once the expected manuscripts were retrieved, a cross-reference investigation was conducted for more results. All collected manuscripts were grouped into each country, and a summary of important information (eg. purpose of study, functional unit, description of scenarios and the results/GHG emission information) was drawn prior to analysis and comparison activities.

RESULTS AND DISCUSSION

OVERVIEW OF THE STUDY AREA

The 25 most populated countries based on World Bank Data have been selected as the object of this study. Table 1 provides information on the population size of each country, it can be seen that the total population of 25 countries is 5,792,624,481 (2021), which is about 74% of the global population. This figure correlates to the fact that the total MSW amount from these countries contributes as much as 77% of the annual worldwide MSW generation as 20 out of 25 countries are on the list of the Top 25 MSW producers. Regarding GHG emissions, among the selected countries, 19 of them are in the Top 25 GHG emitters, and 17 countries are also listed as the Top 25 GHG emitters from the waste sector. In terms of geographical area, the distribution of manuscript producers is as follow 6; 3; 6; 5; 2; and two countries are located in East Asia & Pacific (EAP), South Asia (SA), Europe & Central Asia (ECA), Africa (AF), Middle East & North Africa (MENA), Latin America & Caribbean (LAC) respectively, with United States representing North America (NA). As for the economic condition, following the direction of the World Bank on income level classification, there are six countries with High Income (HI) status, mainly in ECA and seven countries in Upper Middle Income (UMI) level with more even geographical distribution. Meanwhile, ten countries are in Lower Middle Income (LMI) and 2 in Low Income (LI) class (worldbank.org). All countries face urbanization problems; in fact, in 16 countries, more than half of the total population has lived in urban areas in recent times. The variety of income level classifications and urban population conditions for the chosen regions of study will be used for further elaboration in the following section. After carefully selecting all manuscripts on LCA studies in respected countries with the aforementioned criteria there is a total of 74 papers have been identified with distribution as described in Figure 1. In the chosen period, China produced the most, followed by Brazil and Italy, India and Iran in the second and third positions respectively. Meanwhile, publication progress for five countries: Bangladesh, Ethiopia, Egypt, the Democratic Republic of Congo and Tanzania is still awaited.

LCA APPLICATION ON MSWM

The application of LCA on MSWM in the top 25 most inhabited countries with a focus on GHG emissions examination has been summarized and presented in Table 2.

GOAL

Several purposes concerning GHG emissions have been identified during the review process. Most of the goal in conducting LCA on MSWM is to assess the environmental performance (emissions production and reduction) of current MSWM practice and compare it to several possible treatments based on the local or national condition. Some studies mentioned the more specific goal to evaluate the certain type of treatments or waste conditions such as mechanical treatment (Havukainen et al., 2017), biological treatment (Takata et al., 2013), mechanical–biological (Tyagi et al., 2021), source-separated collection/separation/garbage classification (Song et al., 2013; Chen et al., 2020; Yuan et al., 2020), recycling (Geng et al., 2010), high organic fraction and moisture content (Liu et al., 2017c; Mayer et al., 2020; Voss et al., 2021), MRF distribution (Muhamad et al., 2020), RDF (Silva et al., 2021), collection and transportation (Taskin and Demir, 2020) and incineration (Beylot et al., 2018; Di Maria and Micale, 2015). In order to understand the GHG emissions from MSWM in different periods, three studies examined time-based patterns considering changes in MSW generation and improvement in the treatments (Zhou et al., 2018; Yang et al., 2018; Lima et al., 2019; Yaman, 2020; Rigamonti, 2013). All studies were conducted with perhaps could be feedback or input for the decision makers in determining the most suitable MSWM strategy.

FUNCTIONAL UNIT

The functional unit (FU) is a critical factor to be defined in LCA studies. With a clear description of FU, the output of the study can be more easily interpreted and compared, thus may provide higher reliability. In LCA studies for MSWM, FU can be stated in two ways which are (a) input-based FU, the amount of MSW entering the system to be studied, or (b) output-based FU, the amount of product (for example compost, gas, electricity, heat) that being produced during the MSWM system implementation.

NO	COUNTRY NAME	COUNTRY CODE	REGION	INCOME LEVEL CLASSIFICATION	POPULATION		URBAN POPULATION (%)		TOTAL MSW GENERATION (2019) (TON/YEAR)	RANK OF MSW PRODUCER (2019)	GHG EMISSION (2019) (kT CO_2-eq)		RANK OF GHG EMMITER (2019)	
					2020	2021	2020	2021			TOTAL	WASTE	TOTAL	WASTE
1	China	CHN	EAP	UMI	1,411,100,000	1,412,360,000	61.428	62.512	395,081,376	1	12,705,089.84	203,540	1	1
2	India	IND	SA	LMI	1,380,004,385	1,393,409,033	34.926	35.393	189,750,000	3	3,394,870.12	84,260	3	5
3	United States	USA	US	HI	331,501,080	331,893,745	82.664	82.873	265,224,528	2	6,001,209.96	134,350	2	3
4	Indonesia	IDN	EAP	LMI	273,523,621	276,361,788	56.641	57.29	65,200,000	5	1,002,370.00	136,020	7	2
5	Pakistan	PAK	SA	LMI	220,892,331	225,199,929	37.165	37.44	30,760,000	13	432,500.00	9,390	18	38
6	Brazil	BRA	LAC	UMI	212,559,409	213,993,441	87.073	87.317	79,069,584	4	1,057,260.01	70,890	6	6
7	Nigeria	NGA	AF	LMI	206,139,587	211,400,704	51.958	52.746	27,614,830	15	308,179.99	14,450	27	26
8	Bangladesh	BGD	SA	LMI	164,689,383	166,303/494	38.177	38.946	14,778,497	26	215,940.00	20,910	35	15
9	Russian Federation	RUS	ECA	UMI	144,073,139	143,446,060	74.754	74.934	60,000,000	6	2/476,840.09	117,950	4	4
10	Mexico	MEX	LAC	UMI	128,932,753	130,262,220	80.731	81.016	53,100,000	7	653,870.00	47,600	13	7
11	Japan	JPN	EAP	HI	126,261,000	125,681,593	91.782	91.867	42,720,000	9	1,166,510.01	6,690	5	45
12	Ethiopia	ETH	AF	LI	114,963,583	117,876,226	21.695	22.174	6,532,787	43	150,960.01	4,980	40	55
13	Philippines	PHL	EAP	LMI	109,581,085	111,046,910	47.408	47.684	14,631,923	27	234,280.00	14,000	33	27
14	Egypt, Arab Rep.	EGY	MENA	LMI	102,334,403	104,258,327	42.783	42.862	21,000,000	19	351,769.99	28,540	24	10
15	Vietnam	VNM	EAP	LMI	97,338,583	98,168,829	37.34	38.052	9,570,300	36	450,149.99	20,630	16	16
16	Congo, Dem. Rep.	COD	AF	LI	89,561,404	92,377,986	45.638	46.235	14,385,226	28	55,000.00	15,540	73	22
17	Turkiye	TUR	ECA	UMI	84,339,067	85,042,736	76.105	76.569	35,374,156	11	488,470.00	16,980	15	20
18	Iran, Islamic Rep.	IRN	MENA	LMI	83,992,953	85,028,760	75.874	76.345	17,885,000	23	893,719.97	47,260	8	8
19	Germany	DEU	ECA	HI	83,160,871	83,129,285	77.453	77.544	50,627,876	8	749,710.02	8,200	9	40
20	Thailand	THA	EAP	UMI	69,799,978	69,950,844	51.43	52.163	26,853,366	16	422,090.00	12,790	19	29
21	United Kingdom	GBR	ECA	HI	67,081,000	67,326,569	83.903	84.152	30,771,140	12	440,079.99	17,010	17	19
22	France	FRA	ECA	HI	67,379,908	67,499,343	80.975	81.242	36,748,820	10	414,040.01	14,690	20	24
23	Italy	ITA	ECA	HI	59,449,527	59,066,225	71.039	71.346	30,088,400	14	389,000.00	16,740	21	21
24	Tanzania	TZA	AF	LMI	59,734,213	61,498,438	35.227	35.954	9,276,995	37	84,000.00	6,220	56	48
25	South Africa	ZAF	AF	UMI	59,308,690	60,041,996	67.354	67.847	18,457,232	21	555,429.99	25,240	14	11
	Total				5,747,701,953	5,792,624,481			1,545,502,036		35,093,339.98	1,094,870.00		

Table 1 Information on population, MSW and GHG emissions in selected countries.

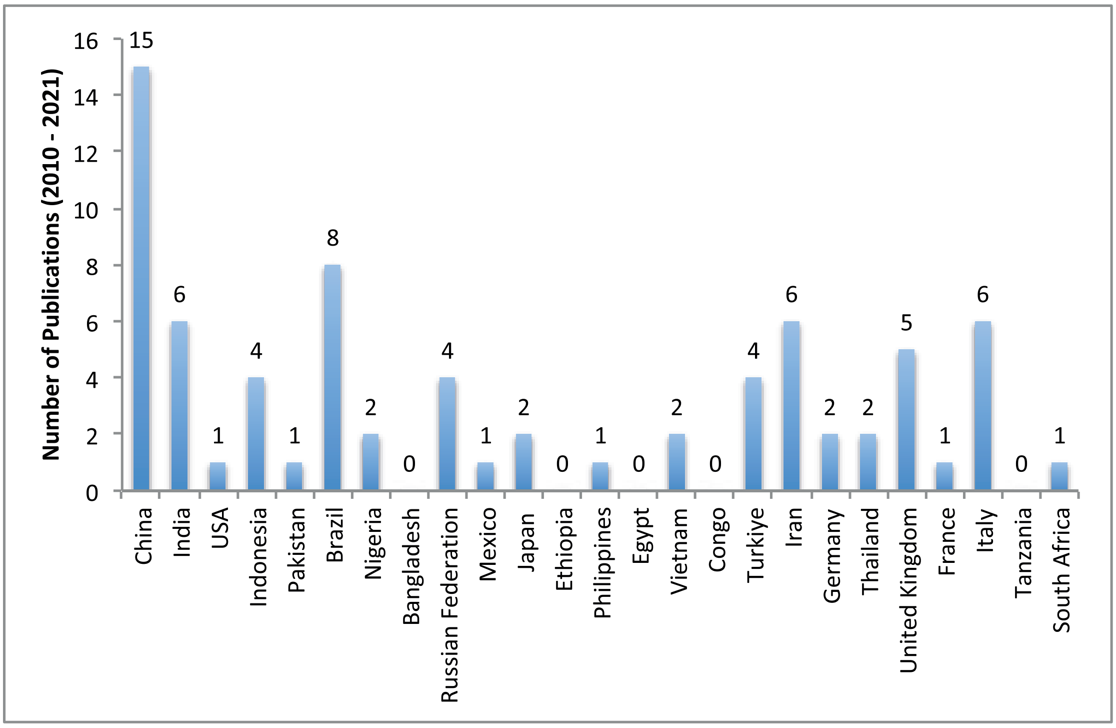

Figure 1 Distribution of LCA studies on MSWM – GHG emissions in the top 25 most populated countries.

Figure 2 portrays that the amount of MSW generated in the study area was used as FU in 36 studies meanwhile a unit of per ton MSW was implemented in another 34 studies. Also, four other LCA studies used different FU expressions per Kg MSW (Yuan et al., 2020) and 100-ton MSW (Tyagi et al., 2021; Thanh and Matsui, 2013; Behrooznia et al., 2020). All LCA analyses involving a wider area of study (whole country, region, several cities to be compared) used the input of per ton MSW as FU. On another side, a study with a city or single area/district utilized either per ton MSW or the amount of MSW generated. Besides dependency on the purpose of the study, the selection of FU is determined by the availability of data, primarily when the amount of waste generation for a specific area and time will be used.

