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Review of appropriate and best-evaluated options with life cycle assessment for municipal solid waste management

Revisión de las opciones apropiadas y mejor evaluadas con análisis de ciclo de vida para la gestión de residuos sólidos urbanos

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Abstract

Life cycle assessment (LCA) is one of the best tools to determine the environmental impact of municipal solid waste (MSW) management. This work analyzed the best-evaluated MSW management options in the world with LCA, to identify future trends. 132 LCA publications (2015-2023), their geographical distribution, and the results obtained according to the ISO 14040 standard were considered; The options evaluated were also compared with those reported by the World Bank. The results showed that the majority of publications come from the Europe and Central Asia region, followed by Latin America and the Caribbean. After comparing the alternatives, it was observed that open dumps and controlled sites will tend to be replaced by landfills with energy recovery in all regions of the world; the technologies for recovering materials and using the organic fraction will continue to be applied; and alternative processes will become more common. This work aims to support decision-making for the selection of treatments and improve the management of MSW according to geographical conditions, as well as the development of strategies to respond to the 2030 agenda.

Keywords: environmental impacts, landfill, recycling, waste-to-energy, waste treatment.

Resumen

El análisis de ciclo de vida (ACV) es una de las mejores herramientas para determinar el impacto ambiental de la gestión de residuos sólidos urbanos (RSU). Este trabajo analizó las opciones de gestión de RSU mejor evaluadas en el mundo con ACV, para identificar tendencias futuras. Se consideraron 132 publicaciones de ACV (2015-2023), su distribución geográfica y los resultados obtenidos según la norma ISO 14040; también se compararon las opciones evaluadas con las reportadas por el Banco Mundial. Los resultados mostraron que la mayoría de las publicaciones provienen de la región de Europa y Asia Central, seguido por América Latina y el Caribe. Después de comparar las alternativas se observó que los tiraderos a cielo abierto y los sitios controlados tenderán a ser reemplazados por rellenos sanitarios con recuperación de energía en todas las regiones del mundo; las tecnologías de recuperación de materiales y de aprovechamiento de la fracción orgánica se seguirán aplicando; y los procesos alternativos serán más comunes. Este trabajo pretende apoyar la toma de decisiones para la selección de tratamientos y mejorar la gestión de los RSU según las condiciones geográficas, así como el desarrollo de estrategias para responder a la agenda 2030.

Palabras clave: conversión de residuos en energía, impactos ambientales, reciclaje, relleno sanitario, tratamiento de residuos.

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1 Introduction

Urbanization, economic development, population growth, rising living standards, and demand for goods and services have caused the generation of a large amount of Municipal Solid Waste (MSW) (Budihardjo *et al.*, 2023). Cohen (2017) and Sharma & Jain (2020) found that the amount of waste generated is related to population size, while the amount of waste generated per capita, as well as its composition, is related to the level of industrialization, the management status of existing MSW, lifestyle, and the level of economic income (Kumar, 2016). The Environmental Protection Agency (EPA) estimated solid waste generation in the United States at 1.21 kg/person-day in 1968, which increased to 2.22 kg/person-day in 2018 (EPA, 2020). In Mexico, waste generation was 0.83 kg/person-day in 1997 and increased to 0.98 kg/person-day in 2017 (SEMARNAT, 2019). The World Bank's most recent estimate found that the world currently generates 2.01 billion tonnes of waste per year, which is expected to increase to 3.4 billion tonnes by 2050 (Kaza *et al.*, 2018). In parallel, there is a drive to protect the environment through decarbonization of all economic sectors, recycling, the circular economy, innovation, long-term investment in energy efficiency, reducing the carbon footprint of products, services, and processes, and increased investment in sustainable technologies and non-polluting solutions; which goes hand in hand, especially with objectives 11,12,13 and 14 of the 2023 agenda (ONU, 2021; NU, 2018).

In addition, the World Bank published that countries with higher income levels are more urbanized and generate more inorganic waste per capita and relatively less organic waste (Kaza *et al.*, 2018) because they consume processed food and generate packaging that can be recycled: plastic, paper, cardboard, metal, and glass packaging. On the other hand, low-middle-income countries generate a greater amount of organic waste. This amount increases when the level of economic development decreases (Correal & Rihm, 2022). Moreover, the exploitation and final disposal of waste types vary significantly by income level and region (Nanda & Berruti, 2021). Higher-income and more developed countries tend to focus on material recovery through recycling, anaerobic digestion (AD), composting, and incineration. Upper-middle-income countries, waste is typically disposed of in landfills, and in low-income countries, waste is burned in the open air or dumped on roads, open land, waterways, or open dumps, resulting in only a small fraction of waste being disposed of in landfills (Kaza *et al.*, 2018). Globally, the use of open dumps remains a common practice of waste disposal, and their improper management contributes to many environmental problems, including Global Warming, Ozone Layer Depletion, Resource Depletion, damage to Human Health, damage to Ecosystems, and the transmission of disease through the proliferation of disease vectors, the increase in respiratory illnesses caused by airborne particles from burning of waste, and the damage to flora and fauna that affects economic development (Cossu & Stegmann, 2018).

Traditionally, environmental impact assessment of projects, plans, and programs is done through the qualitative (subjective) and quantitative evaluation of the potential impacts caused by the physicochemical, biotic, cultural, and socioeconomic components on the environment (Garmendia *et al.*, 2005). However, indicators that scientifically support decision-making are currently needed. Therefore, to understand the extent to which each factor affects the environment, special attention has been given to the life cycle assessment (LCA) tool, which considers the different impacts on the environment from the extraction of raw materials to their final disposal (ISO, 2006a, 2006b).

In the late 1960s, the first Resource and Environmental Profile Analyses (REPA) were conducted. These became the precursors to LCA. One of the first LCA studies focused on MSW was conducted in the United Kingdom around 1993 to look for alternative practices for MSW management (Kirkpatrick, 1993). In the United States, the first LCA was published in 1993 (Bridges & Curran, 1993), while in Latin America and the Caribbean (LA&C), the publication of LCA papers began in 2004 in Brazil; it was not until 2009 that the first work appeared in Mexico (Romero-Hernández *et al.*, 2009). One of the first reviews of the application of LCA to MSW was published in Denmark in 2007 (Villanueva & Wenzel, 2007), and a comparative LCA review of MSW management systems was published in Canada in 2009 (Cleary, 2009). Similarly, there are reviews such as that of Khandelwal *et al.* (2019a), who analyzed 153 manuscripts on MSW management LCA; although this work considered studies conducted in Brazil, it omitted eight important LA&C publications conducted between 2015 and 2018. In the review by Margallo *et al.* (2019), 37 LCA studies were selected to review MSW disposal and management strategies in LA&C (Brazil and Peru) and other parts of the world. The review paper by Iqbal *et al.* (2020) examined and found 79 LCA manuscripts on best practices for MSW management, considering only Brazilian studies for LA&C.

The objectives of this paper were to analyze the most appropriate and best-evaluated options for MSW management in the world through the critical review of 132 LCA articles; and to identify future trends by comparing the options evaluated in the articles with those reported by the World Bank. The results of this paper are expected to provide valuable information for Integrated Solid Waste Management (ISWM) and

LCA practitioners from technical, environmental, and health perspectives.

2 Material and methods

2.1 *Criteria for selecting LCA studies*

Papers published between 2015 and the first half of 2023 were reviewed to provide a global overview of the application of LCA, covering all levels of economic income of the countries involved according to the World Bank classification (Kaza *et al*., 2018). LCA papers addressing ISWM in English were included and that made the comparison between different MSW treatment options and that met the requirements of ISO 14040 and 14044 standards (ISO, 2006a, 2006b). Excluded were LCA papers that involved social and economic aspects, as well as sewage sludge treatment, wastewater treatment, hazardous waste, construction waste, and electronic waste, because this waste requires another type of treatment and final disposal. Search engines such as Scopus and Google Scholar were used to find articles using keywords such as "life cycle assessment of municipal solid waste" and cross-referencing from the cited articles. Although more articles related to the topic were found, only 132 met the criteria described above, listed in Table A for supplemental information.

2.2 *Considerations for the Review*

The review included the categorization of LCA by country of origin; the 132 LCA articles were categorized into each of the seven regions defined by the World Bank (World Bank, 2010). They were also grouped by date of publication.

The main characteristics of the four phases of LCA were then reviewed: a) goal and scope definition (functional unit, system boundaries, attributional and consequential modeling approach), b) data collection and quality, c) impact evaluation methods (choice of impact categories, software and criteria used in LCA), and d) interpretation of results (significative issues, sensitivity, and uncertainty analyze).

A comparative table of the 132 articles was prepared, listing the articles meeting the characteristics of the first three phases of LCA and, in the fourth phase, the best-evaluated options for MSW management (Table A. Supplementary Information).

2.3 *Analysis of the identified characteristics*

The characteristics mentioned in Section 2.2 were reviewed, highlighting the similarities and differences identified in the different reviewed papers and the implications for the reported results.

Based on the results reported in the IV phase of the selected papers, the most appropriate and best-evaluated options for MSW management were identified and classified based on their contributions to the impact categories.

2.4 *Comparison of the options assessed with those reported by the World Bank*

The evaluated treatment options classified by country of origin were compared with those reported by the World Bank in each region (Kaza *et al*., 2018), which are currently being applied to determine the trends of technologies that will replace current options due to their lower environmental impact.

3 Results and discussion

3.1 *Publications over time and mapping of the study area*

Figure 1a) shows the geographical distribution of the published LCA articles, which were divided into seven regions. Most publications were found in the Europe and Central Asia region (44), followed in descending order by Latin America and the Caribbean (26), East Asia and the Pacific (25), South Asia (13), the Middle East and North Africa (11), North America (7), and Sub-Saharan Africa (6).

Figure 1b) shows the studies conducted in 48 countries between 2015 and 2023. China is one of the countries contributing the most to global waste generation (228 million tonnes in 2018) (Ding *et al*., 2021), and conducted the most LCA studies (16), followed by Italy (11), Brazil (11), and India (9). In contrast, countries such as Canada, Ecuador, Peru, Croatia, Finland, Kazakhstan, France, Greece, Poland, Romania, Serbia, Mauritius, Tanzania, Zimbabwe, Lebanon, Jordan, Kuwait, Indonesia, Malaysia, Nepal, and Vietnam produced only a single publication. The use of LCA tool is beginning to catch on in some countries, and the lack of LCA studies in others may be due to its low acceptance (Life Cycle Initiative, 2023).

