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Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: a review for policy support

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Abstract

Waste remains a serious environmental and human health hazard in developing nations, including those in Latin America and the Caribbean (LAC). Despite important breakthroughs in waste management in LA&C, the region still faces many challenges that require special attention, such as the existence of uncontrolled open dumpsters (33%) or the low recovery rates of certain waste fractions (below 4%). Moreover, the adoption of sophisticated waste management technologies, such as incineration or anaerobic digestion, is still lagging. This review paper provides environmentally-sound and relevant policy support for municipal solid waste management stakeholders through a critical review of the current situation of the waste management sector in LA&C from an environmental perspective. Thereafter, Life Cycle Assessment (LCA) bibliography linked to waste management, namely collection, sorting, recycling and landfilling applications and technologies worldwide, is used in order to understand potential alternative waste management strategies in LA&C, as well as the potential environmental benefits that could be attained. Finally, based on the holistic review and analysis, the adoption of more sophisticated technologies in landfill sites (e.g. landfill

gas flaring), waste-to-energy, as well as higher recycling rates, would enhance waste management in the region and mitigate environmental impacts. A holistic view to support policy formulations, including climate action, for the adoption of integrated waste management strategies in LA&C is imperative.

Keywords: industrial ecology; landfill; Life Cycle Assessment; municipal solid waste; waste management.

1. Introduction

The waste management sector has evolved from careless disposition to integrated – and sophisticated – systems throughout human history. In fact, it is a sector that has gained importance in the past few decades given the ever-growing amounts of residues that are being generated by human communities due to higher consumption rates and demographic growth (Turcott Cervantes et al., 2018; Dlamini et al., 2019; Khandelwal et al., 2019). Waste, as defined by several environmental protection agencies worldwide, is considered to be any discarded or unwanted material, regardless of whether they are considered to be recoverable by a separate operation from that which produced the matter or not (European Commission, 2019; USEPA, 2019).

Currently, trends in the waste management sector are being aimed at attaining what is known as a circular economy, especially in the European Union with its Circular Economy package (European Commission, 2015) and in China with its Circular Economy Promotion Law (Geissdoerfer et al., 2016). Circular economy focuses on boosting reuse and reducing landfilling, in order to make the most out of the already exploited resources and expand their life span (Ghisellini et al., 2016; Ragazzi et al., 2017; Cobo et al., 2018). In contrast, the situation in developing and emerging economies is substantially different. While developed countries seek more integrated

and sustainable waste management systems (Laurent et al., 2014a), emerging nations are still basically struggling to switch from the disposal of residues, including those of urban origin, in open dumpsites to disposing of them in controlled landfills (Guerrero et al., 2013; Marshall and Farahbakhsh, 2013; Ferronato et al., 2017, 2019). This is of particular interest considering that these countries are currently experiencing high urban population growth and sustained economic expansion, leading to higher rates of municipal solid waste (MSW) generation (Hoornweg and Bhada-Tata, 2012). Even though landfilling has a higher overall environmental impact than other MSW treatment alternatives, such as recycling or incineration (Laurent et al., 2014a), in developing countries it is still the backbone of MSW management. This is due to the fact that landfilling is a cheap and well-known technology, with lower environmental, economic and social impacts when compared to uncontrolled dumpsters (Manfredi and Christensen, 2009; Guerrero et al., 2013).

With this in mind, it is fundamental that stakeholders in the waste management sector are aware of the implications of landfilling, as well as the associated benefits linked to implementing good practices in the sector, in order to improve the sector's efficiency and its environmental profile. In fact, Guerrero et al. (2013) identified the challenges that more than 30 cities are addressing in 22 developing countries throughout 4 continents and concluded that municipal action must be coordinated with stakeholders, national governments and educational institutions in order to improve the existing precarious situation of waste disposal.

In the particular case of Latin America and the Caribbean (LAC), for instance, the situation appears to be relatively homogeneous, with most countries struggling to eradicate dumpsters, while shifting to landfilling technologies. A considerable percentage of residues are disposed of in "Sanitary Landfills" or "Controlled Landfills".

However, waste disposition in open dumpsites remains high throughout the region. Regardless of the environmental issues related to inadequate disposition, this sector is a significant contributor to greenhouse gas (GHG) emissions and, therefore, critical in complying with the related climate change commitments of LA&C countries (Vazquez-Rowe et al., 2019). It appears evident that if these compromises are met, this will have been accomplished with a formalization of the waste management sector and an improvement of final disposition technologies.