SYSTEM BOUNDARY

System boundary plays a significant role in LCA studies. ISO 14044 refers to the standards for identifying which unit processes are part of a product system. System boundary defines specific modules included or excluded in the system modeling (Jolliet et al., 2016). In the case of MSWM, the system boundary may include all stages such as waste generation, collection, transportation, treatment and disposal. However depending on the goal of LCA studies, the adjustment in system boundary may be done as long as relevant required inputs and environmental impacts to the ecosystem are covered (Herrmann and Moltesen, 2014). Raw materials and energy (MSW, electricity, fuel) as inputs and environmental impacts, in this case emission, as output for every involved process should be defined based on the reference flow. This review found that in studies with broader areas, particularly for country size, and studies for specific treatments, collection and transportation were excluded from the model system (Hong et al., 2010; Liu et al., 2017a; Liu et al., 2017b; Liu et al., 2017c; Pandyaswargo et al., 2012; Gunamantha and Sarto, 2012; Tunesi, 2011; Beylot et al., 2018). Collection and transportation are considered minimum or insignificant in contributing GHG emissions compared to other waste treatments; therefore, they may be excluded from the inventory analysis (Liu et al., 2017b; Liu et al., 2017b; Yadav and Samadder, 2017; Chen et al., 2016; Cherubini et al., 2009).

TOOLS FOR LCA MODELLING

Recently, numerous software tools have assisted LCA study in data organization and analysis, modeling and evaluation of environmental impacts. The presence of this computer-based instrument is conducive since the study involves a massive set of data. Manual or hand calculation will be tedious and tends to create mistakes. Moreover the description of results interpretation and/or evaluation of environmental impacts only can be done in a limited version. Another favorable consideration for using it is the association with relevant databases for assessing products or processes. Among the commercial LCA software tools, SimaPro and GaBI are two dominant products that have been widely used by academicians or practitioners. Both products provide (i) a user interface for the modeling system; (ii) process database; (iii) an impact assessment database and (iv) a system to calculate numbers from the database according to

NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
1.	China – Tianjin	To assess current MSWM and several proposed alternatives concerning the balance between economic and environmental (GHG mitigation) perspectives.	Amount of MSW		S0: Landfill without landfill gas (LFG) utilization S1: Landfill with LFG Utilization S2: Incineration (MSW to energy plant) S3: Material Recovery Facility (MRF) to convert mixed metals, glass, paper & plastics into secondary materials S4: Centralized Composting S5: Integrated System	Landfill was the most significant source of GHG emissions. However the utilization of produced gas will cut 38.9% of emissions. An integrated approach consists of composting – recycling – incineration and landfill with energy recovery provided minimum GHG emissions.	Zhao et al., 2011
2.	China – China	To estimate the environmental impacts of MSW treatments.	Per ton MSW	(M) IMPACT2002+	S0: Landfill S1: Incineration with energy recovery S2: Composting + Landfill S3: Composting + Incineration	Incineration with energy recovery gave GHG emissions benefit	Hong et al., 2010
3.	China – Macau	To compare the environmental impacts of current and proposed MSWM.	Amount of MSW	(S) SimaPro	S0: Incineration (with electricity generation) + Landfill (fly ash & bottom ash) S1: Landfill S2: Source Separation + Composting + Landfill S3: Incineration + Composting S4: Source Separation + Incineration (with electricity generation) S5: Source Separation + Composting + Incineration	Source separation played a significant role in reducing GHG emissions. Being combined with advanced incineration, this brought 117.55% emissions benefit.	Song et al., 2013
4.	China – Hangzhou	To assess the performance of the MSWM system after the introduction of a source-separated collection policy.	Amount of MSW	(S) IPCC (M) EDIP97	S1: No source separation – Landfill (BAU) S2: 25% food waste & 17% recyclable separation S3: Landfill with LFG collection (food waste) S4: Composting (food waste) S5: Anaerobic Digestion (food waste) S6: Source separation + Anaerobic Digestion for food waste + Landfill + Incineration	Source separation (S2) gave environmental benefits of as much as 23% less GHG emissions. For food waste treatment, Anaerobic Digestion performed better than Composting in terms of GHGs production.	Dong et al., 2013
5.	China – Hangzhou	To assess the environmental impact of the application of mechanical treatment and its combination.	Amount of MSW	(S) GaBI (M) CML2010	S0: no Refuse-Derived Fuel (RDF) S1: RDF to replace MSW and coal co-incineration in 3 incineration plants (with four different treatments for rejected organics) S2: same as S1 but with a totally new plant (incineration plant)	The involvement of mechanical treatment (RDF production) had a significant impact on lowering GHG emissions. It was noted that the reduction could be up to 33%, 1800 kT/year with the current system to 1200 kT/year with scenario 2 (replacing the incineration plants with the new ones and introducing anaerobic digestion and/or ethanol production to treat the rejected organics from RDF plants). Landfill contributed the highest share of GHG in all scenarios, 48–67% of the total GHG emitted.	Havukainen et al., 2017

(Contd.)

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6.	China – China	To evaluate environmental performance and clarify the advantages and disadvantages of different treatment routes for MSW characterized by high organic fraction and moisture content.	Per ton MSW	(S) EaseTech	S1: Landfill without energy recovery S2: Landfill with energy recovery S3: Incineration S4: Composting and all of its products sent to Landfill with energy recovery S5: Composting and the products sent for land application S6: Anaerobic Digestion and all of its products sent to Landfill with energy recovery S7: Anaerobic Digestion and the products sent for land application	Incineration gave the most significant benefit of 124.3 kg CO_2-eq GHG reductions The application of Anaerobic Digestion brought less emission compared to composting The utilization (land application) of the biological product (from composting/Anaerobic Digestion) will reduce the GHG emission, compared to if the products are just being dumped in a landfill.	Liu et al., 2017 (a)
7.	China – China	To determine the carbon, energy flow and GHG emissions for each MSWM strategy.	Per ton MSW	(S) EaseTech	S1: Landfilling with LFG flaring S2: Landfilling with LFG recovery S3: Incineration S4: Composting +Incineration + Landfilling S5: Anaerobic Digestion (biogas to energy) + Incineration + Landfilling	Incineration brought the biggest benefit in terms of GHG reduction (–124 kg CO_2-eq) Anaerobic digestion performed better than composting resulting in lower GHG emissions, although in no significant context. The net emissions in bio-process were minimum since high energy consumption needed and GHG leakage during the process.	Liu et al., 2017 (b)
8.	China – China	To investigate the suitable MSW strategy for high organic fraction waste.	Per ton MSW	(S) EaseTech	S1: Landfilling with LFG flaring S2: Landfilling with LFG to energy S3: Incineration with energy recovery S4: Anaerobic Digestion for organic fractions & Landfilling for non-biodegradable fractions S5: Anaerobic Digestion for organic fractions + incineration for high calorific value components (HCVCs) + Landfilling for inorganic fractions	Integrated treatments with a focus on high calorific waste as the input for incineration (S5) presented the most considerable emission reduction among the scenarios (–54.5 kg CO_2-eq per ton waste).	Liu et al., 2017 (c)
9.	China – Hangzhou	To analyze the environmental performance evolution of integrated MSWM during the last decade.	Amount of MSW	(S) GaBI (M) EDIP97	S1.1: Landfill (mixed waste – before separate collection) S1.2: Landfill (mixed waste – after separate collection) S2.1: Incineration (mixed waste – before separate collection) S2.2: Incineration (mixed waste – after separate collection) S3.1: Landfill (food waste) S3.2: Anaerobic Digestion (food waste)	Incineration (with energy recovery) provided better environmental performance compared to landfill. Source-separated collection improved the Low Heating Value (LHV) of MSW and benefits the incineration with more electricity production. Anaerobic digestion for treating food waste was considered important to reduce the environmental impacts (GHGs).	Zhou et al., 2018
10	China – Xiamen	To evaluate the spatial pattern of urban waste change and its emissions consequences & to identify the waste-carbon relationship and feasible low-carbon strategies.	Amount of MSW	(S) IPCC	S1: Baseline (current system) S2: Waste Reduction S3: Waste disposal optimism S4: Integration	The study provided a projection of waste-related CO_2 emissions from 2015 to 2050. From the assessment of developed scenarios, the combination of reduction at source and proper collection (for optimum disposal arrangement) gave the lowest increment (6.61%) compared to three others which were reduction (6.90%), disposal optimization (8.42%) and business as usual (8.86%).	Yang et al., 2018

(Contd.)

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11.	China – Beijing	To assess the environmental impacts of integrated MSWM involving different separation and recycling methods.	Amount of MSW	(S) IPCC	S1: Landfill + Incineration S2: Landfill + Incineration + Composting S3: Incineration + Composting S4: Landfill + Incineration + Composting + Recycling S5: Incineration + Composting + Recycling	Landfill produced the most significant emissions meanwhile, incineration provided the biggest emissions reduction Separation was crucial for saving the recyclables which brought emission reduction and for proper treatment (for food waste especially)	Xin et al., 2020
12.	China – Hohhot	To identify the environmental impacts of a complete MSWM system.	Amount of MSW	(S) SimaPro (M) CML-1A	S1: Incineration (2): Landfill (7) S2: Incineration (11): Landfill (6) S3: Incineration (5): Landfill (1) S4: Incineration (5): Landfill (1) + CO_2 capture system	The landfill was the biggest source of GHG emissions. The increased portion of MSW to be incinerated levels up the GHG emissions unless the CO_2 capture system is installed.	Liu et al., 2020
13.	China – Putuo District, Shanghai	To estimate and compare GHGs during the treatment of food waste and residual waste in domestic waste.	Amount of MSW (2365 families)	(S) IPCC	Mode 1: Traditional mixing + incineration Mode 2: Garbage classification + in situ reductions of food waste (food waste was crushed & aerobically composted). Mode 3: Garbage classification + anaerobic digestion *Residue & separated food waste were incinerated. The landfill received residue from incineration and WWTP/ sludge treatment.	Incineration was an effective method to reduce carbon emissions compared to landfill due to the energy recovery and land saving. The application of aerobic composting did lessen the carbon emission, but anaerobic digestion performed much better, achieving 44.1% CO_2 emissions reduction compared to landfill.	Chen et al., 2020
14.	China – Xian	To compare the performance of landfill and incineration from the perspective of energy use and GHG emissions.	Amount of MSW	(S) IPCC	Case 1: Landfill + Anaerobic (all MSW) Case 2: Landfill + Semi Aerobic (all MSW) Case 3: Incineration (all MSW) Case 4: Incineration (combustible waste, non-burnable waste to landfill)	Separation played a significant role in minimizing GHG emissions. The existence of non-burnable MSW required more power supply.	Wang and Nakakubo, 2020
15.	China – China	To investigate the environmental effects of garbage classification on the MSWM system.	Per Kg MSW	(M) IMPACT2002+	S1: Mixed to Incineration + Composting + Landfill S2: Sorted to Hazardous – Perishable – Other – Recyclable S3: Sorted to Hazardous – Perishable – Other – (Paper/ Cardboard; Plastics; Metals; Glass; Textiles)	Source separation reduced the GHG emissions.	Yuan et al., 2020
16.	India – Mumbai	To analyze different potential options for MSWM.	Amount of MSW	(S) GaBI	S0: Open Dumping (69%) + Bioreactor Landfill (31%) S1: Material Recovery Facility (20%) + + residue to Sanitary Landfill with 50% biogas collection & electricity production S2: Material Recovery Facility (20%) + Composting (80%) + residue to Sanitary Landfill with 50% biogas collection & electricity production S3: Material Recovery Facility (20%) + Anaerobic Digestion (80%) + residue to Sanitary Landfill with 50% biogas collection & electricity production S4: Material Recovery Facility (20%) + Composting (40%) + Anaerobic Digestion (40%)+ residue to Sanitary Landfill with 50% biogas collection & electricity production S5: Material Recovery Facility (20%) + Composting (20%) + residue to Incineration with electricity production S6: Material Recovery Facility (20%) + residue to Incineration with electricity production	There was a linear correlation between the increase in recycling rate and the decrease in global warming potential. Anaerobic digestion performed better than composting. Incineration was the best strategy to avoid emissions.	Sharma and Chandel, 2016