3.2 *LCA Phase I: Goal and scope definition*

3.2.1 *Goal of the studies reviewed*

84.5% of the studies evaluated existing systems or advanced technologies on proposed scenarios; 3.1% evaluated a specific impact category, while 12.4% of the studies focused on a specific waste fraction, so the goal was to determine the optimal strategy for that waste category.

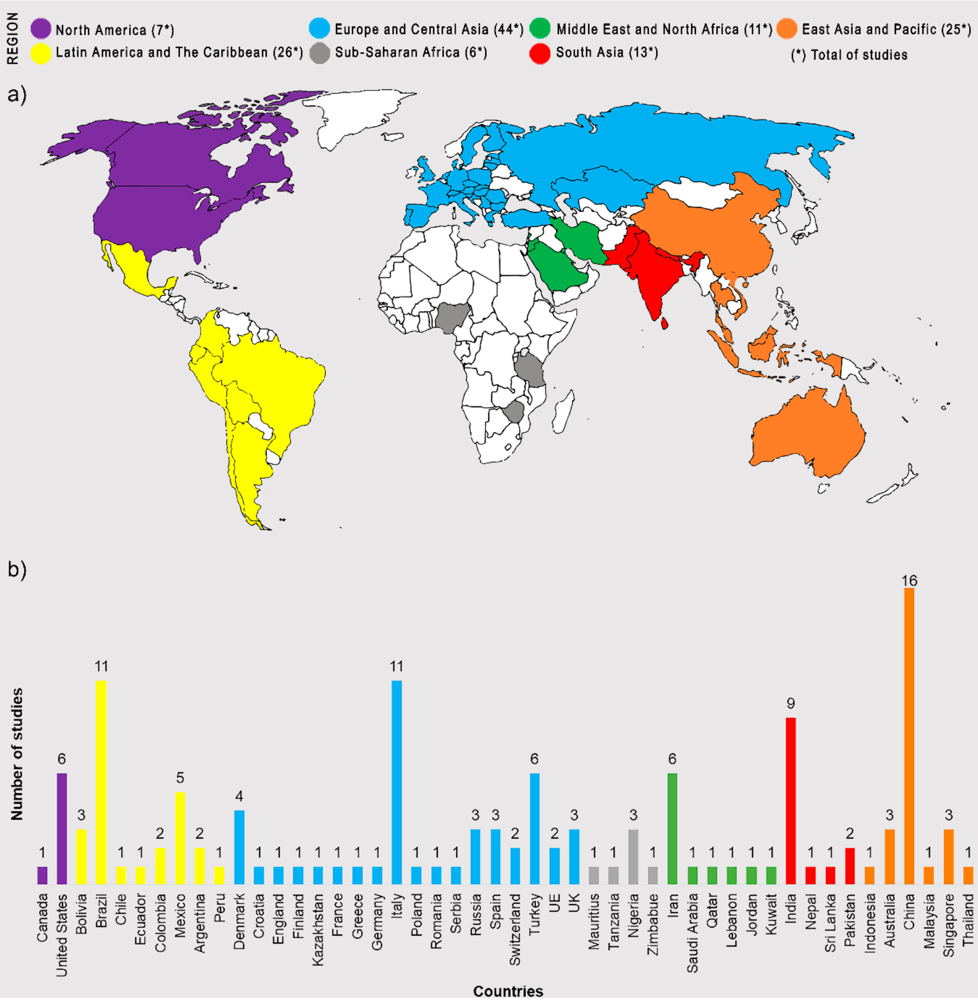

Fig. 1. Regions and number of studies: a) Mapping of the study area by region; b) Number of studies per country.

3.2.2 *System function and functional unit*

Four types of functional unit (FU) were identified: "i) mass unitary functional unit, e.g., 1 tonne of MSW; ii) based on waste generation in a limited region during a given period; iii) input-based, i.e., based on the amount of waste entering a given facility; and iv) output-based, defined by the waste by-product, e.g., the amount of energy recovered or material recycled", where the most used FU was type i), with 1 tonne of MSW (Fig. 2). It was detected that 4% of the studies did not report FU, such as the works of Suryawan *et al.* (2021), Çetinkaya *et al.* (2018), Edwards *et al.* (2018), Huang *et al.* (2018), Bisinella *et al.* (2016) and Raharjo *et al.* (2016), which reduces the reliability of the results.

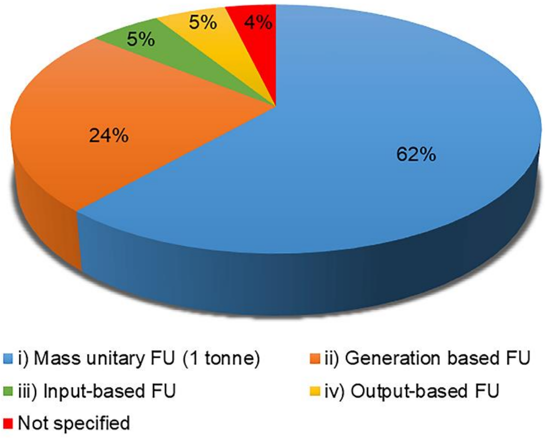

Fig. 2. Functional units used in MSW management LCA studies.

The selection of the FU is based on the objective and scope of the study and, depending on it, the values of the impact indicators will be obtained, without affecting the results of the best MSW treatment option. Some authors have used different FUs to corroborate the results, such is the case of Corvalán *et al.* (2021), that compared hydrothermal carbonization and gasification technologies using types i) and iv) FU (1 tonne of organic waste and 1 MWh of electricity produced), obtaining hydrothermal carbonization as the best option, regardless of the FU. Jeswani & Azapagic (2016) estimated and compared the environmental impacts of MSW disposal, with energy recovery through incineration and landfilling, they used type i) and iv) FU of 1 tonne of MSW and 1 kWh of electricity generation, the results indicated that incineration had lower impacts for both FUs.

3.2.3 System boundaries

In the reviewed studies, the boundaries vary in terms of inclusion or exclusion of four aspects: i) capital goods; ii) collection and transportation; iii) transportation of secondary products and process waste; and iv) emissions and impacts of secondary products and final residuals (Laurent *et al.*, 2014).

Capital goods refer to the construction/manufacture, maintenance, and dismantling of facilities, machinery, and vehicles used in the waste management process (Iqbal *et al.*, 2020). Among the 132 reviewed studies, 11% considered the impact of capital goods within the system boundaries, such as Ziegler-Rodríguez *et al.* (2019), who analyzed the environmental performance of MSW disposal in the construction, operation, and closure stages of three landfills, and as well as Slorach *et al.* (2019), who estimated the life-cycle environmental impacts and economic costs of the current MSW management system, considering the construction of treatment facilities, but excluding the dismantling.

Regarding ii) collection and transportation, 81% of the studies included these, such as Popiţa *et al.* (2017), who assessed the environmental performance of different MSW management and transportation options, or Khandelwal *et al.* (2019b), who considered MSW transportation when comparing the current scenario with the proposed options. The remaining 19% excluded this aspect, assuming that the impacts were negligible or outside the scope of the studies.

Factor iii) transportation of secondary products and process waste is considered in 15% of the papers, such as Hadzic *et al.* (2018), who considered the transportation of the ash of the incinerated waste; or Yadav & Samadder (2018), who considered the transportation of secondary products in the intermediate stages in the baseline scenario.

Finally, regarding factor iv) emissions and impacts of secondary products and final residues, these were considered in 90% of the works, such as Havukainen *et al.* (2017), who considered emissions caused by the MSW treatment and management. In the remaining studies, this factor was not considered or not mentioned within the system boundaries (Fig. 3).

Regarding the configurations used at the system limits, 26 manuscripts considered one of the four aspects, 79 papers included two, 24 took into account three, and three publications considered all four aspects. Some authors justified the exclusion of some of the aspects because their impact was similar in all scenarios (Iqbal *et al.*, 2019), it was insignificant or there was not enough data (Dastjerdi *et al.*, 2021).

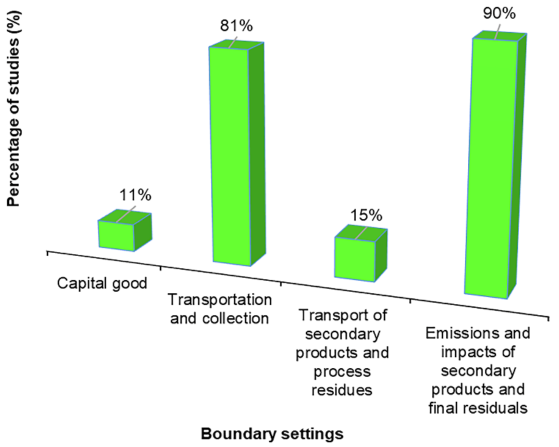

Fig. 3. Boundary settings used in MSW management.

3.2.4 Attributional and consequential modeling approach

Among the reviewed 132 LCA studies, 110 considered the attributional approach, 21 used the consequential, and Bernstad Saraiva *et al.* (2017), applied both approaches, finding that the application of the consequential approach could vary the results of environmental benefits, depending on the processes included in the modeling of the compared options. It is confirmed that the use of the consequential approach requires experience and information to identify the detailed consequences and marginal processes, like future provision or substitution of a product generated by a particular technology, such as electricity or heat generated from municipal waste, or the substitution of compost and digestate to produce inorganic fertilizers that will reduce impacts (Hadzic *et al.*, 2018; Bernstad Saraiva *et al.*, 2017).

In the 132 papers analyzed, the problem of multifunctionality in the two approaches was addressed in three ways, 82% expanding the system boundaries considering aggregate products (ISO 2006b), as in the case of Hadzic *et al.* (2018), who considered the expansion of the system boundaries for the recovery of electrical energy from biogas and residual waste from the analyzed processes. Also, 8% applied the substitution approach or avoided loads, such as Buratti *et al.* (2015), who assumed that the electricity generated by the combustion of biogas would substitute the electricity generated by the Italian energy mix and the substitution of chemical fertilizers with compost.