Taking into consideration demographic sprawl, improving living standards and environmental concerns, it seems clear that waste management is a critical sector to focus on in developing countries. Hence, regardless of the economic and social pillars intrinsic to waste management, it is imperative for the waste management sector to be studied and improved from an environmental perspective with adequate and holistic proposals. It is in this setting that Life Cycle Assessment (LCA), an internationally standardized methodology to identify environmental impacts and hotspots in products or services (Hellweg and Milà i Canals, 2014), gains relevance as a decision support tool. In fact, throughout the past 25 years LCA has earned importance to such an extent that it has become a critical tool for decision- and policy-making in developed countries (i.e., the European Union, Japan, etc.) (Manfredi et al., 2010a). Moreover, waste management LCA has become a more specific and specialized research area as the distinct treatment methods to address it may have different benefits and disadvantages depending on the environmental burdens that are being evaluated (Christensen et al., 2007; Gentil et al., 2010; Starostina et al., 2014). For instance, depending on the plant and treatment characteristics, plastic incineration can be more beneficial than recycling, but recycling paper and cardboard is usually a better option than incineration (Merrild et al., 2012). Understanding the trade-offs in terms of environmental impacts and waste

technologies is becoming a priority matter in many areas of the world. In fact, an increasing number of countries are venturing into more integrated and sustainable solid waste management systems with lower environmental impacts (Hannan et al., 2015; Zhao et al., 2017; Yadav et al., 2018). However, this is not the case yet in LA&C, where rapid urban growth has neutralized the timid efforts to reduce risks to human health and the environment (Medina, 2010).

In this context, the main objective of this study is to provide environmentally-sound and relevant policy support for waste management stakeholders through a critical review of the current situation of the MSW management sector in LA&C from an environmental perspective. Thereafter, LCA bibliography linked to waste management, namely collection, sorting, recycling and landfilling applications and technologies worldwide, is used in order to understand potential alternative waste management strategies in LA&C, as well as the potential environmental benefits that could be attained. As far as the authors were able to ascertain, there is a lack of critical review of the waste management sector in LA&C. In this context, the main novelty of the current review is to provide a holistic assessment of waste management in the region, including current trends and environmental challenges. The paper is structured in two main parts. On the one hand, Section 2 describes the current situation of MSW in LA&C. On the other hand, Section 3 introduces the environmental impact considerations in MSW management. In particular, the first part includes a full discussion of the generation (2.1) and characterization of MSW (2.2), as well as the main management practices LA&C (2.3), i.e., waste collection, sorting and recycling (2.3.1), and landfilling (2.3.2). Section 3 reviews the LCA studies regarding MSW landfilling in order to determine environmental performance and expected improvement measures. The review ends with an analysis of the future challenges in the sector in LA&C.

2. Current situation of municipal solid waste in Latin America and the Caribbean

2.1 Generation of Municipal Solid Waste

Global MSW generation levels reached in 2012 approximately 1.3 billion metric tons, and were expected to increase to approximately 2.2 billion metric tons by 2025 (Hoornweg and Bhada-Tata, 2012). These projections seem to be underestimated, since in 2016, MSW generation reached 2.0 billion metric tons, and in 2050 this number could grow to 3.4 billion metric tons (Hoornweg and Bhada-Tata, 2012). This represents a generation rate of 0.74 kg per person and day in 2016. However, this global generation rate ranges widely, from 0.11 to 4.54 kilograms kg per person and day (Kaza et al., 2018). Although waste generation varies as a function of affluence, local, regional and country variations can be significant (Hoornweg and Bhada-Tata, 2012). These variations reflect differences in consumption patterns and economic wealth, as well as municipal waste collection and management strategies (Margallo, 2014).

According to Khan et al. (2016), several authors have conducted research to establish the relationship between waste generation, their composition and socio-economic factors. Different socio-economic indicators per capita are often cited to illustrate these relationships: i) gross domestic product (GDP); ii) gross national income (GNI), which includes the GDP and the net income received from overseas; and, iii) the human development index (HDI), which states that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone (UNDP, 2017). The use of these indicators has allowed finding a direct relationship between solid waste generation and income level. In this sense, upper-income countries and urban areas with a high consumption rate of manufactured products generally have higher waste generation rates than low income countries and rural communities (Mohee et al., 2015; Kawani and Tasaki, 2016). In fact, Rajaeifar and

colleagues (2017) point out that there is a direct relation between MSW generation and GDP per capita. This can be observed on a temporal scale, since the amount of solid waste has grown steadily coupled to increases in GDP over recent decades (Sjöström and Östblom, 2010).