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NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
17.	India – Kolhapur	To identify the optimum MSWM concerning environmental impacts	Per ton MSW	(S) SimaPro (M) CML-1A	S1: Open dump (100%) S2: Recycling (16.88%) + Composting (70.33%) + Landfilling (17.64%) S3: Recycling (16.88%) + Anaerobic Digestion (70.33%) + Landfilling (17.64%) S4: Recycling (16.88%) + (Pyrolysis-gasification (70.33% + 7.23%) + Landfilling (10.56%)	The application of advanced technologies (pyrolisis – gasification) offered lower emissions production than BAU practice (Open Dump). However due to energy auxiliary need, the benefit was still under composting or anaerobic digestion.	Mali and Patil, 2016
18.	India – Dhanbad	To evaluate the current MSWM system and to analyze different options for developed MSWM from the perspective of the environmental impacts.	Per ton MSW	(S) SimaPro	S1: Collection & Transportation S2: Open Dump S3: Composting + Landfilling without energy recovery S4: Recycling + Composting + Landfilling without energy recovery	Open dump & landfilling without energy recovery produced high GWP. Recycling (MRF) contributed to the reduction of GHG emissions.	Yadav and Samadder, 2017
19.	India – Nagpur	To compare the environmental impacts of different potential MSWM	Per ton MSW	(S) GaBI (M) CML-1A	S1: Composting (17%) + Landfill (83%) (no LFG & leachate treatment) S2: Material Recovery Facility (20%) + Composting (80% of organic fraction) + Landfill S3: Material Recovery Facility (20%) + Anaerobic Digestion (80% of organic fraction) + Landfill S4: Material Recovery Facility (20%) + Composting (40%) + Anaerobic Digestion (40%) + Landfill	Recycling (MRF) reduced the environmental impacts (including GHG emissions). The implementation of composting or anaerobic digestion offered relatively equal GHG emissions benefits.	Khandelwal et al., 2019
20.	India – Chandigarh, Mohali, Panchkula	To analyze the impacts of different potential MSWM scenarios.	Per ton MSW	(S) SimaPro	S1: RDF (only in Chandigarh)+ Open Dump S2: Material Recovery Facility (20%) + Sanitray Landfill (with 50% biogas collection & electricity production) S3: Material Recovery Facility (20%) + Composting (80% of biodegradable materials) + Sanitary Landfill (with 50% biogas collection & electricity production) S4: Material Recovery Facility (20%) + Composting (60%) + Anaerobic Digestion (20%) + Sanitary Landfill (with 50% biogas collection & electricity production) S5: Material Recovery Facility (20%) + Composting (40%) + Incineration (with electricity production)	S3 followed by S4 were the two optimum strategies for the three cities. The involvement of anaerobic digestion (S4) in treating biodegradable waste seemed insignificant compared to the application of single bio-treatment (composting)(S3).	Rana et al., 2019
21.	India – Goa	To assess the feasibility of building 100 tons per day of MBT Plant for MSW.	Per 100-ton MSW		This study focused on mechanical–biological treatment applications for making RDF and the recycling process for separated waste materials.	RDF production with a capacity of 100 tons MSW per day brought emissions benefits. However, the most contribution was from plastic recycling, with RDF production at the second position.	Tyagi et al., 2021

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22.	USA – California	To assist policymakers by analyzing waste treatment scenarios for their climate mitigation potential.	Per ton MSW	(S) EASY WASTE	S1: Landfill with 64% of LFG is collected S2: Reduction (40%) – same consumption lower waste rate S3: Incineration for the combustible fraction with 20% of biogenic waste w/ Electricity production. The rest of the waste sent to landfill S4: Anaerobic Digestion for biogenic waste (mainly food waste) with methane recovered for electricity production. The remaining waste in landfill S5: Maximization of WtE – biogenic waste to Anaerobic Digestion; combustible inorganic to incineration & non-flammable to landfill	Waste reduction contributed a significant amount of GHG emissions benefit. Recovery facility was vital in determining the amount of environmental benefits.	Vergara et al., 2011
23.	Indonesia – Indonesia		Per ton MSW		S1: Incineration + Energy recovery S2: Composting + Sanitary Landfill + LFG collection for energy recovery S3: Biogas/Anaerobic Digestion + Sanitary Landfill + LFG collection for energy recovery	The involvement of bioprocess was significant in MSWM. Anaerobic digestion and composting offered relatively equal benefits in terms of GHG emissions reduction (anaerobic was more beneficial with higher reduction)	Pandyaswargo et al., 2012
24.	Indonesia (Yogyakarta, Sleman, Bantul)	To compare various energetic valorization options of MSWM.	Per ton MSW		S0: Landfilling S1: Landfilling with energy recovery S2: Anaerobic Digestion + Incineration + Landfill S3: Anaerobic Digestion + Gasification + Landfill S4: Incineration + Landfill S5: Gasification + Landfill	Gasification played a significant role in minimizing GHG emissions (S5 provided benefits as much as –0.168 ton CO2-eq per ton waste.	Gunamantha and Sarto, 2012
25.	Indonesia – Depok	To develop MSWM options with the most negligible environmental impacts.	Amount of MSW		S1: Composting (40) + Open Burning (70) + Waste Treatment Unit (60) + Anaerobic Digestion (340) + Landfill (600) S2: Composting (150) + Waste Treatment Unit (80) + Anaerobic Digestion (500) + Landfill (390) S3: Composting (200) + Waste Treatment Unit (100) + Anaerobic Digestion (500) + Incineration (100) + Landfill (220) S4: Composting (250) + Waste Treatment Unit (120) + Anaerobic Digestion (500) + Incineration (150) + Landfill (100)	Landfill contributed the highest emissions. Anaerobic digestion was a suitable treatment for food waste and produced fewer emissions than composting.	Kristanto and Koven, 2019
26.	Indonesia – Surabaya	To propose a new strategy with small-sized distributed MRFs with improved transportation efficiency.	Per ton MSW		S0: Transfer Station + Material Recovery Facility + Composting + Landfill S1: Merged Transfer Station (Transfer Station with <1 a day of transportation freq. & those nearby the landfill) S2: Upgraded Transfer Station (Transfer Station with 3–6 trips/day will be upgraded into Material Recovery Facility) S3: Distributed Material Recovery Facility System	This study focus on the importance of MRF distribution over the city area. The availability (more than the existing condition) will help reduce GHGs emissions. The shifting of the Transfer Station to MRF indicated the potential for getting more advantageous.	Muhamad et al., 2020

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27.	Pakistan – Gulberg Town, Lahore	To evaluate the global warming potential of the current MSWM.	Amount of MSW	(S) EASETECH	S0: Dumpsite with a clay cover S1: Material Recovery Facility (17.94%) + Composting (12.08%) + Dump Site (remaining) S2: Material Recovery Facility (17.94%) + Biogas/Anaerobic Digestion (12.08%) + Dump Site (remaining) S3: Material Recovery Facility (17.94%) + Biogas/Anaerobic Digestion (12.08%) + RDF (remaining)	The implementation of dumpsite without LFG & leachate collection gave the highest emissions. Recycling (MRF) and biogas contributed most significantly, while the production of RDF was not a good option in terms of global warming potential.	Syeda et al., 2017
28.	Brazil – Betim	To evaluate different alternatives of MSWM from the perspective of environmental and economic aspects.	Per ton MSW	(S) SimaPro	S1: Incineration + Landfill (for the residue) S2: Landfill without LFG Collection S3: Landfill with LFG collection (75% efficiency) for supplying internal combustion engine S4: Landfill with LFG collection (75% efficiency) for supplying gas turbine	Landfill produced the highest emissions, with CH4 as the primary contributor. Incineration to produce electricity brought the highest environmental benefit.	Leme et al., 2014
29.	Brazil – Rio de Janeiro	To investigate MSWM solutions.	Amount of MSW	(S) LCA – IWM	S1: Composting (2.7%) + Recycling (0.9%) + Landfilling (remaining) S2: Composting (2.7%) + Recycling (0.9%) +Incineration (56%) + Landfilling (remaining) S3: Composting (2.7%) + Recycling (0.9%) + Anaerobic Mechanical Biological Treatment (56%) + Landfilling (remaining) S4: Composting (2.7%) + Recycling (0.9%) + Aerobic Mechanical Biological Treatment (56%) + Landfilling (remaining) S5: Composting (50%) + Recycling (60%) + Landfilling (remaining) S6: Anaerobic Digestion (50%) + Recycling (60%) + Landfilling (remaining) S7: Composting (15%) + Anaerobic Digestion (15%) + Recycling (45%) + Incineration (25%) + Landfilling (remaining) S8: Composting (25%) + Anaerobic Digestion (25%) + Recycling (60%) +Incineration (50%) + Landfilling (remaining)	Separation and material recovery was more preferable to incineration or landfill in terms of minimizing GHG emissions. The application of anaerobic digestion to back up recycling was the best combination (S6) in reducing the emissions.	Coelho and Lange, 2016
30.	Brazil – Rio de Janeiro	To compare two different identification approaches of the MSWM process and technologies.	Per ton MSW	(S) EASETECH & SimaPro (for fertilizer)	S1: Landfill all MSW with LFG collection for electricity production S2: 50% Separation of organics for AD w/biogas combustion; digestate for fertilizer on farmland; Landfill for the remaining with LFG collection for electricity production. S3: All MSW & Post-Separation of organics (75% of total) in Material Recovery Facility; Anaerobic Digestion for organics with biogas combustion & digestate for fertilizer; Landfill for the remaining with LFG collection for electricity production.	The application of landfill only resulted in the highest production of GHG emissions. The application of digestate for fertilizer gave environmental benefits rather than mineral fertilizer utilization.	Saraiva et al., 2017