Finally, 10% of the studies used the partitioning method in the multifunctional process to attribute the impacts to the different products, since it tends to be more subjective, because the partition occurs depending on the context of each study (Schaubroeck *et al.*, 2021) and the judgment of the experts participating in the study; where the criteria can be mass (Ferronato *et al.*, 2021; Mannheim, 2022.), energetic (Tagliaferri *et al*., 2016) or economical (Chhabra *et al*., 2020).

3.3 LCA Phase II: Life cycle inventory data collection and quality

In the distribution of inventory data collection (Fig. 4), most of the reviewed studies in this work, as reported by Sauve & Van Acker (2020), Buratti *et al*. (2015), Behrooznia *et al*. (2020) and Rajaeifar *et al*. (2015), are based on: i) field data; ii) data from the literature; iii) database software; and iv) data from specific countries. It should be noted that the most commonly used data are from Ecoinvent. Regarding data quality, it was found that some studies did not specify the temporality of its publication; furthermore, some authors did not mention the name or version of the database used, referring to it simply as "the LCA database software".

In addition, it was found that 111 of the 132 manuscripts reported the general content of the waste fraction without addressing the chemical composition of the organic waste, the calorific value, or the heavy metals content, limiting the reproducibility of the results.

In 77% of articles, it was detected that the authors used data from Ecoinvent, arguing that there are no databases in their countries, which can lead to large biases in the results. Although some authors adapted such imported data or processes to local conditions, such as Mehr *et al*. (2021), who adapted the inventories of processes for primary and secondary production of metals from Ecoinvent to the specific conditions of the study; and Weligama Thuppahige & Babel (2022), who modified the Ecoinvent database to calculate emissions from water and electricity consumption for their country.

For cases where it was required to evaluate biogas emissions at final disposal sites, the authors used different options, in seven manuscripts the EPA LandGEM model was used (Çetinkaya *et al*. (2018), 35 papers used the IPCC first order decay method (Demetrious & Crossin, 2019), 11 carried out in-situ measurements (Popiţa *et al*., 2017) and 11 studies used data reported in other papers (Rajcoomar & Ramjeawon, 2017).

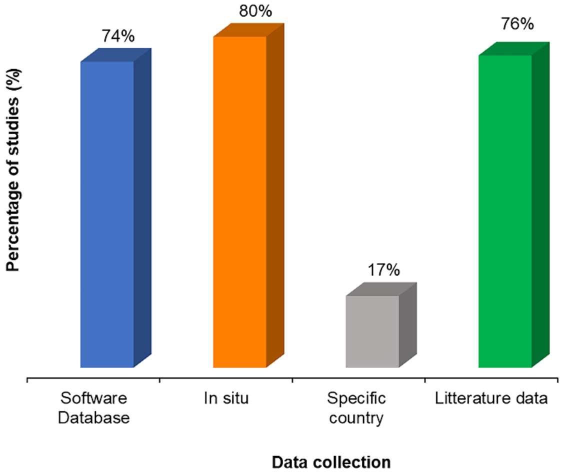

Fig. 4. Data sources used in MSW management LCA studies.

Regarding the generation of leachate, Ouedraogo *et al*. (2021) and Istrate *et al*. (2021) used the HELP model. 18 manuscripts made considerations, Yay (2015) estimated that the production of these represents around 10% of the precipitation in the landfill and Aldana-Espitia et (2017) calculated that the production of leachates generated by rain is 112.5 l/ton. of waste, and that waste provides 45% of the water for their formation. 10 papers performed in-situ measurements (Hadzic *et al*., 2018), and 17 articles used data reported in other papers (Khandelwal *et al*., 2019b).

3.4 LCA Phase III: Life cycle impact assessment

3.4.1 Reported impact categories

Figure 5a) shows the number of publications between 2015 and the first half of 2023, with a larger number of publications observed in 2017 and 2021. According to Table A (Supplementary Information) and Fig. 5 a), among the categories assessed in the LCA studies from 2015 to the first half of 2023, Climate Change (100.0%), Acidification (80.0% to 100.0%), Eutrophication (72.2% to 100.0%) and Human Toxicity (50% to 100.0%) stand out as having the highest percentage and decreasing order because they are the most accurate and well known; while 20.0% to 73.3% assessed Particulate Matter Formation, Ozone Layer Depletion, and categories related to Ecotoxicity, Resource Depletion, and Photochemical Oxidant Formation. Other categories, such as Ionizing Radiation or Cumulative Energy, were used in 3.3% to 50.0% of studies.

Midpoint impact categories were used most frequently because they have lower uncertainty when modeling a small portion of the environmental mechanism, whereas the endpoint categories may have substantial uncertainty. However, the latter are easier to understand and interpret for decision-making.

3.4.2 Impact assessment methodologies

As can be observed in Table A (Supplementary Information) and Fig. 5 b), the most reported methodology in the reviewed papers was CML (34.1%), followed by ReCiPe (23.5%). The least frequently used methods were IMPACT 2002+, EDIP, Eco-indicator 99, Traci, and Environmental Footprint. In 6.1% of the studies, the method was not reported.

It has been shown that there is a correlation between the method used and the region in which the studies were conducted, so that in the European and Asian regions the main method used was CML, in the USA Traci, and in Latin America and other regions the ReCiPe method. It is worth mentioning that the ReCiPe method was applied to a greater extent in the 2019 to 2023 period to allow a more detailed impact assessment.

In addition, 5.3% of the studies mentioned the use of more than one methodology to complement the impact assessment. This was the case of Ziegler-Rodriguez *et al.* (2019), who used IPCC 2013 and ReCiPe 2008, where the choice of IPCC was justified because it was the most complete and up-to-date method at the time the study was conducted. Rajcoomar & Ramjeawon (2017) used CML and ReCiPe, arguing that ReCiPe was used to determine endpoint impacts. Edwards *et al.* (2018) used IPCC 2013 and CML, to include the updated IPCC characterization factors. De Feo *et al.* (2016) used IPCC 2007, Ecological Footprint, and ReCiPe 2008 to supplement the impacts they assessed; they also justified that Global Warming is the only impact category that accounts for 100% of the IPCC method, whereas in other methods each impact is weighted according to the perspective chosen. Ali *et al.* (2018) used IPCC and Eco-indicator-99 to calculate the impacts of Global Warming and Human Health categories. Finally, Haupt *et al.* (2018) applied IPCC, ILCD, CED, and USETox to complete the impact assessment, using an updated IPCC.

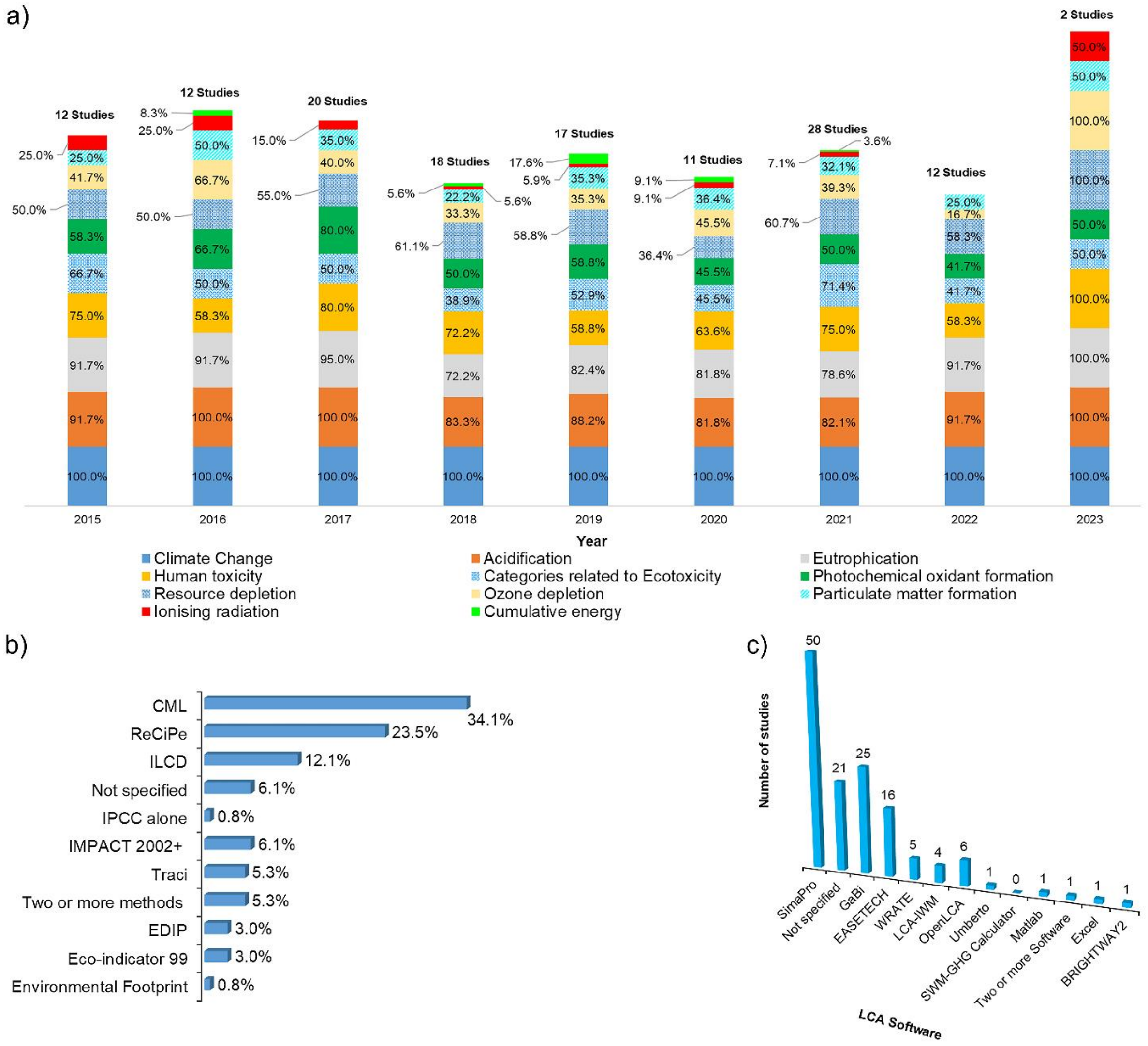

Fig. 5. Characteristics assessed in MSW management LCA publications: a) Impact categories over time; b) Impact assessment methods; c) Types of software used.

In reviewing the LCA articles published by year, differences were found because the different impact assessment methods do not consider the same impact categories or the same characterization factors. This is the case with the CML method, which was the most commonly used between 2015 and 2018 and does not consider the Particulate Matter Formation category when assessing technologies related to the combustion of waste or biogas (Xu *et al*., 2015). On the other hand, during this period, some of the reviewed LCA articles used methods such as ReCiPe, Impact 2002+, Eco-indicator 99, or ILCD which included the Particulate Matter Formation category (Rajaeifar *et al*., 2015). However, some authors did not consider this category, although they evaluate combustion scenarios where the impact of Particulate Matter emissions (PM_{10} and $PM_{2.5}$) is relevant (Jensen *et al*., 2016).

3.4.3 Life cycle assessment software

SimaPro was the generic software mainly used in the reviewed papers, followed by GaBi and Easetech. This could be due to the selling price of the software, the different application areas, the use of complete tools, and the extensive database. To a lesser extent, specialized software for MSW management or even open-access software such as OpenLCA was used. The use of specialized MSW management software allows the monitoring of materials, modeling of specific processes such as biogas production, verification of mass balances, and access to databases that integrate waste composition and management processes (Laurent *et al*., 2014). The use of LCA software for a study is not mandatory, but it is preferable as it facilitates the calculation process and saves time. It is worth noting that 21 LCA studies did not specify the software used (Fig. 5 c).

3.5 LCA Phase IV: Results and interpretation

Although ISO 14040 and 14044 establish that the Life Cycle Impact Assessment (LCIA) results should be presented first, followed by data quality analysis; this study considered reversing that and then discussing the LCA results with those of the World Bank.

3.5.1 Data quality analysis methods

Sensitivity analysis was used in 40% of the reviewed LCA studies, as shown in Fig. 6 and Table A (Supplementary Information). Sensitivity analysis makes it possible to estimate whether a scenario is beneficial. Ripa, *et al.* (2017) varied source separation and reduced transportation distance and confirmed that increasing the level of separate collection (and the resulting reduction in waste) brings significant global improvement and benefits at both environmental and energy levels; while Khandelwal *et al.* (2019b) evaluated the impact of the recycling rate of valuable resources in all scenarios considered, with sensitivity analysis showing an inversely proportional relationship between the change in recycling rate and total environmental burdens.

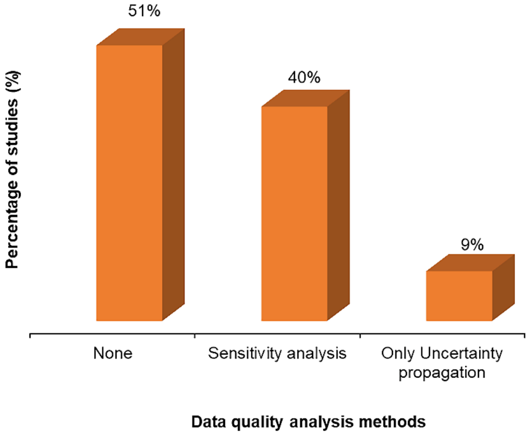

Fig. 6. Methods for data quality insurance of the data used for MSW management.

Uncertainty analysis was performed in only 9% of the reviewed articles. For example, Wang *et al.* (2020) used the statistical Monte Carlo method; in their work, the composition of collected MSW and the calculation of inputs and outputs of the processes were based on data obtained in 2018 for the city of Horqin Left Rear Banner, China. Demetrious & Crossin (2019) mainly used background data for the inventory based on literature and Ecoinvent 3.0 database for the city of Victoria, Australia. Güereca *et al.* (2015) used both foreground and background data from samples collected in Mexico in 2008, 2009, and 2010 for their inventory.

The probability functions used in the uncertainty analysis were the triangular one, where the uncertainty of the composition of the waste, physicochemical data of the waste and emissions of heavy metals were analyzed (Bisinella *et al*., 2017); the log-normal for electricity demand and generation and heavy metal emissions (Edwards *et al*., 2017), as well as used to estimate the uncertainty of the inputs (e.g. electricity and water consumption) (Wang *et al.* , 2020); the uniform for the amount of biogas captured, methane emissions and electricity generated (Demetrious & Crossin, 2019); and the normal and uniform distribution, for gas recovery efficiency, degradable organic carbon content and organic waste fraction (Iqbal *et al*., 2019).

It is worth noting that 51% of the reviewed studies did not report any type of data quality analysis.

3.5.2 Waste management options reported

In the 132 manuscripts reviewed, management options were found ranging from segregation, recycling,

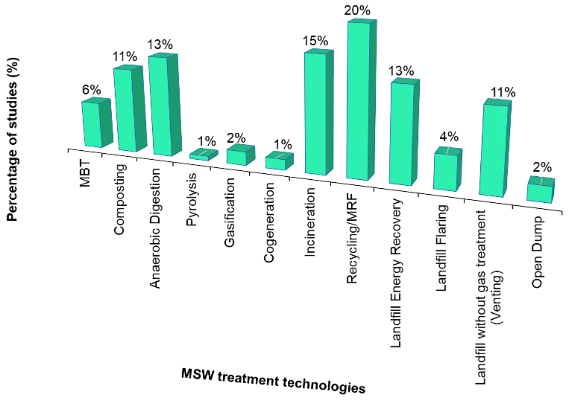

Fig. 7. Percentage of options used in MSW management LCA.

biological, chemical, physical, or thermal treatment, to final disposal.

In comparative scenarios, landfills and open dumps are still mainly used for MSW disposal (Kaza *et al*., 2018). From the options evaluated in the reviewed articles (Fig. 7), landfill was the most frequently cited option in the comparison scenarios: landfill with energy recovery (13%), landfill with gas flaring (4%), and landfill without gas treatment (venting) (11%); since this is the option currently applied in much of the world.

The second most frequently mentioned waste management treatment was recycling and material recovery facility (MRF), which was mentioned in 20% of the contributions. Thermal treatment was the third most analyzed (19%), consisting of incineration (15%), cogeneration (1%), gasification (2%), and pyrolysis (1%). In addition, mechanical biological treatment (MBT), composting, and AD were investigated for organic fraction treatment in 6%, 11%, and 13% of the studies, respectively. To a lesser extent, open dump was considered (2%).

3.5.3 Impact of waste management options

The results of the reviewed LCA studies showed that the option that caused the greatest impact was the open dump. The lack of a MSW management system contributes to the uncontrolled release of methane (CH_4) into the atmosphere, leading to Global Warming. Accidental or incidental open burning of waste is the main contributor of substances that cause Human Toxicity. Methane, particulate matter (PM), and other fossil fuel emissions cause Photochemical Oxidation (Yadav & Samadder, 2018). According to the results of Siddiqua *et al*., 2022, leachates together with gases such as hydrogen sulfide (H_2S), also contribute to the acidification potential; in addition, nitrogen (N) and phosphorus (P) dissolved in the leachate contribute to Eutrophication. The lack of geomembrane and leachate collection and treatment systems can cause leachate to reach bodies of water, causing Ecotoxicity (Rana *et al*., 2019).

Second in impacts is landfill, especially landfill without gas treatment (venting) in terms of Global Warming, due to CH_4 and carbon dioxide (CO_2) emissions from biogas extraction wells and filtration at the surface of the final cover (Cossu & Stegmann, 2019); followed by the landfill with gas flaring, installed in the venting wells, obtaining CO_2 and water (H_2O) (Ziegler-Rodríguez *et al*., 2019); and the landfill with energy recovery, replacing fossil fuels for electricity generation (Caicedo-Concha *et al*., 2021). It should be noted that in the landfill scenarios with energy recovery, biogas capture efficiency rates increased from 30% to 45% in the first five years, from 75% from six to ten years, from 79% from 11 to 15 years, 85% from 16 to 45 years, and 0% from 46 to 100 years (Istrate *et al*., 2021; Fiorentino *et al*., 2015). Among the midpoint categories, Inorganic Respiratory/Particulate Matter Formation is the second most crucial impact caused by landfill gas flaring. As precursors of PM, there are the reactions that can occur between nitrogen oxides (NO_x), sulfur oxides (SO_x), water vapor, ammonia, volatile organic compounds (VOCs), ashes and inorganic compounds (Chiu & Lo, 2016), as well as the MSW transportation generate $PM_{2.5}$ and PM_{10}. To a lesser extent, Acidification is caused by SO_x and NO_x, which are emitted due to the absence of treatment (Maalouf & El-Fadel, 2019); Ozone Layer Depletion and Resource Depletion by the treatment of landfill gas and leachates, and diesel consumption during MSW collection and machinery operation. Moreover, emissions caused by leachate such as phosphate (PO_4^{3-}), nitrate (NO_3^-), and heavy metals cause Eutrophication. In the paper by Istrate *et al*. (2021) it is reported that around 95% of leachate from landfills is collected for treatment in the first 20 years and 70% between 21 to 40 years, while uncollected leachate can reach bodies of water. Likewise, in the article by Yay (2015) he mentions that 99% of the leachate is collected and the remaining 1% is filtered into bodies of water.

Mechanical biological treatment is in third place. This technology combines the mechanical separation of the inorganic components of MSW (screens, sieves and magnets) with biological treatments for the organic components, such as composting or AD (Starostina *et al*., 2018). In the case of aerobic biological processes, the final products generated have significant impacts, such as energy consumption required for the process. The lower stabilization of the organic fraction, combined with the VOCs emitted during waste transportation, leading to the Photochemical Oxidant Formation (Fiorentino *et al*., 2015); ammonia (NH_3) emissions from compost contribute to Eutrophication (Grzesik & Malinowski, 2017). NO_x contributes to Acidification, and these together with the heavy metals and microplastics present in the compost cause Human Toxicity. (De Morais Lima *et al*., 2018).

Composting ranks fourth, as it generates NO_x and NH_3 emissions that cause even more Acidification than landfills and waste-to-energy technologies (Zarea *et al*., 2019). In terms of Global Warming, the decomposition of the organic fraction and the operation of the facilities without energy recovery generate Greenhouse Gases (GHGs) that are emitted directly into the atmosphere. Rajcoomar & Ramjeawon (2017) mention that biogenic CO_2 does not significantly affect Global Warming. Marine Eutrophication is due to the use of compost on land and the leaching of nutrients (Jensen *et al*., 2016). It should be noted that by collecting and recirculating leachate between compost piles, the potential for contamination can be reduced (Yay, 2015).