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31.	Brazil – Sao Paulo	To assess the environmental impacts of MSWM.	Amount of MSW	(S) GaBI	S0: 100% MSW to Landfill S1: Home Composting (5% of organics) + Landfill (for the remaining MSW) S2.1: Home Composting (5% of organics) + Composting Plant (20% of organics/9.8% of total MSW) + Landfill (for the remaining MSW) S2.2: Home Composting (5% of organics) + Anaerobic Digestion (20% of organics/9.8% of total MSW) + Landfill (for the remaining MSW) S3.1: Home Composting (5% of organics) + Composting Plant (20% of organics/9.8% of total MSW) + MBT/ Incineration (20%of residual MSW or 17.6% of total MSW) + Landfill (for the remaining MSW) S3.2: Home Composting (5% of organics) + Anaerobic Digestion (20% of organics/9.8% of total MSW) + MBT/ Incineration (20%of residual MSW or 17.6% of total MSW) + Landfill (for the remaining MSW) S4.1: Home Composting (5% of organics) + Composting Plant (20% of organics/9.8% of total MSW) + MBT/ Cement Kilns (20%of residual MSW or 17.6% of total MSW) + Landfill (for the remaining MSW) S4.2: Home Composting (5% of organics) + Anaerobic Digestion (20% of organics/9.8% of total MSW) + MBT/ Cement Kilns (20%of residual MSW or 17.6% of total MSW) + Landfill (for the remaining MSW)	Anaerobic digestion is a better option than composting. The utilization of RDF for substituting coal in Cement Kilns provides more avoided emissions compared to the use in incineration.	Liikanen et al., 2018
32.	Brazil – Campo Grande	To evaluate the environmental performance of MSWM planned development and to explore potential alternatives.	Amount of MSW	(S) EASETECH	There were three scenarios including the business as usual (BAU) condition, to test the impact of MSWM on the environment. The other two were (a) planned development which focused on sanitary landfill with gas valorization and without selective biowaste collection and (b) planned development + mixed waste treatment with a focus on RDF utilization in the cement industry and biogas upgrading for vehicle fuel.	Landfill was the biggest contributor. Selective collection for biowaste provided a significant impact on the reduction of GHG. The decline was more drastic whenever the MBT was introduced to the system and used in cement kilns. Recycling also contributed significantly to reducing emissions. In a smaller portion, introducing anaerobic digestion for separately collected biowaste and organic fraction also lowered the production of emissions.	Lima et al., 2019
33.	Brazil – Sao Paulo, Sorocaba, Piedade, Santa Cruz do Sul, Humaita	To analyze the transition towards eco-efficiency of MSWM aimed at reducing GHG at the local and national scale for future reference in BRICS and other developing countries.	Per ton MSW	(S) CO2ZW	S0: 100% Landfill S1: 10% Composting & Recycling + 90% Landfilling S2: 10% Composting & Recycling + 90%MBT & Incineration S3: 40%Composting & Recycling + 60% Landfilling S4: 40%Composting & Recycling + 60% MBT & Incineration S5: 70% Composting & Recycling + 30% Landfilling S6: 70% Composting & Recycling + 30% MBT&Incineration	The involvement of advanced technology such as MBT and incineration provided more immense emissions benefits (76% – 96%) but required higher costs for the settlement (up to 196%). The implementation of landfill accompanied by recycling & composting was able to lower the emission (up to 83%) with a lower increase in operating & investment costs (up to 70% for more populated municipalities and up to 97% for lower populated cities).	Paes et al., 2020

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34.	Brazil – Joao Pessoa	To analyze improvement options that could allow the medium/long-term MSW recovery goals.	Amount of MSW	(S) SimaPro	S0: no improvement (DRR = 4.5%) S1 (A1): partial implementation of selective collection (DRR = 5.6%) S2 (A2): total implementation of selective collection (DRR = 6.8%) S3 (B1): partial implementation of MRF (DRR = 9.2%) S4 (B2): partial implementation of MBCF (DRR = 16.5%) S5 (C1): partial implementation of selective collection + partial implementation of MRF (DRR = 10.3%) S6 (C2): total implementation of selective collection + partial implementation of MBCF (DRR = 18.8%) S7 (C3): total implementation of selective collection + partial implementation of MRF (DRR = 11.5%) S8 (C4): partial implementation of selective collection + partial implementation of MBCF (DRR = 17.6%) S9 (D1): partial implementation of MBCF (DRR = 9.2%; WRR = 13.8%) S10 (D2): total implementation of MBCF (DRR = 16.5%; WRR = 27.6%) S11 (E1): partial implementation of selective collection + partial implementation of MBCF (DRR = 10.3%; WRR = 13.7%) S12 (E2): total implementation of selective collection + total implementation of MBCF (DRR = 18.8%; WRR = 27.4%) S13 (E3): total implementation of selective collection + partial implementation of MBCF (DRR = 11.5%; WRR = 13.7%) S14 (E4): partial implementation of selective collection + total implementation of MBCF (DRR = 17.6%; WRR = 27.5%) *DRR: Dry Recovery Rate; WRR: Wet Recovery Rate	This study focused on the effect of improvement in the area of collection (S1 & S2); material recovery facility (S3 & S4); combination between collection and material recovery facility (S5, S6, S7, S8); Incorporating composting through Mechanical Biological and Composting Facility (MBCF) (S9 & S10); the combination of collection improvement and MBCF (S11, S12, S13, S14). Minimizing the amount of wet fraction (organic) in the landfill would limit the GHG emission, and maximizing recovering dry fraction (inorganic) would elevate the recycling rate. Door-to-door selective collection and the implementation of a mechanical biological and composting facility (MBCF) were the proposed strategy as well as increasing and fixing the waste picker's income.	Fores et al., 2021
35.	Brazil – Brasilia	To compare the environmental benefits of RDF production from MSW within the current MSWM system.	Per ton MSW	(S) IPCC (M) CML	S0 = MBT + Landfill (89%) S1 = All collected MSW sent to Landfill S2 = MBT +5% RDF Asa Sul + 84% landfill S3 = MBT + 23% RDF P Sul + 66% landfill S4 = MBT + 5% RDF Asa Sul + 18% RDF Sobradinho + 66% landfill *MBT: Mechanical Biological Treatment	RDF production to substitute the use of coke in cement kilns offered environmental benefits, including reducing GHG emissions.	Silva et al., 2021

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36.	Nigeria – 12 Cities	To evaluate the implementation of MSWM in terms of electricity generation, global warming, acidification and dioxin/furan potential	Amount of MSW in each city (average of 2016 – 2035)	(S) IPCC (M) EcoIndicator 99	S1: Landfill without energy recovery S2: Landfill with energy recovery S3: Anaerobic Digestion (putrescible)(w/biogas collection for electricity generation & digestate for fertilizer) + Incineration (with electricity production) + Landfill S4: Incineration + Landfill with electricity production	Landfill without energy recovery contributed the highest GHG emissions. Incineration/ Anaerobic Digestion provided a GWP reduction of 75.7–93.3%, Incineration/Landfill with energy recovery gave a 75.3–84.8% reduction and landfill with energy recovery only reduced GWP by 75%. Among the selected cities, one with a dense population had higher emissions since more MSW was generated. Incineration/ Anaerobic Digestion provided the most increased energy generation.	Ayodele et al., 2017
37.	Nigeria – Ibadan	To determine the economic and environmental benefits of MSWM for electricity generation.	Amount of MSW (average of 2017 – 2036)	(S) IPCC	S1: Anaerobic Digestion S2: Landfill with Energy Recovery	Anaerobic Digestion provided less GHG emissions than Landfill with energy recovery, better in terms of economic – environmental and energetic points of view.	Ayodele et al., 2018
38.	Russia – Irkutsk	To assess the sustainability of the MSWM application.	Amount of MSW (2020 – forecasting)	(S) LCA – IWM (M) CML	S1: Landfill without LFG collection S2: Recycle + Landfill without LFG collection S3: Composting + Recycle + Landfill S4: Aerobic MBP + Recycle + Landfill	Landfill was the biggest contributor to GHG emission. Recycle played a significant role in avoiding emissions compared to the proposed treatments (composting, aerobic MBP).	Tulokhonova and Ulanova, 2013
39.	Russia – Khanty Mansiysk & Surgut	To assess the environmental impact of current MSWM and compare it to other alternatives.	Amount of MSW in each city	(S) LCA – IWM (M) CML	S1: Landfill S2: Aerobic MBT + Recycling (metals) + RDF + Landfill S3: Anaerobic MBT+ Recycling (metals) + RDF + Landfill S4: Incineration + Landfill S5: Recycling+Landfill S6: Recycling + Aerobic MBT + Recycling (metals) + RDF +Landfill S7: Recycling + Anaerobic MBT+Recycling (metals) + RDF + Landfill S8: Recycling + Incineration + Recycling(metals) + Landfill	Landfill was the biggest contributor to GHG emission. Recycling and the implementation of Anaerobic MBT played significant roles in avoiding emissions. S7 provided the highest emission benefits.	Kaazke et al., 2013
40.	Russia – Irkutsk	To evaluate alternative MSWM approaches to be used in planning or developing existing systems.	Amount of MSW	(S) EASETECH	S1: Landfill w/o LFG collection S2: Landfill w/LFG collection for energy generation (80% efficiency) S3: Landfill w/LFG collection & flaring system (50% oxidation of methane) S4: Landfill W/leachate treatment	LFG collection was essential to prevent GHG emissions into the atmosphere. The treatment itself (flared or energy recovery) gave no significant difference. The crucial time to treat the LFG is up to 30 years from the operational starting extension only provides minor improvement – this is mainly due to the majority of degradable fraction decomposing in the first 30 years.	Starostina et al., 2014

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41.	Russia – Moscow	To analyze the environmental impacts of the current and proposed MSWM	Amount of MSW	(S) GaBI	S1: Recycle (12.4%) + Incineration (7.4%) + Landfill (80.2%) S2: Recycle (13.1%) + Incineration (24.2%) + Landfill (62.7%) S3: Recycle (24.2%) + Composting (5.2%) + Incineration (24.2%) + Landfill (57.5%) S4: Recycle (13.1%) + Composting (5.2%) + RDF (9.3%) + Incineration (24.2%) + Landfill (48.2%) S5: Recycle (12.9%) + Composting (4.5%) + Biowaste Tr./Composting (7.1%) + RDF (8.8%) + Incineration (21.9%) + Landfill (44.8%) S6: Recycle (12.9%) + Composting (4.5%) + Biowaste Tr./Anaerobic Digestion (7.1%) + RDF (8.8%) + Incineration (21.9%) + Landfill (44.8%)	Most GHG emissions from MSWM is from landfill (direct emissions without LFG collection generated 0.65 t CO2-eq per ton waste, contributing 76% of total emissions. In Rome 1.31, in Turkey, 1.84). Recycling contributed a reduction of 21%, Composting 7%. RDF utilization was beneficial to avoid emissions (total GHG emissions dropped as much as 50% in S4 compared to S3). A separate collection of biowaste before the treatment could reduce GHG emissions by 20% – 23%. Anaerobic digestion brought less emission than composting.	Vinitskaia et al., 2021
42.	Mexico – Mexico City	To evaluate GHG emissions from several combinations of treatments.	Amount of MSW	(S) IPCC	S0: Composting + Compacting Unit (produce RDF) + Landfill S1: Recycling + Composting + Aerobic MBP + Compacting Unit (produce RDF) + Landfill S2: Recycling + Anaerobic Digestion + Anaerobic MBT + Compacting Unit (produce RDF) + Incineration + Landfill S3: Composting +Recycling + Compacting Unit (produce RDF) + Landfill S4: Recycling + Composting + Anaerobic Digestion + Compacting Unit (to produce RDF) + Incineration + Landfill S5: Recycling + Composting + Aerobic MBP + Compacting Unit (produce RDF) + Landfill	MSWMs involving incineration (S2,S4) had lower GHG emissions, as those that depend on Landfill (S1, S3, S5) produced higher emissions because of more organic-rich residual waste.	Hernandez, 2021
43.	Japan – Kawasaki	To evaluate the impact of the recycling process on the reduction of GHG emissions.	Per ton MSW		S0: Incineration + Landfill S1: Recycle mixed paper + Incineration + Landfill S2: Recycle waste packaging plastics + Incineration + Landfill S3: Recycle organic waste + Incineration + Landfill S4: Recycle (paper, plastic, organic) + incineration + Landfill	Plastic recovery contributed the most to reducing GHG emissions. The waste plastics recycled product could substitute coke in steel production. Meanwhile paper recycling and organic waste treatment have a lower impact.	Geng et al., 2010
44.	Japan – Japan	To evaluate GHG emissions of various Anaerobic Digestion and Composting systems.	1 t organic waste (including paper)		S1: Integrated Wet Anaerobic Digestion (>90% MC) (80% food waste) S2: Integrated Dry Anaerobic Digestion (60–85% MC) (70% food waste; 30% paper waste) S3: Simple Wet Anaerobic Digestion (w/o pre-treatment)(90% food waste; 10% pruning waste) S4: Simple Dry Anaerobic Digestion (w/o pre-treatment) (70% food waste; 30% paper waste) S5: Machine-integrated Composting (pre-treatment; composting; deodorisation)(90% food waste;10% pruning waste) S6: Conventional Composting (manual with heavy machines)(75% food waste; 25% pruning waste)	The wet treatment produced more emissions since involving WWT, the dry treatment produced a smaller amount of methane yield Installing dry anaerobic digestion and mixing paper waste to adjust MC is beneficial	Takata et al., 2013