Fifth in terms of impacts are the scenarios that considered AD, where the low direct emissions generated by organic waste decomposition influence the Climate Change category; these emissions occur in waste storage tanks, feed tanks, leachate collection tanks and digestate storage tanks, as well as in the reactor and gas transport pipelines (Weligama Thuppahige & Babel, 2022). Furthermore, the release of PO_4^{3-}, NO_x and NH_3 causes Eutrophication (Parkes *et al*., 2015); emissions of pollutants such as PM_{10}, $PM_{2.5}$, SO_x, NO_x and heavy metals are the cause of Human Toxicity (Xu *et al*., 2015); and the release of NO_x and SO_x causes Acidification (Behrooznia *et al*., 2020).

Technologies for energy exploitation from materials through thermal treatments (incineration, cogeneration, gasification, and pyrolysis) to generate electricity rank sixth (Zhou *et al*., 2018). These processes primarily contribute to Inorganic Respiratory impacts associated with direct and indirect emissions of carbon monoxide (CO), NH_3, SO_x, NO_x, sedimentary particles, PM_{10} and $PM_{2.5}$ (Liu *et al*., 2021); Human toxicity with emissions of nickel (Ni), cadmium (Cd) and NO_x that come from the same process. Low GHG emissions can be achieved whether materials are separated/classified prior to combustion. Resource Depletion impact receives the greatest benefit due to the energy recovery, metals, and bottom ash as cover material for the landfill. Eutrophication impact has also been reported due to the treatment of leachate generated from MSW storage, as well as acidification caused by NO_x and sulfur dioxide (SO_2) generated from MSW combustion (Zarea *et al*., 2019). In the manuscript by Parkes *et al*. (2015) it was found that gasification and pyrolysis prevent the formation of dioxins and reduce the formation of NO_x; however, the thermal efficiency of both processes is usually much lower than incineration.

In seventh place in terms of impacts are the processes of separation, MRF, and recycling of materials due to the positive effect of using inorganic materials for their exploitation, avoiding the effects of Resource Depletion such as the consumption of energy and materials used in the extraction process and in the production of new materials (Aryan *et al*., 2019; Rajaeifar *et al*., 2015). According to several studies, as the recycling rate increases, the environmental benefits also increase, so emissions from the MSW management system are also affected (Sharma & Chandel, 2017; Cheela *et al*., 2021). It is worth mentioning that recycling rates of 40% are commonly considered. (Yay, 2015; Yadav & Samadder, 2018). For mixed wastes containing materials that could be recycled whether perfectly separated and cleaned, MBT allows the separation of the biomass from the residual fractions, reducing the Human Toxicity potential (Fiorentino *et al*., 2015).

3.5.4 Comparison of the most appropriate options for MSW management

The choice of the most appropriate options for ISWM depends on the amount of waste generated, composition, physicochemical properties, the exploitation of energy and by-products, and socio-economic and political aspects (Batista *et al*., 2021). It is important to clarify that socioeconomic and political aspects are beyond the scope of this work.

For the organic fraction, AD had a better performance in terms of generating environmental impacts (Table 1). Out of a total of 132 reviewed papers, 66 evaluated AD, and 64% considered it the best option, as AD has a positive effect in reducing the impact of Resource Depletion through electricity generation from biogas (avoiding the use of large amounts of natural gas for electricity generation), heat recovery, and the production of organic fertilizer as a by-product of anaerobic digestion, which can replace inorganic fertilizer (Khandelwal *et al*., 2019b; Parkes *et al*., 2015), and use it as a soil improver (Espinosa-Salgado *et al*., 2020).

On the other hand, composting was mentioned and evaluated as a recommended technology for the organic fraction in 41% of the studies because the production of organic fertilizer avoids the use of inorganic fertilizer (N, P, and potassium (K)), which partially reduces GHG emissions (Yadav & Samadder, 2018), and in particular it reduces CH_4 production by correctly aerating the organic matter, preventing anaerobic processes from occurring (Table 1) (Estrada-Martínez *et al*., 2021; Zarea *et al*., 2019).

Regarding the inorganic fraction, 96 manuscripts mentioned MRF/recycling, and 54% rated it as the best process (Table 1), as MRF/recycling achieves favorable results in reducing environmental impacts (Aryan *et al*., 2019; Rajaeifar *et al*., 2015), with the

Table 1. Best-rated MSW management options.

Management option	Number of times assessed	Best first place	% of each assessed option that turned out to be the best
Anaerobic digestion	66	42	64%
Composting	56	23	41%
Material Recovery Facility/Recycling	96	52	54%
Incineration	76	41	54%
Pyrolysis	3	3	100%
Gasification	9	6	67%
Cogeneration	7	3	43%
Mechanical biological treatment	31	7	23%
Landfill Energy Recovery	62	20	32%
Landfill without gas treatment (Venting)	54	18	33%
Landfill Flaring	22	4	18%
Open Dump	10	0	

high level of material separation and their exploitation, replacing the consumption of energy and raw materials in extraction and production, which benefits the entire MSW management system by reducing resource consumption (Sharma & Chandel, 2017; Cheela *et al*., 2021).

For mixed waste, incineration with energy recovery was considered a good option in 54% of the studies that evaluated it in terms of impacts caused by emissions (Table 1), as low emissions can be achieved whether separation/classification of materials is performed before incineration (Zhou *et al*., 2018), considering replacing fossil fuel-generated electricity that causes emissions (Liu *et al*., 2021).

Other thermal treatments such as pyrolysis, gasification, and cogeneration received a good rating (Table 1) because they reduce the generation of pollutants, NO_x, and SO_2 compared to incineration (Zaman *et al*., 2017). However, their application for MSW is hardly reported because they are still in the development phase, pilot tests, or operated on a small scale, and therefore their costs are not yet competitive (Breeze, 2018).

Another treatment option for mixed waste is MBT, which was evaluated as a good option in 23% of the studies (Table 1), as it includes the process of material separation and the production of refuse-derived fuel (RDF), which reduces the environmental impact of GHGs (Grzesik & Malinowski, 2017; De Morais Lima *et al*., 2018).

The last option evaluated in 107 studies was landfill use. Landfilling with energy recovery was considered in 62 papers, with 32% ranking this option as the best (Table 1), as several authors propose the exploitation of biogas through energy recovery to reduce GHGs and use it as a substitute for fossil fuels to generate electricity (Ziegler-Rodríguez *et al*., 2019; Caicedo-Concha *et al*., 2021). In the case of Mexico, the work of Rueda-Avellaneda *et al*. (2021) corroborates the above, reporting that whether electrical energy is generated with 4.6% of the suitable final disposal sites, the emission of 1.45 Mt CO_2e would be avoided.

In 22 papers that considered the use of landfills with biogas flaring using flares installed in the venting wells, 18% of the studies rated this option as suitable because biogas flaring reduces environmental impacts by releasing CH_4, which generates water (H_2O) and biogenic CO_2 which is considered neutral and has no effect on climate change (Ziegler-Rodríguez *et al*., 2019).

Moreover, the use of landfills without gas treatment (venting) was analyzed in 54 studies, and 33% considered it a better option than open dump, although it contributes to Global Warming impact when the biogas produced is released directly into the atmosphere through venting wells since it could include infrastructures for the collection or treatment (as the case may be) of biogas and leachate (Yadav & Samadder, 2018).

3.6 *Comparison between the LCA studies and the methods reported by the World Bank*

According to the recent report of the World Bank, the following methods were used for the treatment and disposal of MSW in different regions of the world until 2018: recycling, composting, incineration, landfill, and open dump. The reviewed LCA studies include these methods as well as alternative options such as MBT, AD, cogeneration, and pyrolysis. Figure 8 shows a comparison between the options used and those evaluated in the LCA studies.

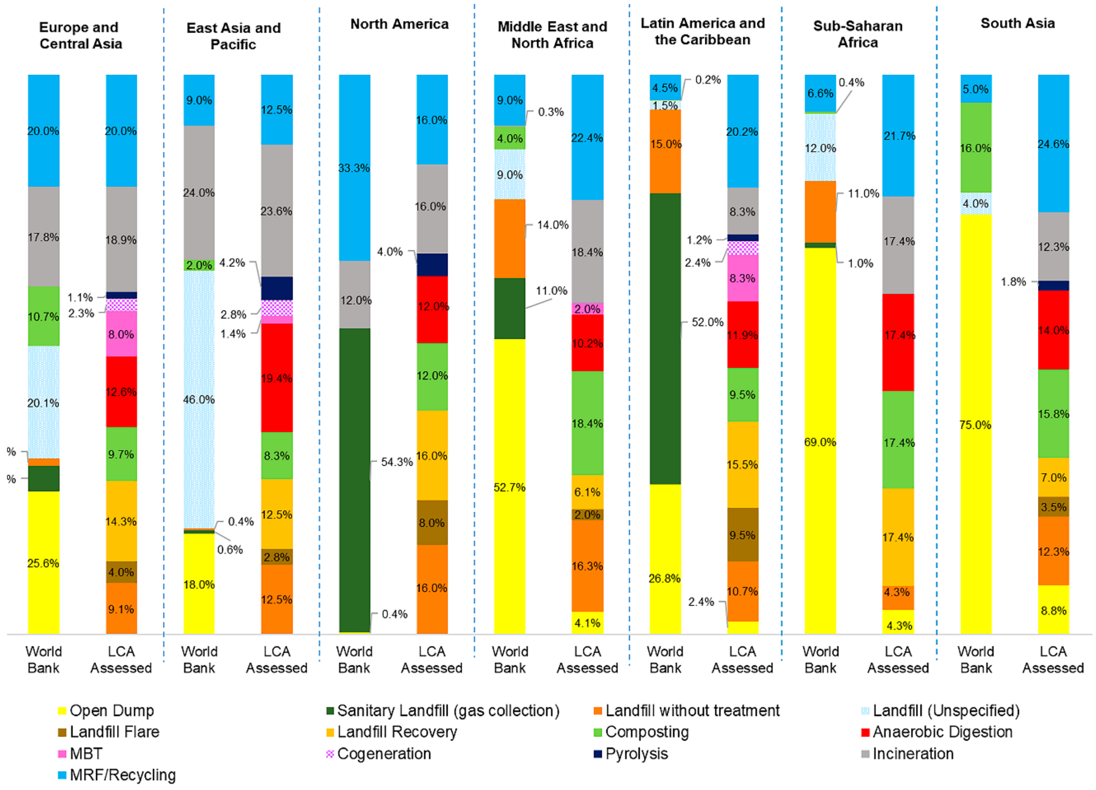

Fig. 8. Percentage of MSW treatments assessed in the studies in different regions.