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45.	Philippines – Philippines	To review the status of MSWM from the perspective of GHG and short-lived climate pollutants.	Per ton MSW	(S) IPCC	S0: recycling (19%)) + open dump + control disposal + landfill. Only 65% of collectable waste S1: recycling (55%)+ open dump + controlled disposal + landfill. 20% of uncollected waste is assumed to be dumped indiscriminately (50%) or burned openly (50%) S2: recycling (55%) + controlled disposal + landfill (42%). 10% of uncollected waste is assumed to be dumped indiscriminately (50%) or burned openly (50%) S3: recycling (55%) + landfill w/LFG collection for energy recovery. 100% collection rate	Open dumping contributed significantly to GHG emissions, with contributions as high as 0.9 t CO2-eq per ton waste, followed by control disposal (0.51 t CO2-eq per ton waste) & sanitary Landfill 0.1 t CO2-eq per ton waste). Applying improper treatments for uncollected waste also produced considerable emissions (0.363 t CO2-eq per ton of waste). Recycling gave the highest avoid emission impact on the MSWM (–1.315 t CO2-eq per ton waste)	Premakumara et al., 2018
46.	Vietnam – Mekong Delta Region (12 Provinces) & 1 Central City (Can Tho City was used as the representative model)	To assess the impact of household solid waste on the environment	Amount of MSW	(S) IPCC	S1: Landfill without LFG recovery S2: Landfill with LFG recovery S3: Landfill with LFG recovery and electric generation S4: Composting (for compostable waste) S5: Incineration with thermal power system	Incineration brought the highest emissions reduction. Meanwhile, landfill utilization is only beneficial if equipped with an electric generation and flaring system.	Thanh and Matsui, 2013
47.	Vietnam – Hanoi, Hai Phong, Hue, Da Nang, Ho Chi Minh, Long An, Can Tho & Hau Giang	To identify a less impactful waste management system.	Per 100-ton MSW	(S) IPCC	S0: Open Dumping (100% total waste – dumping) S1: Sanitary Landfill without LFG recovery (100% total waste – dumping) S2: Sanitary Landfill with LFG recovery (100% total waste – dumping) S3: Composting (100% biodegradable waste – remaining: dumping) S4: Incinerator with energy recovery (100% combustible waste – remaining: dumping) S5: Composting + Sanitary Landfill with energy recovery (100% biodegradable waste: composting; 100% combustible: burning; – remaining: dumping)	S4 provided the lowest GHGs emissions followed by S2, S3, S5, S0 and S1.	Thanh and Matsui, 2012
48.	Turkiye – Sakarya	To identify a less impactful waste management system	Per ton MSW	(M) CML	S1: Landfill without energy recovery S2: MRF + landfill wIth energy recovery S3: MRF + Composting + Landfill with energy recovery S4: Incineration + Landfill with energy recovery S5: MRF + Composting + Incineration + Landfill with energy recovery	Landfill without energy recovery contributed the highest GHG emissions. The introduction of MRF and energy utilization in landfill, reduced GHG emissions by as high as 72%. Composting enlarged the reduction up to 27% (S3). The addition of an incineration unit brought the most beneficial value in terms of GHG emission (S5).	Yay, 2015

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NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
49.	Turkiye – Aksaray	To analyze the characteristic CO2 and CH4 from the MSWM.	Per ton MSW	(S) SimaPro	S1: Composting (25%) + Landfill (75%) S2: Anaerobic Digestion (35%) + Incineration (15%) + Landfill (50%) S3: Composting (25%) + Anaerobic Digestion (25%) + Incineration (15%) + Landfill (35%) S4: Incineration (70%) + Landfill (30%)	Composting and landfilling gave the lowest GHG emissions.	Cetinkaya et al., 2018
50.	Turkiye – Kocaeli	To quantify the GHG reduction potential and energy recovery from MSWM	Amount of MSW in 2018 and its projection until 2028.	(S) IPCC	S1: MRF + Landfill w/LFG recovery S2: MRF + Composting S3: Incineration	The incineration option gave the highest GHG savings. GHG emissions due to process and energy use in composting were higher than the saving therefore there was no emissions benefit.	Yaman, 2020
51.	Turkiye – Kayseri	To analyze the environmental and energy impacts of sustainable municipal solid waste collection and transportation system.	Per ton MSW	(S) SimaPro (M) CML	S1: 3 Transfer Station to be constructed in 3 different regions S2: 1 Transfer Station in one region and 2 SL in two other regions S3: 2 Transfer Station in two regions and 1 SL in one region	This study provided information on the importance of Transfer Station (TS) availability. The presence of TS contributed to as much as a 44.9% reduction in GWP. Construction of TS for transferring MSWs was more efficient compared to direct sending to sanitary landfill.	Taskin and Demir, 2020
52.	Iran – Tehran	To improve the current practice of MSWM by comparing the environmental impacts.	Per ton MSW		S1: Landfill S2: Composting + Landfill	The application of composting reduced GHG emissions of MSWM.	Abduli et al., 2011
53.	Iran – Region 4 (one of the 22 regions in Tehran municipality)	To evaluate comparatively current and future scenarios of MSWM, to propose the best strategy which could be implemented generally in Iran (regions with similar/same characteristics as the study area – metropolitan areas).	Per ton MSW	(S) SimaPro (M) CML, IMPACT2002	S0: Sorting + Anaerobic Digestion with biogas treatment + Composting + Landfill S1: Sorting + Composting + Landfill S2: Sorting + Incineration with electricity production S3: Sorting + Composting +Incineration with electricity production S4: Sorting + AD w/biogas collection for electricity production + Composting +Incineration w/electricity production	Landfill was the main contributor to GHG emissions. Meanwhile, incineration, anaerobic digestion and sorting (to a lesser extent) improved the reduction, respectively.	Rajaeifar et al., 2015
54.	Iran – Tehran	To assess MSWM scenarios with the least environmental impacts.	Amount of MSW	(S) IWM	S1: Landfill (100%) S2: Composting (35%) + Landfill (72%) S3: Composting (70%) + Landfill (44%) S4: Composting (70%) + Incineration (22%) + Landfill (28%) S5: Composting (70%) + Recycle (20%) + Landfill (25%)	Landfill was the main GHG emissions contributor, especially with CH_4 production. Integration of composting, incineration and landfill provided the least emissions (S4) (for both CO_2 and CH_4)	Limoodehi et al., 2017

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55.	Iran – Tehran	To assess the environmental performance of incineration and landfill for treating MSW.	Amount of MSW	(M) CML	S1: Incineration S2: Landfill without LFG collection	A thorough study comparing incineration and landfill was done in this study. Incineration provided a more beneficial emissions impact with a total production of 4499.07 kg CO_2-eq, while landfill emitted 92,170.30 kg CO_2-eq.	Pelesaraei et al., 2017
56.	Iran – Rash City	To evaluate the environmental impacts of composting and the anaerobic digestion process.	per 100 t MSW	(S) SimaPro (M) IMPACT2002+	S1: Sorting + Composting S2: Sorting + Anaerobic Digestion with biogas collection for electricity production	Anaerobic digestion could save 90% of emissions compared to composting. GHG emissions from S1 was 10.14 t CO_2-eq/ton waste while S2 was only 1.05 t CO_2-eq/ton waste.	Behrooznia et al., 2020
57.	Iran – Tehran	To investigate the feasible strategies to support the decision-makers in selecting the most appropriate MSWM.	Amount of MSW	(S) IPCC	S1: Incineration (100%) S2: Landfill (100%) S3: Incineration (50%) + Landfill (30%) + MRF (20%) S4: Incineration (30%) + Landfill (50%) + MRF (20%)	Landfill is the main GHG emissions contributor. The best combination in terms of reducing/saving the GHG emissions was S3/S4, but need high investment (the higher portion of MSW to be incinerated/S3 offered the lower GHG emissions than one to be landfilled/S4)	Maghmoumi et al., 2020
58.	Germany – Germany	To analyze which treatment path for Organic Fraction of MSW (OFMSW)(among four options) is preferable from an environmental point of view.	Per ton MSW	(S) OpenLCA (M) ReCiPe	S1: Anaerobic Digestion + Composting S2: Incineration (OFMSW is not collected separately and w/o pre-drying) S3: Incineration (separated and pre-dried) S4: Anaerobic Digestion + Incineration	Anaerobic Digestion + Composting was the best option in terms of emissions reduction. Incineration performed a relative contribution but higher in investment. Pre-drying did not have a significant impact.	Mayer et al., 2020
59.	Germany – Germany	To compare the GWP impact from 3 different treatments of residual MSW.	Per ton MSW	(S) EASETECH	S1: Incineration S2: RDF + Incineration S3: RDF + Gasification	Incineration-based treatment gained emissions benefit significantly from heat and electricity substitution effects. Incineration with RDF performed better emissions reduction because of biogas and RDF utilization. Although RDF+Gasification had the lowest emissions reduction, its contribution increased as the energy system's proportion of renewable energy increased.	Voss et al., 2021
60.	Thailand – Phuket	To compare the environmental impacts of several integrated waste management options.	Per ton MSW	(S) IPCC (M) EDIT	S1: BAU S2: Incineration + Landfill + Sorting (30%) S3: Recycling (source) + Incineration + Landfill S4: Anaerobic Digestion (source) + Incineration + Landfill S5: Incineration + Landfill S6: Anaerobic Digestion (source) + Incineration + Recycling + Landfill S7: Recycling (source) + Anaerobic Digestion (source) + Incineration + Landfill	Landfill was the biggest contributor to GHGs (CH_4). Incineration also produced a significant amount of GHGs. Separation at source reduced the environmental impact significantly.	Suwan and Gheewala, 2012