Comparing the percentages of options reported by the World Bank (2018) for the Europe and Central Asia region with the percentages of options evaluated in the reviewed articles (Fig. 8), the elimination of open dumps and unspecified landfills is evident. For example, the use of landfills with biogas flaring and energy recovery virtually halves the final disposal options. The percentages of composting, incineration, and MRF/recycling are similar, but LCA studies are looking at new ways of exploitation, such as AD, MBT, cogeneration, and pyrolysis.

In the East Asia and Pacific region, the methods evaluated in the papers about those reported by the World Bank (Fig. 8) show the trend of reducing and replacing open dumps and unspecified landfills, for landfills with biogas flaring and energy recovery. Moreover, the use of AD, MBT, cogeneration, and pyrolysis, as well as increases in composting and MRF/recycling, are also considered.

In North America, the proportion of options such as open dumps and landfills with biogas collection systems (Fig. 8) indicated by the World Bank could be replaced for landfills with biogas flaring, landfills with energy recovery, and composting. In the reviewed LCA studies, incineration and MRF/recycling are decreasing; AD and pyrolysis are being introduced.

In the Sub-Saharan Africa and South Asia region, methods reported by the World Bank such as open dumps and unspecified landfills are expected to be replaced for landfills with biogas flaring, and energy recovery. Moreover, an increase in MRF/recycling and the introduction of new technologies such as AD and incineration are being considered. Composting in South Asia appears to be similar; an increase in this treatment in Sub-Saharan Africa is contemplated.

For the Middle East and North Africa and LA&C, the LCA articles assessed the replacement of open dumps for landfills with biogas flaring and landfills with energy recovery, and increases in composting and MRF/recycling, compared to the options reported by the World Bank (Figure 8). New exploitation technologies are being considered, such as AD and incineration. In the Middle East and North Africa, MBT is proposed, while in LA&C, the use of cogeneration and pyrolysis is also valued.

In the case of LA&C, while landfill is the least recommended option, it remains the cornerstone of MSW management because it is an economical and well-known option, so efforts to eliminate open dumps continue (Ziegler-Rodriguez *et al.*, 2019; Margallo *et al.*, 2019). In this region, recycling and organic waste exploitation processes present an opportunity because increasing the recovery rate of organic and inorganic material will reduce the amounts that need to be disposed of, thus increasing environmental, economic, and social benefits (Rajaeifar *et al.*, 2015).

Conclusions

In this work, the results of 132 LCA articles on MSW management were analyzed. The discussion was based on all aspects of the LCA methodology, the software used and the most appropriate and best evaluated options for the management of MSW. The best evaluated options were compared with those reported by the World Bank. The largest number of LCA studies was found in China and Europe, while 26 articles were found in LA&C. The choice of different ISWM scenarios depended on the composition, physicochemical properties, and amount of waste generated, as well as regional socio-economic and political factors.

Regarding the objective and scope phase, it was found that the definition of FU varies widely, although some studies do not define it or omit it, which limits reliability and the possibility of comparing the results. In terms of system boundaries, most of the studies reviewed considered emissions and impacts of secondary and residual products and, to a lesser extent, capital goods, whose impacts were negligible. The 132 articles analyzed addressed the problem of multifunctionality, and the vast majority expanded the boundaries of the system and considered aggregated products.

In terms of inventory, most studies relied on field data, followed by literature data, database software, and data from specific countries. However, most manuscripts did not include information on waste characteristics, limiting the reproducibility of results.

The main impacts evaluated in the LCA studies were Climate Change Category, Human Toxicity, Eutrophication, and Acidification, which represent the main environmental problems associated with solid waste treatment options. The most cited methods were CML and ReCiPe, and the most used software was SimaPro.

It was found that in the interpretation stage, most of the articles did not use sensitivity and uncertainty analysis, limiting the results to a contribution analysis.

Regarding the waste treatment options evaluated in the reviewed articles, the landfill was the most frequently mentioned option in the comparison scenarios. MRF and recycling were the second most frequently mentioned, followed by thermal technologies, which include incineration, cogeneration, gasification, and pyrolysis. Anaerobic digestion, composting, and MBT were the least examined. The best options were in descending order, the separation process and recycling, technologies with energy exploitation, AD, composting, MBT and landfill. Open dump is the option with the greatest negative impact associated with most of the categories evaluated. It is worth mentioning that the ranking of the best alternatives for waste management and disposal was not affected by the use of different FU and approaches (attributional or consequential) in the LCA studies reviewed.

The choice of the most appropriate options for the organic fraction was AD since the impact on the resource consumption of electricity generation from biogas, heat recovery, and the production of organic fertilizer as a substitute for inorganic fertilizer was reduced. On the other hand, composting is a recommended process for the production of organic fertilizer that avoids the use of inorganic fertilizer.

For inorganic fractions, MRF/recycling was the best option as it replaces the consumption of energy and raw materials in extraction and production.

For mixed waste, incineration was considered a good option because it takes into account energy recovery, which replaces electricity generated by fossil fuels that cause emissions. Pyrolysis, gasification, cogeneration and MBT received a good rating. The last option mentioned was the use of the landfill, where the landfill with energy recovery was preferred to replace fossil fuels for electricity generation.

After comparing the options evaluated in the LCA papers with those reported by the World Bank in 2018, it was found that open dumps and unspecified landfills tend to be replaced by landfills with energy recovery in all regions; material recovery and organic fraction exploitation technologies will continue to be applied to generate compost and biogas. Alternative processes such as MBT, AD, cogeneration, and pyrolysis will become more common.

The results of this work are intended to support decision-making related to improving MSW management, selecting appropriate treatment according to the geographical and socioeconomic conditions of each study, and future development of waste management strategies of each region of the world.

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References

Aldana-Espitia, N., Botello-Álvarez, J., Rivas-García, P., Cerino-Córdova, F., Bravo-Sánchez, M., Abel-Seabra, J. and Estrada-Baltazar, A. (2017). Environmental impact mitigation during the solid waste management in an industrialized city in Mexico: an approach of life cycle assessment. *Revista Mexicana de Ingeniería Química 16*(2), 563-580. ISSN: 1665-2738

Ali, M., Marvuglia, A., Geng, Y., Chaudhry, N. and Khokhar, S. (2018). Emergy-based carbon footprinting of household solid waste management scenarios in Pakistan. *Resources, Conservation and Recycling 131*, 283-296. `http://dx.doi.org/10.1016/j.resconrec.2017.10.011`

Aryan, Y., Yadav, P. and Samadder, S. (2019). Life Cycle Assessment of the existing and proposed plastic waste management options in India: A case study. *Journal of Cleaner Production 211*, 1268-1283. `https://doi.org/10.1016/j.jclepro.2018.11.236`

Batista, M., Gusmão Caiado, R.G., Gonçalves Quelhas, O.L., Alves Lima, G.B., Leal Filho, W. and Rocha Yparraguirre, I.T. (2021). A framework for sustainable and integrated municipal solid waste management: Barriers and critical factors to developing countries. *Journal of Cleaner Production 312*, 1-14. `https://doi.org/10.1016/j.jclepro.2021.127516`

Behrooznia, L., Sharifi, M. and Hosseinzadeh-Bandbafha, H. (2020). Comparative life cycle environmental impacts of two scenarios for managing an organic fraction of municipal solid waste in Rasht-Iran. *Journal of Cleaner Production 268*, 1-16. `https://doi.org/10.1016/j.jclepro.2020.122217`

Bernstad Saraiva, A., Souza, R. and Valle, R. (2017). Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro - Investigating the influence of an attributional or consequential approach. *Waste Management 68*, 701-710. `https://doi.org/10.1016/j.wasman.2017.07.002`

Bisinella, V., Conradsen, K., Christensen, T.H. and Astrup, T.F. (2016). A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems. *International Journal of Life Cycle Assessment 21*, 378-394. `https://doi.org/10.1007/s11367-015-1014-4`

Breeze, P. (2018). Chapter 5 - Steam Turbine Combined Heat and Power Systems. *Combined Heat and Power*, 41-49. `https://doi.org/10.1016/B978-0-12-812908-1.00005-5`

Bridges, J.S. and Curran, M.A. (1993). Life cycle assessment for municipal solid waste management. Report for 1993-1994. Environmental Protection Agency, Cincinnati, OH (United States). Available at: `https://www.osti.gov/biblio/5512167`. Accessed March 10, 2022.

Budihardjo, M.A., Priyambada, I.B., Chegenizadeh, A., Al Qadar, S. and Puspita, A.S. (2023). Environmental impact technology for life cycle assessment in municipal solid waste management. *Global Journal of Environmental Science and Management 9*, 145-172. `https://doi.org/10.22034/GJESM.2023.09.SI.10`

Buratti, C., Barbanera, M., Testarmata, F. and Fantozzi, F. (2015). Life Cycle Assessment of organic waste management strategies: an Italian case study. *Journal of Cleaner Production 89*, 125-136. `https://doi.org/10.1016/j.jclepro.2014.11.012`

Caicedo-Concha, D.M., Sandoval-Cobo, J., Stringfellow, A. and Colmenares-Quintero, R. (2021). An evaluation of final disposal alternatives for municipal solid waste through life cycle assessment: A case of study in Colombia. *Cogent Engineering 8*, 1-17. `https://doi.org/10.1080/23311916.2021.1956860`

Çetinkaya, A.Y., Bilgili, L. and Kuzu, S.L. (2018). Life cycle assessment and greenhouse gas emission evaluation from Aksaray solid waste disposal facility. *Air Quality, Atmosphere & Health 11*, 549-558. `https://doi.org/10.1007/s11869-018-0559-3`

Cheela, V.R.S., John, M., Biswas, W.K. and Dubey, B. (2021). Environmental impact evaluation of current municipal solid waste treatments in India using life cycle assessment. *Energies 14*(11), 1-23. `https://doi.org/10.3390/en14113133`

Chhabra, V., Shastri, Y. and Bhattacharya, S. (2020). Laboratory-scale performance of pyrolysis of unsegregated municipal solid waste. *Industrial & Engineering Chemistry Research 60*(3), 1473-1482. `https://dx.doi.org/10.1021/acs.iecr.0c04746`

Chiu, S. and Lo, I. (2016). Reviewing the anaerobic digestion and co-digestion process of food waste from the perspectives on biogas production performance and environmental impacts. *Environmental Science and Pollution Research 23*, 24435-24450. https://doi.org/10.1007/s11356-016-7159-2

Cleary, J. (2009). Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environment International 35*, 1256-1266. https://doi.org/10.1016/j.envint.2009.07.009

Cohen, B. (2017). Modelling approaches for greenhouse gas emissions projections from the waste sector. *Sustainable Production and Consumption 10*, 15-20. https://doi.org/10.1016/j.spc.2016.12.002

Correal, M. and Rihm, A. (2022). *Hacia la valorización de residuos sólidos en América Latina y el Caribe. Conceptos básicos, análisis de viabilidad y recomendaciones de políticas públicas*, first ed. Banco Interamericano de Desarrollo, Washington DC, USA. http://dx.doi.org/10.18235/0003971

Corvalán, C., Espinoza, A., Díaz-Robles, L.A., Cubillos, F., Vallejo, F., Gómez, J. and Pino-Cortés, E. (2021). Life cycle assessment for hydrothermal carbonization of urban organic solid waste in comparison with gasification process: A case study of Southern Chile. *Environmental Progress and Sustainable Energy 40*, 17032-17050. https://doi.org/10.1002/ep.13688

Cossu, R., Stegmann, R. (2018). *Solid Waste Landfilling: Concepts, Processes, Technologies*. Elsevier, Oxford, UK.

Dastjerdi, B., Strezov, V., Kumar, R., He, J., and Behnia, M. (2021). Comparative life cycle assessment of system solution scenarios for residual municipal solid waste management in NSW, Australia. *Science of The Total Environment 767*, 1-12. https://doi.org/10.1016/j.scitotenv.2020.144355

De Feo, G., Ferrara, C., Iuliano, C. and Grosso, A. (2016). LCA of the collection, transportation, treatment, and disposal of source separated municipal waste: A Southern Italy case study. *Sustainability 8*(11), 1-13. https://doi.org/10.3390/su8111084

De Morais Lima, P., Colvero, D.A., Gomes, A.P., Wenzel, H., Schalch, V. and Cimpan, C. (2018). Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. *Waste Management 78*, 857-870. https://doi.org/10.1016/j.wasman.2018.07.007

Demetrious, A. and Crossin, E. (2019). Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis. *Journal of Material Cycles and Waste Management 21*, 850-860. https://doi.org/10.1007/s10163-019-00842-4

Ding, Y., Zhao, J., Liu, J.W., Zhou, J., Cheng, L., Zhao, J., Shao, Z., Iris, Ç., Pan, B., Li, X. and Hu, Z.T. (2021). A review of China's municipal solid waste (MSW) and comparison with international regions: Management and technologies in treatment and resource utilization. *Journal of Cleaner Production 293*, 126-144. https://doi.org/10.1016/j.jclepro.2021.126144

Edwards, J., Othman, M., Crossin, E. and Burn, S. (2018). Life cycle assessment to compare the environmental impact of seven contemporary food waste management systems. *Bioresource Technology 248*, 156-173. https://doi.org/10.1016/j.biortech.2017.06.070

EPA (2020). Advancing Sustainable Materials Management: 2018 Fact Sheet. United States Environmental Protection Agency. Available at: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management. Accessed: March 30, 2022.

Espinosa-Salgado, R., Saucedo-Castañeda, G., and Monroy-Hermosillo, O. (2020). Composting a digestate from the organic fraction of urban solid wastes. *Revista Mexicana de Ingeniería Química 19*(1), 1-8. https://doi.org/10.24275/rmiq/IA1236

Estrada-Martínez, R., Carrillo-Sancen, G., Cerón-Montes, G., Garrido-Hernández, A., and Martínez-Valdez, F. (2021). Mathematical modeling for monitoring and controlling aerobic degradation conditions of the organic fraction of urban solid waste. *Revista Mexicana de Ingeniería Química 20*(3), 1-11. https://doi.org/10.24275/rmiq/IA2479

Ferronato, N., Gorritty Portillo, M.A., Guisbert Lizarazu, E.G. and Torretta, V. (2020). Application of a life cycle assessment for assessing municipal solid waste management systems in Bolivia in an international cooperative framework. *Waste Management & Research 38*, 98-116. https://doi.org/10.1177/0734242X20906250

Fiorentino, G., Ripa, M., Protano, G., Hornsby, C. and Ulgiati, S. (2015). Life cycle assessment of mixed municipal solid waste: Multi-input versus multi-output perspective. *Waste Management 46*, 599-611. http://dx.doi.org/10.1016/j.wasman.2015.07.048

Garmendia, A., Salvador, A., Crespo, C. and Garmendia, L. (2005). *Evaluación de Impacto Ambiental*. Pearson, Madrid, Spain.

Grzesik, K. and Malinowski, M. (2017). Life cycle assessment of mechanical-biological treatment of mixed municipal waste. *Environmental Engineering Science 34*(3), 207-220. https://doi.org/10.1089/ees.2016.0284

Güereca, L.P., Torres, N. and Juárez-López, C.R. (2015). The co-processing of municipal waste in a cement kiln in Mexico. A life-cycle assessment approach. *Journal of Cleaner Production 107*, 741-748. https://doi.org/10.1016/j.jclepro.2015.05.085

Hadzic, A., Voca, N. and Golubic, S. (2018). Life-cycle assessment of solid-waste management in city of Zagreb, Croatia. *Journal of Material Cycles and Waste Management 20*, 1286-1298. https://doi.org/10.1007/s10163-017-0693-2

Haupt, M., Kägi, T. and Hellweg, S. (2018). Modular life cycle assessment of municipal solid waste management. *Waste Management 79*, 815-827. https://doi.org/10.1016/j.wasman.2018.03.035

Havukainen, J., Zhan, M., Dong, J., Liikanen, M., Deviatkin, I., Li, X. and Horttanainen, M. (2017). Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou, China. *Journal of Cleaner Production 141*, 453-461. http://dx.doi.org/10.1016/j.jclepro.2016.09.146

Huang, J., Zhao, R., Huang, T., Wang, X. and Tseng, M.L. (2018). Sustainable municipal solid waste disposal in the belt and road initiative: A preliminary proposal for Chengdu City. *Sustainability 10*(4), 1-15. https://doi.org/10.3390/su10041147

Iqbal, A., Liua, X. and Chen, G. (2020). Municipal solid waste: Review of best practices in application of life cycle assessment and sustainable management techniques. *Science of The Total Environment 729*, 1-13. https://doi.org/10.1016/j.scitotenv.2020.138622

Iqbal, A. Z., Liu, X., and Chen, G. (2019). Integrated municipal solid waste management scheme of Hong Kong: A comprehensive analysis in terms of global warming potential and energy use. *Journal of Cleaner Production 225*, 1079-1088. https://doi.org/10.1016/j.jclepro.2019.04.034

ISO. (2006a). ISO 14040:2006 Environmental Management-Life Cycle Assessment-Principles and Framework. International Organization for Standardization.

ISO. (2006b). ISO 14044:2006 Environmental Management-Life Cycle Assessment-Requirements and Guidelines. International Organization for Standardization.

Istrate, I., Galvez-Martos, J., and Dufour, J. (2021). The impact of incineration phase-out on municipal solid waste landfilling and life cycle environmental performance: Case study of Madrid, Spain. *Science of The Total Environment 755*, 1-13. https://doi.org/10.1016/j.scitotenv.2020.142537

Jensen, M.B., Møller, J. and Scheutz, C. (2016). Comparison of the organic waste management systems in the Danish-German border region using life cycle assessment (LCA). *Waste Management 49*, 491-504. http://dx.doi.org/10.1016/j.wasman.2016.01.035

Jeswani, H.K. and Azapagic, A. (2016). Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. *Waste Management 50*, 346-363. http://dx.doi.org/10.1016/j.wasman.2016.02.010

Kaza, S., Yao, L., Bhada-Tata, P. and Woerden, F.V. (2018). *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, first ed. The World Bank Group, Washington, Washington DC, USA. https://doi.org/10.1596/978-1-4648-1329-0

Khandelwal, H., Dhar, H., Thalla, A.K. and Kumar, S. (2019a). Application of life cycle assessment in municipal solid waste management: A worldwide critical review. *Journal of Cleaner Production 209*, 630-654. https://doi.org/10.1016/j.jclepro.2018.10.233

Khandelwal, H., Thalla, A.K., Kumar, S. and Kumar, R. (2019b). Life cycle assessment of municipal solid waste management options for India. *Bioresource Technology 288*, 1-7. https://doi.org/10.1016/j.biortech.2019.121515

Kirkpatrick, N. (1993). Selecting a waste management option using a life-cycle analysis approach. *Packaging Technology and Science 6*, 159-172. https://doi.org/10.1002/pts.2770060308

Kumar, S. (2016). *Municipal Solid Waste Management in Developing Countries*, first ed. CRC Press, Boca Raton, Florida, USA. https://doi.org/10.1201/9781315369457

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z. and Christensen, T.H. (2014). Review of LCA studies of solid waste management systems - Part II: Methodological guidance for a better practice. *Waste Management 34*, 589-606. http://dx.doi.org/10.1016/j.wasman.2013.12.004

Life Cycle Initiative. (2023). Life Cycle Initiative. Life Cycle Networks. Available at: https://www.lifecycleinitiative.org/networks/life-cycle-networks/#1675120212985-49257530-fef3. Accessed: March 1, 2022.