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NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
61.	Thailand – Bangkok	To compare 2 Waste to Energy (WtE) technologies.	Per ton MSW	(S) IPCC	S1: Landfill Gas to Energy S2: Incineration	The implementation of both WtE technologies showed potential opportunities to reduce GHG emissions. Compared to the current treatment (Landfill without energy recovery), Landfill Gas to Energy and Incineration may reduce GHG emissions by as much as 13% and 55%, respectively.	Menikpura et al., 2016
62.	United Kingdom – England	To evaluate three different strategies of energy recovery from waste management.	Amount of MSW	(S) WRITE	S1: Established Combustion Plant S2: Combined Heat & Power/Mechanical Biological Treatment-Fluidized Bed Gasification S3: Combined Heat & Power / Establhised Combustion Plant S4: Combined Heat & Power / Mechanical Biological Treatment-Anaerobic Digestion/ Fluidized Bed Gasification S.5.1 Mechanical Biological Treatment –Anaerobic Digestion/ Mechanical Biological Treatment –Anaerobic Digestion/ Fluidized Bed Gasification S5.2: SRF to Landfill S5.3:SRF to cement kiln S6.1: New recyclate to export S6.2: New recyclate to EC	Gasification and Anaerobic Digestion provided emissions reduction while the other processes produced emissions. MBT contributed the most extensive emissions followed by composting and EC-CHP, respectively. Recycling was the most strategic effort to save GHG emissions and avoid more MSW to the Landfill.	Tunesi, 2011
63.	United Kingdom – Great London	To analyze the current MSWM and three different alternatives for the treatment of plastic solid waste sent to MRF.	Amount of MSW	(S) GaBI	S0: Landfill S1: MRF + incineration (current) S2.1: MRF + Landfill S2.2: Low Temperature Pyrolysis/LTP + Landfill S2.3: Cracking Hydrogenation Reactor/VCC + Landfill	MRF application gave the best reduction emissions impact followed by LTP.	Al-Salem et al., 2014
64.	United Kingdom – UK	To estimate and compare the environmental impacts of MSW disposal by incineration and landfill for the UK conditions, with both systems recovering energy.	Per ton MSW	(S) GaBI	S1: Incineration (electricity only) S2: Incineration (Combined Heat & Power/CHP) S3: Landfill (electricity only) S4: Landfill (Combined Heat & Power/CHP)	Stack emissions were the most significant portion of incineration – emissions of fossil-derived CO_2 from the combustion of waste. Incineration has the lowest impact compared to UK grid, coal, oil and natural gas-based electricity production. The emission of biogas into the atmosphere contributed to most of the total GHG emissions from landfill operations. Increasing the capture rate is the key to reducing the GWP from this system. Landfill biogas system for electricity has 8–10 higher emissions than UK grid & natural gas, and 4x higher than electricity from coal and oil	Jeswani and Azapagic, 2016

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NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
65.	United Kingdom – Nottingham	To quantify and compare the GWP of 3 historical MSWM strategies in Nottingham and a future scenario in response to the EU directives.	Per ton MSW	(S) IPCC	S1: Recycle (3.4%) + Composting (1.2%) + Incineration (40.7%) + Landfill w/o LFG collection (54.7%) S2: MRF/Recycle (17.5%) + Composting (8.6%) + Incineration (41.2%) + Landfill (32.7%) S3: MRF/Recycle (31.5%) + Composting (12.9%) + RDF/Incineration (57.6%) + Landfill (7.3%) S4: MRF/Recycle + Composting + AD for food waste + RDF/Incineration + Landfill	When the portion of MSW sent to landfills decreased GHG emissions reduced, recycling was the key to emissions savings.	Wang et al., 2020
66.	United Kingdom – Nottingham	To analyze the suitability of MSWM for Nottingham to maximize the economic benefit if the legislative target is fulfilled.	Per ton MSW	(S) IPCC	S1: Recycling (3.4%) + Composting (1.2%) + Incineration (40.7%) + Landfill (54.7%) S2: Recycling (17.6%) + Composting (8.6%) + Incineration (56.5%) + Landfill (35.3%) S3: Recycling (31.9%) + Composting (13%) + Incineration (61.9%) + Landfill (7.3%) S4: Recycling (35%) + Composting (11.7%) + Incineration (65.1%) + Landfill (6.8%)	Recycling was an essential effort to minimize GHG emissions. Composting contributed to reducing emissions.	Wang et al., 2022
67.	France – France	To assess the environmental performance of MSW incineration in France.	Per ton MSW	(S) WILCO	S1: Incineration without energy recovery S2: Incineration with recovery as electricity only S3: Incineration with recovery as heat only S4: Incineration with recovery as CHP	The application of incineration technology in France brought environmental benefits. In the case of GHG emissions, the best saving could be earned when its equipped with recovery as CHP (–0.04 t CO_2-eq/t waste), followed by heat (–0.018 t CO_2-eq/t waste).	Beylot et al., 2018
68.	Italy – Italy	To assess some indications for optimization of the Integrated Waste Management System (ISWM).	Amount of MSW	(S) SimaPro	S1: Separate collection level of 35% + composting + recycling +WtE Plant (Incineration) S2: Separate collection level of 50% + composting + recycling +WtE Plant (Incineration) S3: Separate collection level of 50% (including food waste)+ composting + recycling +WtE Plant (Incineration) S4: Separate collection level of 65% + composting + recycling +WtE Plant (Incineration)	Recycling had the most significant contribution to emissions reduction (saving) – the top three fractions that give the most reduction contribution are aluminium, steel and glass. As for energy/material recovery for green wastes and food waste were at lower level where anaerobic digestion performs better than composting. As for larger ISWM, The WtE system with CHP provided more benefit than electricity.	Giugliano et al, 2011
69.	Italy – Milano, Bergamo, Pavia, Mantova	To evaluate the environmental performance of the implementation of MSWM in 4 provinces and investigate the opportunity for improvements.	Amount of MSW		S1: Baseline (2009 condition) S2: Increase of MSW generated (for 2020) & separate collection level (BAU) S3: same as S3 with improvements on food waste and residual waste system	An increase in separate collection levels affected energy recovery and environmental benefits for four provinces. The introduction of technological improvement (with a special focus on the utilization of RDF) brought benefits to emission reduction.	Rigamonti et al., 2013

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NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
70.	Italy – Italy (urban)	To assess the impact of different levels of source segregation (SS) followed by several waste management processes in an urban area.	Per ton MSW	(S) SimaPro (M) CML	S1: Source Segregation (0%) S2: Source Segregation (25%) S3: Source Segregation (30%) S4: Source Segregation (35%) S5: Source Segregation (52%)	This study focused on the impact of SS followed by landfill, incineration, MBT/MBS to produce SRF (which will be used as coal substitution in cement kilns). The result showed that the increase in SS level contributed positively to environmental impact (lower GHG emissions). Meanwhile, the implementation of incinerator brought lower emissions than landfill. However the optimum GWP benefit was achieved by producing SRF. In addition, for organics fraction – a combination between composting and anaerobic digestion offered a more comprehensive GHG emissions benefit. Still, the net value is more or less the same with the implementation of composting only. The minimum net value difference is because of the materials and energy needed for the anaerobic digestion facility's construction and operational purposes.	Di Maria and Micale, 2014
71.	Italy – Italy	To investigate the environmental impact of incineration and anaerobic digestion followed by composting in treating organics fraction of MSW after source segregation (SS).	Per ton MSW		S1: SS (0%) + Incineration + Landfill S2: SS (52%) + AD (w/WWTP) + Composting + Landfill	The implementation of incineration to manage the organic fraction of MSW was better in terms of GHG emissions reduction compared to the combination between AD and Composting. This is mainly due to more energy recovery in incineration.	Di Maria and Micale, 2015
72.	Italy – Naples	To analyze the environmental impacts of different MSWM strategies that could be implemented in Naples with the consideration that landfill utilization will be diminished	Amount of MSW	(S) SimaPro (M) Recipe	S0a: SS (0%) + Recycling + Composting/AD +MBT + WtE + Landfill S0b: SS (0%) + Recycling + Composting/AD +MBT + WtE + Landfill (w/higher capacity or new plant of WtE) S1a: SS (50%) + Recycling + Composting/AD +MBT + WtE + Landfill S1b: SS (50%) + Recycling + Composting/AD +MBT + WtE + Landfill (w/higher capacity or new plant of WtE) S2a: SS (65%) + Recycling + Composting/AD +MBT + WtE + Landfill S2b: SS (65%) + Recycling + Composting/AD + WtE + Landfill	In mixed conditions, all treatment components of MSW emitted GHGs. The highest GWP came from MBT followed by Landfill and WtE (incineration). Meanwhile, for the organic fraction of MSW, transportation contributed the most, followed by Landfill and composting, respectively. A higher level of source segregation gave more GHG emissions reduction (S2b provided the optimum environmental benefit)	Ripa et al., 2016

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NO.	COUNTRY & AREA OF STUDY	GOAL	FUNCTIONAL UNIT	SOFTWARE (S) & METHOD (M)	DEVELOPED SCENARIO	SUGGESTED PROCESS/TREATMENT FOR GHG REDUCTION	REF.
73.	Italy – Bari	To evaluate the suitability of separate collection (SC) scenarios and waste management systems of a large metropolitan area	Amount of MSW	(S) WRITE (M) CML	S1: SC rate 39.9% with bring-points system w/MBT for mixed waste S2: SC rate 87% with door-to-doo system w/MBT for mixed waste S3: SC rate 68.6% with a combination of bring-point (25%) and door-to-door (75%) system with wet/dry collection & secondary raw material recovery	Source Collection (SC) played a significant role in determining GHG emissions. The door-to-door collection system (S2) was the most suitable method that gave the biggest emissions saving. However, S3 was considered more efficient if involving an economic perspective	Gadaleta et al., 2022
74.	South Africa – eThekwini	To provide information on GHG emissions from the current MSWM and to estimate the future emissions	Amount of MSW		S1: 2012 – 3 landfills (2 with LFG collection and electricity production: Bisasar & Mariannhill and one no gas facility: Buffelsdraai) + recycling S2: 2014 – the closure of 1 landfill (Bisasar), 75% of total MSW to Buffelsdraai (still no LFG treatment in 2014–205) & 25% to Mariannhill + increasing recycling level S3: 2020 – Landfill Buffelsdraai (with and without LFG treatment) + increase in composting (and Anaerobic Digestion as an alternative) & recycling level S3.1: 2020 – with increased recycling S3.2: 2020 – with increased composting S3.3: 2020 – with Anaerobic Digestion	Recycling played an important role in minimizing GHG emissions. Landfill with LFG treatment facilities was essential to gain GHG emissions	Friedrich and Trois, 2016

Table 2 Summary of reviewed LCA studied in the top 25 most populated countries (2010–2021).

the modeling of product system in the user interface (Herrmann and Moltesen, 2014). This review found that the top three LCA software were SimaPro, GaBI and EASETECH/EASEWASTE (EASEWASTE was the former version of EASETECH) that have been used by 14, 9 and 7 studies, respectively in various regions. Following that, four studies employed IWM, one study worked with OpenLCA and another operated two software types (Figure 3). Meanwhile 35 studies did not specify the usage of modeling tools however, the utilization of IPCC guidance for emissions calculation was mentioned in most papers.

PROPOSED TREATMENTS FOR OPTIMIZING GHG EMISSIONS REDUCTION

Based on the developed scenarios and obtained results, several highlights on GHG emissions reduction through MSWM are identified. All studies with landfill as one of the scenarios agreed that this site was the main emissions contributor. Different amounts of produced landfill gas were reported in regions such as 0.65 tCO2-eq/ton waste in Moscow, 0.25 tCO2-eq/ton waste in the Siberian area, 1.31 tCO2-eq/ton waste in Rome and 1.84 tCO2-eq/ton

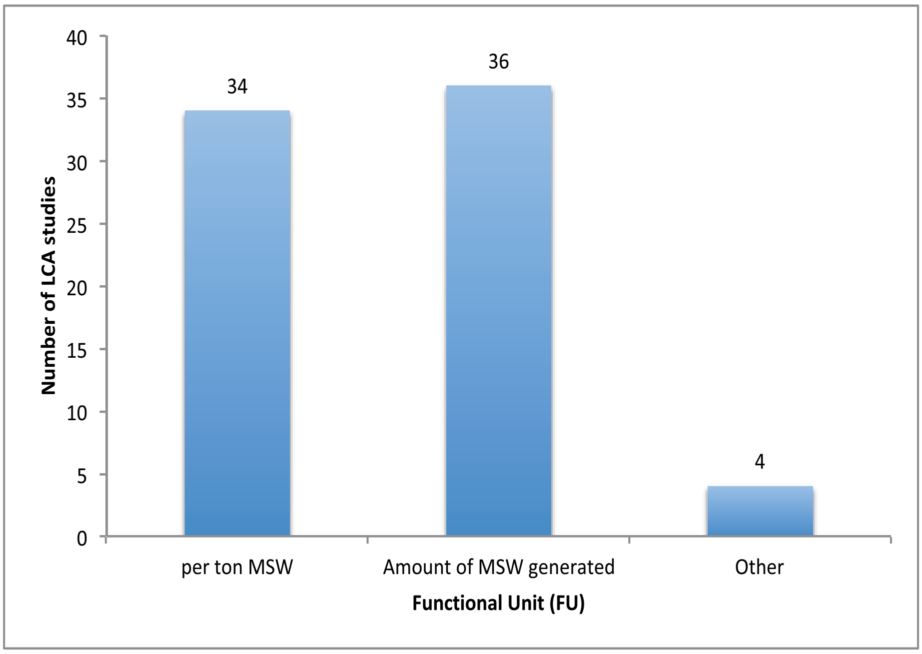

Figure 2 Distribution of FU in the reviewed LCA studies.