Liu, M., Tan, Z., Fan, X. and Chang, Y. (2021). Application of life cycle assessment for municipal solid waste management options in Hohhot, People's Republic of China. *Waste Management and Research 39*, 63-72. https://doi.org/10.1177/0734242X20959709

Maalouf, A. and El-Fadel, M. (2019). Life cycle assessment for solid waste management in Lebanon: Economic implications of carbon credit. *Waste Management & Research 37*, 14-26, https://doi.org/10.1177/0734242X18815951

Mannheim, V. (2022). Comparison of end-of-life scenarios of municipal solid waste from viewpoint of life cycle assessment. *Frontiers in Built Environment 8*, 1-7. https://doi.org/10.3389/fbuil.2022.991589

Margallo, M., Ziegler-Rodriguez, K., Vázquez-Rowe, I., Aldaco, R., Irabien, A. and Kahhat, R. (2019). Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: A review for policy support. *Science of The Total Environment 689*, 1255-1275. https://doi.org/10.1016/j.scitotenv.2019.06.393

Mehr, J., Haupt, M., Skutan, S., Morf, L., Adrianto, L., Weibel, G. and Hellweg, S. (2021). The environmental performance of enhanced metal recovery from dry municipal solid waste incineration bottom ash. *Waste Management 119*, 330-341. https://doi.org/10.1016/j.wasman.2020.09.001

Nanda, S. and Berruti, F. (2021). Municipal solid waste management and landfilling technologies: a review. *Environmental Chemistry Letters 19*, 1433-1456. https://doi.org/10.1007/s10311-020-01100-y

NU. (2018). Naciones Unidas, La Agenda 2030 y los Objetivos de Desarrollo Sostenible: una oportunidad para América Latina y el Caribe. Available at: https://repositorio.cepal.org/server/api/core/bitstreams/cb30a4de-7d87-4e79-8e7a-ad5279038718/content. Accessed November 1, 2023

ONU. (2021). Agenda 2030 sobre el Desarrollo Sostenible: Cambio Climatico. Available at: https://www.un.org/sustainabledevelopment/es/climate-change-2/. Accessed March 1, 2022

Ouedraogo, A., Frazier, R., and Kumar, A. (2021). Comparative life cycle assessment of gasification and landfilling for disposal of municipal solid wastes. *Energies 14*, 1-15. https://doi.org/10.3390/en14217032

Parkes, O., Lettieri, P. and Bogle, I.D.L. (2015). Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park. *Waste Management 40*, 157-166. https://doi.org/10.1016/j.wasman.2015.03.017

Popiţa, G., Baciu, C., Rédey, A., Frunzeti, N., Ionescu, A., Yuzhakova, T. and Popovici, A. (2017). Life cycle assessment (LCA) of municipal solid waste management systems in cluj county, Romania. *Environmental Engineering and Management Journal 16*(1), 47-57. https://doi.org/10.30638/eemj.2017.006

Raharjo, S., Junaidi, N.E., Bachtiar, V.S., Ruslinda, Y., Rachman, I. and Matsumoto, T. (2016). Development of community-based waste recycling (garbage bank and 3R waste treatment facility) for mitigating greenhouse gas emissions in Padang City, INDONESIA. Management and Innovation Technology International Conference (MITicon). MIT-8-MIT-12. https://doi.org/10.1109/MITICON.2016.8025259

Rajaeifar, M.A., Tabatabaei, M., Ghanavati, H., Khoshnevisan, B. and Rafiee, S. (2015). Comparative life cycle assessment of different municipal solid waste management scenarios in Iran. *Renewable and Sustainable Energy Reviews 51*, 886-898. `http://dx.doi.org/10.1016/j.rser.2015.06.037`

Rajcoomar, A. and Ramjeawon, T. (2017). Life cycle assessment of municipal solid waste management scenarios on the small island of Mauritius. *Waste Management and Research 35*(3), 313-324. `https://doi.org/10.1177/0734242X16679883`

Rana, R., Ganguly, R. and Gupta, A.K. (2019). Life-cycle assessment of municipal solid-waste management strategies in Tricity region of India. *Journal of Material Cycles and Waste Management 21*, 606-623. `https://doi.org/10.1007/s10163-018-00822-0`

Ripa, M., Fiorentino, G., Vacca, V. and Ulgiati, S. (2017). The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). *Journal of Cleaner Production 142*, 445-460. `https://doi.org/10.1016/j.jclepro.2016.09.149`

Romero-Hernández, O., Romero Hernández, S., Muñoz, D., Detta-Silveira, E., Palacios-Brun, A. and Laguna, A. (2009). Environmental implications and market analysis of soft drink packaging systems in Mexico. A waste management approach. *The International Journal of Life Cycle Assessment 14*, 107-113. `https://doi.org/10.1007/s11367-008-0053-5`

Rueda-Avellaneda, J., Gomez-Gonzalez, R., Rivas-García, P., Benitez-Bravo, R., Botello-Álvarez, J., and Wang, Z. (2023). Application of a sustainable location index approach to landfill site selection in Monterrey, Mexico. *Waste Management & Research 41*(5), 1014-1025. `https://doi.org/10.1177/0734242X221138733`

Sauve, G. and Van Acker, K. (2020). The environmental impacts of municipal solid waste landfills in Europe: A life cycle assessment of proper reference cases to support decision making. *Journal of Environmental Management 261*, 1-12. `https://doi.org/10.1016/j.jenvman.2020.110216`

Schaubroeck, T., Schaubroeck, S., Heijungs, R., Zamagni, A., Brandão, M., and Benetto, E. (2021). Attributional & consequential life cycle assessment: Definitions, conceptual characteristics and modelling restrictions. *Sustainability 13*, 1-47. `https://doi.org/10.3390/su13137386`

SEMARNAT (2019). Informe del Medio Ambiente en México 2018. Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT). Available at: `https://apps1.semarnat.gob.mx:8443/dgeia/informe18/tema/cap7.html#tema1` Accessed February 5, 2022.

Sharma, B.K. and Chandel, M.K. (2017). Life cycle assessment of potential municipal solid waste management strategies for Mumbai, India. *Waste Management and Research 35*(1), 79-91. `https://doi.org/10.1177/0734242X16675683`

Sharma, K.D. and Jain, S. (2020). Municipal solid waste generation, composition, and management: the global scenario. *Social Responsibility Journal 16*(6), 917-948. `https://doi.org/10.1108/SRJ-06-2019-0210`

Siddiqua, A., Hahladakis, J.N. and Al-Attiya, W.A.K.A. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. *Environmental Science and Pollution Research 29*, 58514-58536. `https://doi.org/10.1007/s11356-022-21578-z`

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R.M. and Azapagic, A. (2019). Environmental and economic implications of recovering resources from food waste in a circular economy. *Science of the Total Environment 693*, 1-18. `https://doi.org/10.1016/j.scitotenv.2019.07.322`

Starostina, V., Damgaard, A., Eriksen, M., and Christensen, T. (2018). Waste management in the Irkutsk region, Siberia, Russia: An environmental assessment of alternative development scenarios. *Waste Management & Research 36*(4), 373-385. `https://doi.org/10.1177/0734242X18757627`

Suryawan, I.W.K., Rahman, A., Septiariva, I.Y., Suhardono, S. and Wijaya, I.M.W. (2021). Life cycle assessment of solid waste generation during and before pandemic of Covid-19 in Bali province. *Journal of Sustainability Science and Management 16*(1), 11-21. `http://doi.org/10.46754/jssm.2021.01.002`

Tagliaferri, C., Evangelisti, S., Clift, R., Lettieri, P., Chapman, C. and Taylor, R. (2016). Life cycle assessment of conventional and advanced two-stage energy-from-waste technologies for methane production. *Journal of Cleaner Production 129*, 144-158. `https://doi.org/10.1016/j.jclepro.2016.04.092`

Villanueva, A. and Wenzel, H. (2007). Paper waste - Recycling, incineration or landfilling? A review of existing life cycle assessments. *Waste Management 27*, S29-S46. `https://doi.org/10.1016/j.wasman.2007.02.019`

Wang, Z., Jingxiang, L., Gu, F., Yang, J. and Guo, J. (2020). Environmental and economic performance of an integrated municipal solid waste treatment: A Chinese case study. *Science of the Total Environment 709*, 1-16. `https://doi.org/10.1016/j.scitotenv.2019.136096`

Weligama Thuppahige, R. and Babel, S. (2022). Environmental impact assessment of organic fraction of municipal solid waste treatment by anaerobic digestion in Sri Lanka. *Waste Management & Research 40*, 236-243. `https://doi.org/10.1177/0734242X211013405`

World Bank. (2010). How does the World Bank classify countries? (The World Bank Group). Available at: `https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries` Accessed May 1, 2023.

Xu, C., Shi, W., Hong, J., Zhang, F. and Chen, W. (2015). Life cycle assessment of food waste-based biogas generation. *Renewable and Sustainable Energy Reviews 49*, 169-177. `http://dx.doi.org/10.1016/j.rser.2015.04.164`

Yadav, P. and Samadder, S.R. (2018). Environmental impact assessment of municipal solid waste management options using life cycle assessment: a case study. *Environmental Science and Pollution Research 25*, 838-854. `https://doi.org/10.1007/s11356-017-0439-7`

Yay, A. (2015). Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. *Journal of Cleaner Production 94*, 284-293. `https://doi.org/10.1016/j.jclepro.2015.01.089`

Zaman, C.Z., Pal, K., Yehye, W.A., Suresh Sagadevan, S., Shah, S.T., Adebisi, G.A., Emy Marliana, E., Rafique, R.F. and Johan, R.B. (2017). Pyrolysis: A Sustainable Way to Generate Energy from Waste. *IntechOpen*, 3-36. `https://doi.org/10.5772/intechopen.69036`

Zarea, M.A., Moazed, H., Ahmadmoazzam, M., Malekghasemi, S. and Jaafarzadeh, N. (2019). Life cycle assessment for municipal solid waste management: a case study from Ahvaz, Iran. *Environmental Monitoring and Assessment 191*(131), 1-13. `https://doi.org/10.1007/s10661-019-7273-y`

Zhou, Z., Tang, Y., Dong, J., Chi, Y., Ni, M., Li, N. and Zhang, Y. (2018). Environmental performance evolution of municipal solid waste management by life cycle assessment in Hangzhou, China. *Journal of Environmental Management 227*, 23-33. `https://doi.org/10.1016/j.jenvman.2018.08.083`

Ziegler-Rodriguez, K., Margallo, M., Aldaco, R., Vázquez-Rowe, I. and Kahhat, R. (2019). Transitioning from open dumpsters to landfilling in Peru: Environmental benefits and challenges from a life-cycle perspective. *Journal of Cleaner Production 229*, 989-1003. `https://doi.org/10.1016/j.jclepro.2019.05.015`