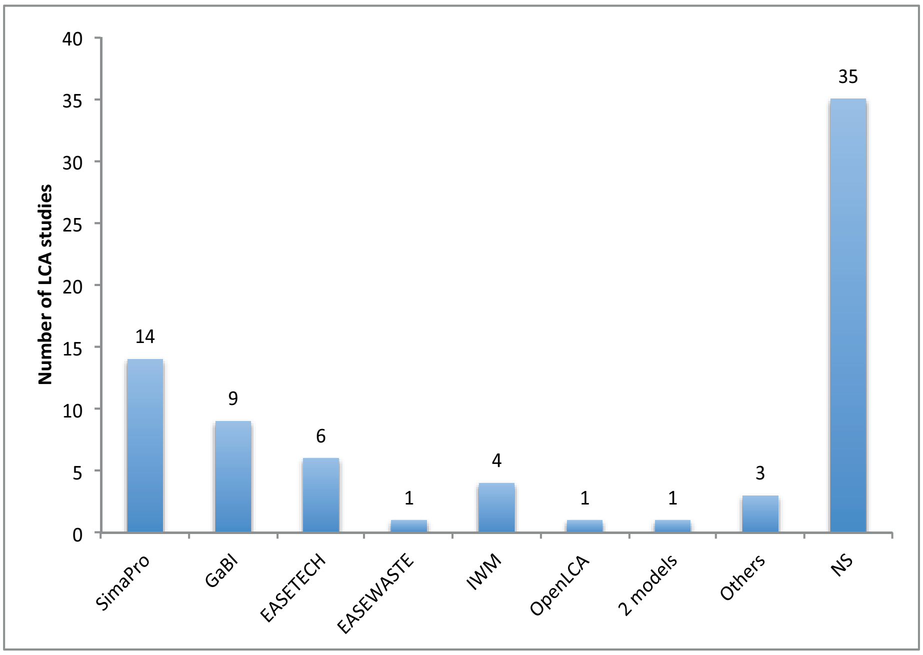

Figure 3 Utilization of LCA modeling tools in reviewed LCA studies.

waste in Turkey (Kaazke et al., 2013; Vinitskaia et al., 2021; Yay, 2015; Cherubini et al., 2009). The dissimilar production rate could be triggered by several factors such as temperature, precipitation rate, storage time, cover material, and the landfill's design and operational parameters (Scarlat et al., 2015). Despite variations in production, uncontrolled landfill emissions seriously affect climate change. Improvement by equipping with a gas collection system was advised to elevate the environmental performance of landfill. 20 out of 73 studies addressed the reduction of GHG emissions whenever the collection system was introduced. The treatment of collected gas also determined the scale of reduction, in this case gas utilization as energy provided higher benefit than gas flaring (Liu et al., 2017b). Other Wastes to Energy (WtE) approaches were reported potentially bring environmental advantages. Incineration, a thermal process for treating MSW, was reported by 23 studies to bring the most considerable GHG emissions reduction if combined with an electricity generation system. More specifically, incineration with combined heat and power (CHP) gave more emissions benefit compared to electricity only (Tunesi, 2011; Beylot et al., 2018; Giugliano et al., 2011). MSW conversion to refuse-derived fuel (RDF) through mechanical–biological treatment (MBT) also became an alternative for suppressing GHG emissions. 17 LCA studies included MBT/RDF as an option in the developed scenarios. Although not as big as incineration in giving the emissions benefit MBT/RDF can be considered as a strategic effort compared to conventional processes. A study in Hangzhou – China reported that RDF production lowered the level of emissions up to 33% when used as co-fuel with coal in incineration plants (Havukainen et al., 2017). The utilization of RDF as coal substitution in cement kilns resulted in more avoided emissions than in incineration units (Liikanen et al., 2018; Lima et al., 2019; Paes et al., 2020; Silva et al., 2021). In addition, aerobic MBT to produce RDF was more environmentally friendly than anaerobic MBT (Coelho and Lange, 2016). Reviewed LCA studies also included more advanced technologies for converting waste to energy. The implementation of gasification with landfill reduced more emission than the combination between incineration and landfill. Meanwhile in combination with RDF, gasification provided less reduction compared to the joined application of RDF and incineration (Gunamantha and Sarto, 2012; Voss et al., 2021). LCA studies in the United Kingdom portrayed the usage of fluidized bed gasification, low-temperature pyrolysis and crackinghydrogenation reactor. However, despite the advancement of the process, the provided emission benefit was similar or less compared to the more common treatments (Mali and Patil, 2016; Tunesi, 2011; Al-Salem et al., 2014).

Since organic fraction is one of the major parts of MSW composition, biological treatment is also involved in MSWM. Composting and anaerobic digester are two well-known processes for degrading biodegradable materials and converting them into products. 36 LCA studies took composting into developed scenarios while 35 studies analyzed the impact of anaerobic digester in reducing GHG emissions. All ten studies with comparison scenarios for both processes concurred that anaerobic digester performed better than composting in terms of minimum GHG emissions production. Lower environmental performance in composting may be caused by uncontrolled GHG production during the process and higher energy used than the savings (Yaman, 2020). As for anaerobic digester, several papers highly recommended applying it, particularly for treating food waste (Zhou et al., 2018; Chen et al., 2020; Wang and Nakakubo, 2020). Adding to that, increasing the efficiency of food waste treatment by anaerobic digester could be done by adjusting the moisture content by mixing the feed with paper waste and setting a long sludge retention time. The process optimization resulted in a higher yield, producing methane gas that could be collected and used for alternative energy (Takata et al., 2013).

Waste recovery is an integral part of MSWM; the effectiveness of its application will also determine the magnitude of GHG emissions production. In association with the recycling process, separation/sorting is a critical activity that can be done independently in the generation site (source) or together in a material recovery facility (MRF). The 19 papers reported that recycling significantly reduced the number of emissions whenever introduced to the system. Studies in several countries (China, India, Brazil, Russia, Mexico, Philippines, Thailand, Turkey, Iran and the United Kingdom) delineated that in combination with one or more treatments (incineration, composting, anaerobic digestion, RDF, landfill, incineration), recycling contributed massive reduction on GHG emissions (Xin et al., 2020; Wang and Nakakubo, 2020; Yadav and Samadder, 2017; Coelho and Lange, 2016; Lima et al., 2019; Tulokhonova and Ulanova, 2013; Kaaszke et al., 2013; Vinitskaia et al., 2021; Hernandez, 2021; Premakumara et al., 2018; Yay, 2015; Yaman, 2020; Rajaeifar et al., 2015; Behrooznia et al., 2020; Maghmoumi et al., 2020; Suwan and Gheewala, 2012; Al-Salem et al., 2014; Wang et al., 2020). In the condition where the recycling rate increased (either for inorganic or organic) it was found that the GHG reduction potential was also inflated (Coelho and Lange, 2016; Saraiva et al., 2017; Premakumara et al., 2018; Wang et al., 2020). More specific research elaborated that recycle for plastic material lent the most in GHG emissions reduction compared to any other recyclable materials (Tyagi et al., 2021; Geng et al., 2010). Intensive studies for source separation and collection were conducted in China and Italy. The investigation in both countries revealed that source separation strongly supported recycle process and other waste treatments since causing the suitability between waste characteristics and process mechanisms. In regards to the collection system, door-to-door system was reported to have the biggest emissions saving; however, the combination with the point-collection method (waste producer put it in specific/point collection) was more feasible from an economic perspective (Gadaleta et al., 2022). On top of it, reduction a basic yet crucial concept in MSWM was evaluated by a study in the USA. A model was developed to assess the impact of a lower waste generation rate with a constant consumption pattern on the emitted GHG. The result depicted that if 40% waste reduction was achieved, a notable positive impact on climate change was obtained as the emissions benefit was more extensive than other treatments (Gunamantha and Sarto, 2012). Confirmation of this result came from a study in China mentioning that reduction at source was a strategic effort to repress the emissions increment in the observation of 20 years of projection (Yang et al., 2018).

CRITICAL FINDINGS AND DISCUSSION

The trend of LCA utilization for determining the most effective MSWM strategy to diminish GHG emissions has elevated significantly in the last decade. As can be seen in Figure 4, in the last five years the number of publications increased more than double that in the period 2010–2015 (except for the year 2013). This fact evinces the increasing awareness among scientists, academicians and policymakers to use LCA in evaluating GHG emissions from MSWM. However, the distribution of interest in the top 25 most inhabited countries is still uneven. In the ECA region, all listed countries have produced the analysis of GHG emissions from MSWM with LCA as the supporting tool. Similar conditions for countries in EAP and LAC but China and Brazil became the dominant producers with 15 studies out of 36 (42% of contribution) and 8 out of 9 (89% of contribution), respectively. There were in total 7 LCA studies in SA produced by two countries, with India supplying the most among the three classified countries. The same situation occurs in the MENA region, with only Iran has published the LCA results from 2 listed countries, while for AF, only 2 out of 5 countries generated publications. From the perspective of income classification, countries with three categories: HI, UMI and LMI, have been actively involved in LCA studies evaluating GHG emissions from MSWM. All HI and UMI countries in the top 25 most populated classification and covered regions have posted the study results, while only seven from 10 LMI countries did the same. A contrary sitch is observed for the LI group, as no publications were found (Figure 5). Income level is not the single factor governing LCA study productivity, but also the availability of reliable data and active LCA community or organization (Fullana et al., 2008). Concerning that MSW generation will increase following population growth and the degree of urbanization rate, developing countries should anticipate it by preparing an effective MSWM strategy (Moya et al., 2017; worldpopulationreview.com). In that regard, Ethiopia, D.R. Congo and Tanzania are considered vulnerable since the urbanization rate in those countries is in the top five worldwide, as high as 4.40%, 4.33% and 4.89%, respectively (Slezak et al., 2015). It means that there will be a significant increase in GHG emissions from the waste sector in urban areas in those three countries if the business-as-usual condition is applied.

Despite of specific conditions of each country, the representation of LCA study for HI, UMI and LMI categories has been well presented during the last decade. As described in Figure 6, the ratio of publications

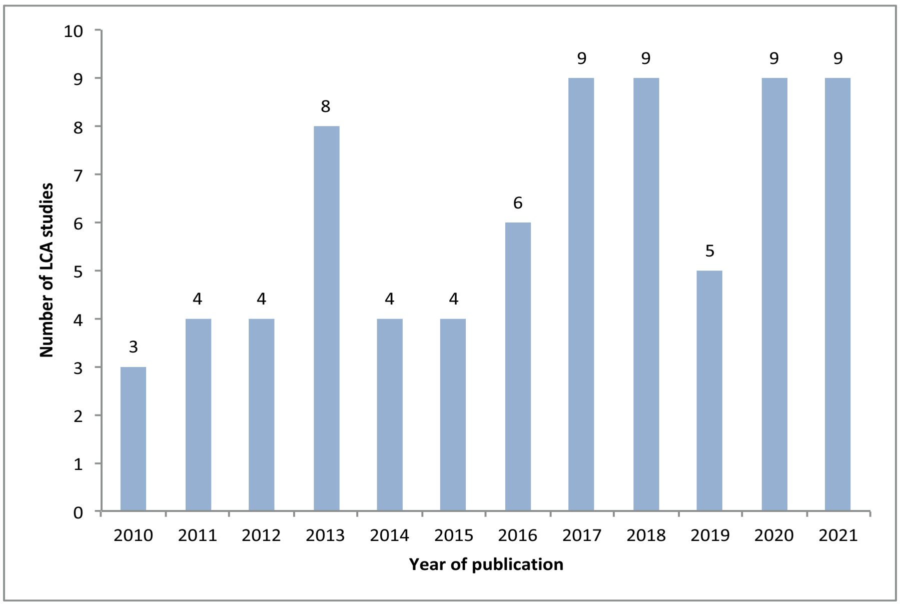

Figure 4 Number of LCA studies produced by countries in the top 25 most populated category (2010–2021).

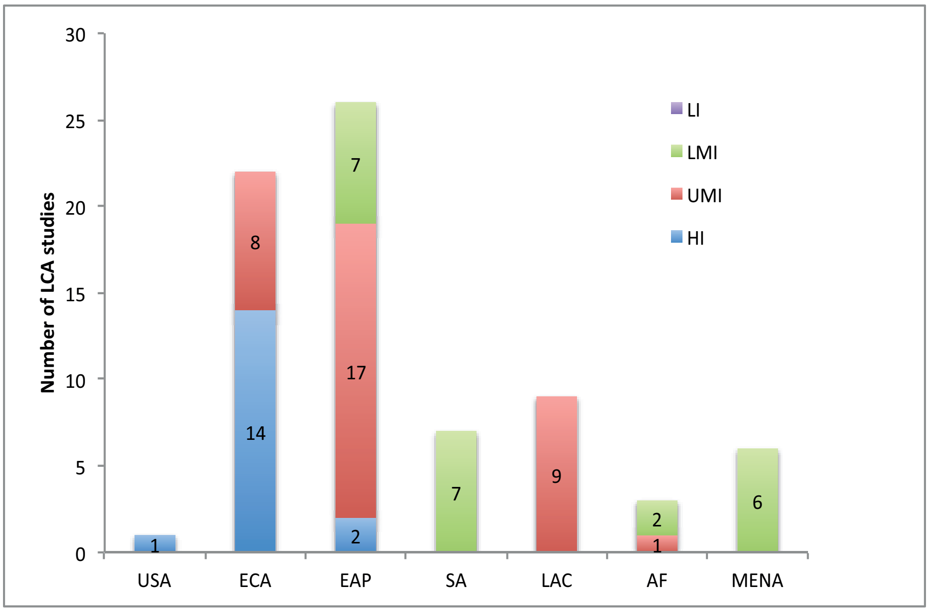

Figure 5 Distribution of LCA studies in every region based on income classification.

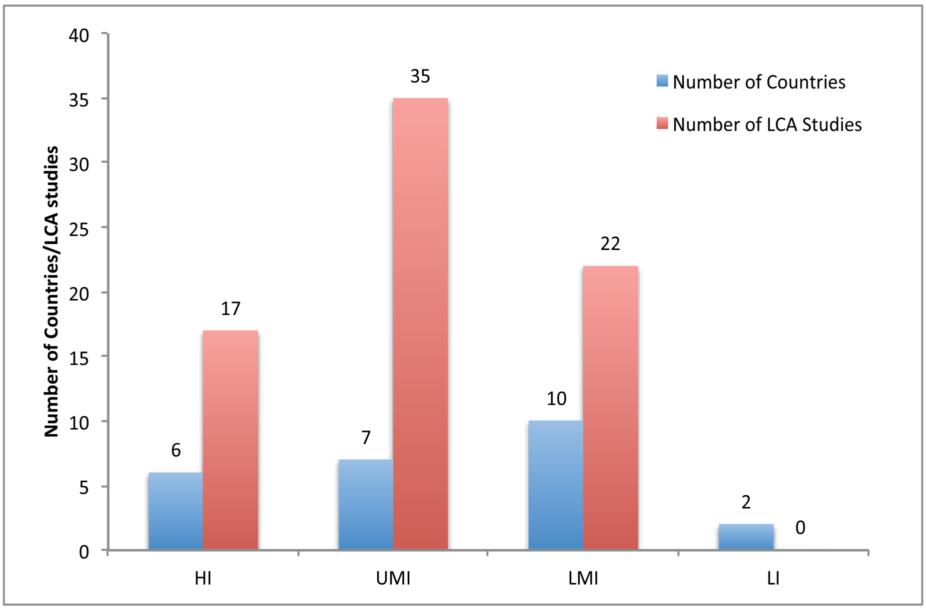

Figure 6 Comparison of the number of LCA studies and country producers based on income classification.

to countries is nearly trifold for HI, fivefold for UMI, and double for LMI.

The composition of MSW treatment may vary from one to another country, different economic status is considered as the main trigger to determine it. It was reported that in LI and LMI countries, food and green waste comprise more than 50 percent of total waste generation, while in HI the organic fraction is about 32 percent. The difference on waste composition regulates the selection of treatment method. Besides the composition, financial capability also governs the technology selection and as waste sector is only one component of urban management budget, prioritization matters (Kaza et al., 2018). Regarding the option of MSW treatment, as presented in Figure 7, a landfill is still needed in any proposed integrated system. Residues from mechanical, biological and thermal processes must be disposed of appropriately. The availability of an engineered landfill or what so-called sanitary landfill, equipped with landfill gas collection system, is necessary to minimize the environmental impacts of the stockpile. The waste treatment hierarchy should be applied accordingly, meaning that landfills are only provided for the remaining or not to be the sole unit that receives all waste load. Consequently, the performance of intermediate processes such as composting, anaerobic digestion (AD), RDF production and incineration should be elevated and gain higher yield without risking the environment. According to the reviewed papers, the implementation of those processes can be set to

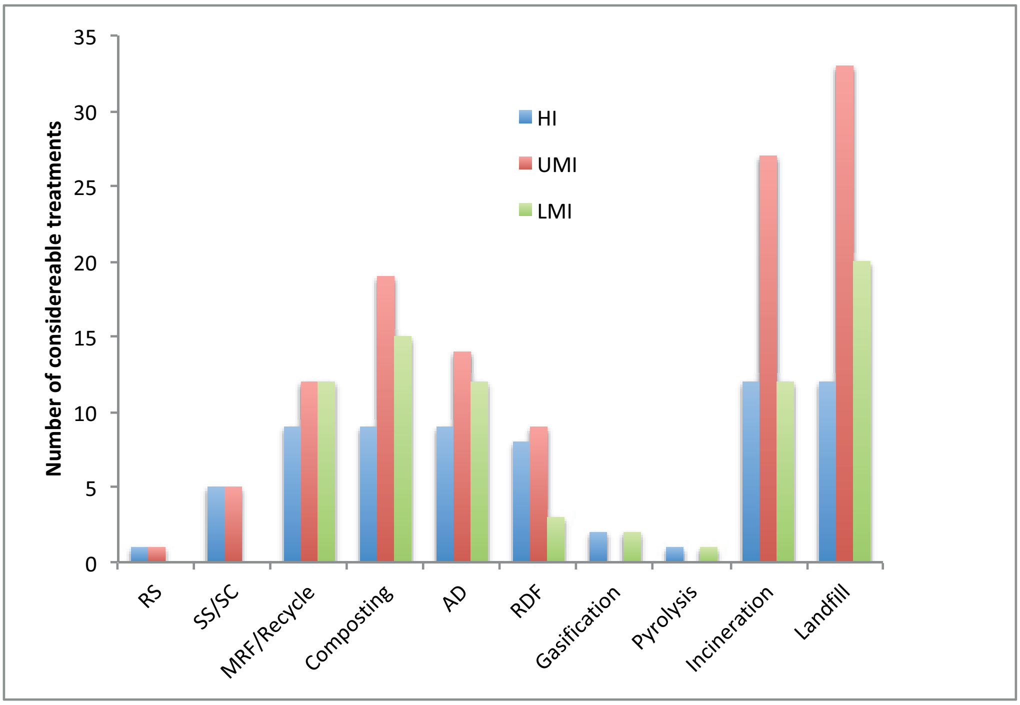

Figure 7 The magnitude of considerable treatments in the selected manuscripts for minimizing GHG emissions.

produce as minimum as possible GHG emissions. More elaboration for other thermal technologies such as gasification, pyrolysis and crackinghydrogenation is needed to convince a minimum emissions production since limited resources were available. In the upstream part, recycling is a strategic effort to secure valuable waste and reduce the amount of waste that is being disposed of in the landfill. Both activities correspond to the minimum GHG emissions production. The success level of recycling strongly depends on the effectiveness of separation; thus, this effort also needs to be analyzed more since studies about source separation (SS) and/or selective collection (SC) were still limited in HI and UMI countries. On top of those treatments as mentioned earlier, reduction at source (RS) is a necessary action in MSWM; this top-rank effort in the waste hierarchy need to be implemented massively. This activity demands active involvement from the community with support from the government and academic institutions. Knowledge is essential to build environmental awareness and a community's willingness to participate in waste reduction, reuse, and resource recovery (Hammed et al., 2018). The level of waste reduction will determine the magnitude of technical and economic requirements in MSWM. There still needs to be more information on the impact of this crucial movement in determining the GHG emissions benefit.

CONCLUSIONS

This study reviewed the application of LCA on MSWM in the top 25 most populated countries regarding finding suitable treatments with minimum GHG emissions. In those listed countries, peer-reviewed publications were not found in 3 LMI and 2 LI countries, while all HI and UMI countries have produced the manuscripts. EAP became the most productive region followed by ECA. On another side, AF produced the least; in MENA, only Iran published a sufficient number of LCA studies. As it can be effectively used to determine effective MSWM strategy, the utilization of LCA in evaluating the potency of gaining GHG emissions benefits can be conducted more intensively and extensively. This is important since 20 out of 25 listed countries also belong to the group of top MSW producers with a high contribution to GHG emissions production. That particular study will enable the government to portray the optimum emissions reduction contribution from the waste sector. Thus facilitation from the government is needed to support the initiative in conducting LCA studies. Arrangement and standardization of data collection systems are crucial since lacking information on MSWM is often the major obstacle. As for countries with no or limited study, consciousness among academicians need to be triggered through various active dissemination such as training, course and seminar. Government initiatives providing research grants or incentives may tackle economic barriers to delivering LCA studies on MSWM.

The analyzed LCA components (FU, computer tool and developed scenarios) provided in this study can be used as a reference to perceive the application but are not necessary for direct use. The selection of LCA components should be carefully made by considering each regional condition. No single treatment can solve the MSW problem; integration of several approaches is needed considering the complexity of MSW. The integration may consist of different compositions due to technical and economic readiness in each country. However, the waste hierarchy concept's introduction could be trusted to have an effective and efficient MSWM strategy including minimum GHG emissions.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHORS CONTRIBUTIONS

Conceptualization (Y.F., I.W. and J.H.); methodology (Y.F., J.H., I.W.); literature investigation (Y.F., A.U.F); writing—original draft preparation (Y.F.); writing—review and editing (Y.F., J.H.); visualization (Y.F., A.U.F); supervision (J.H. and I.W.). All authors have read and agreed to the published version of the manuscript.

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