Nevertheless, other authors have found that the correlation between waste and GDP is not necessarily as strong as initially believed. MSW generation per capita may not always increase in line with the economic growth of a country (Kawani and Tasaki, 2016), with GDP increases at a faster pace than waste generation (Hernández-Berriel et al., 2016). In this context, these authors defend that policies should aim at achieving full decoupling, where waste generation rates tend to stabilize or decrease, while GDP still increases (Sjöström and Östblom, 2010).

Moreover, within a country, province or district, differences in waste generation are related not only to income level, but also to other important variables, such as number people living in a same household (Dennison et al. 1996), educational attainment or occupation, among others (Khan et al., 2016). For instance, the research by Ojeda-Benítez and colleagues (2008) evaluated the influence of household socio-economic profile on solid waste generation and characterization. Results showed that family typology and socio-economic stratum had a great influence in waste generation, whereas no significant differences existed in terms of general waste characterization.

In addition, beyond socio-economic aspects, climatic, geographical and cultural conditions, the existence of waste planning systems, dietary patterns and the quality of supplied goods and food products are important factors in waste generation and composition (Taghipour et al., 2016).

Figure 1 shows the waste generation rate per capita in several regions of the world. Data from developing countries, and in particular for LA&C, where the current

review is focused, were generally difficult to obtain and open data sources were limited. As a result, the reliability and timeliness of data cannot be guaranteed for all emerging and developing countries (Kawani and Tasaki, 2016; Massukado et al., 2012).

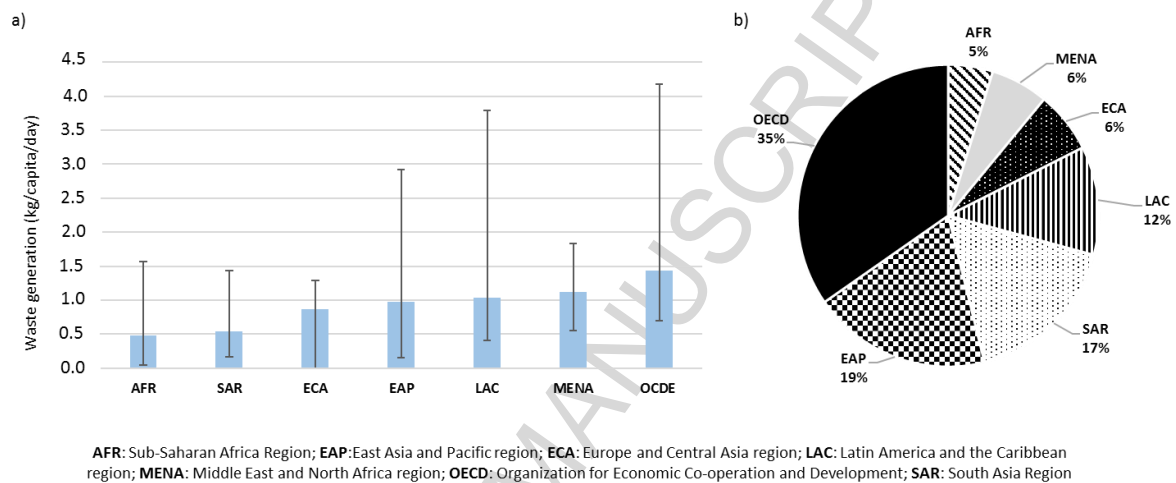


Figure 1. a) Waste generation per person per day by region taking into account the lower and upper boundaries; and, b) contribution of each region to the total worldwide waste generation (Hoornweg and Bhada-Tata, 2012; Kaza et al. 2018; OECD, 2018; EUROSTAT, 2017, Acurio et al., 1997; Aguilar-Virgen et al., 2010, 2013, 2014a, 2014b; Bezama et al., 2013; Duran et al., 2013; Hernandez- Berriel et al., 2016; Massukado et al., 2012; Mohee et al., 2015; Moreira and Cardiani, 2016; Valencia-Vázquez et al., 2014). *Sub-Saharan Africa (AFR), East Asia and the Pacific region (EAP), Europe and Central Asia region (ECA), Latin American and the Caribbean (LAC), Middle East and North Africa (MENA), Organization for Economic Co-operation and Development countries (OECD) and South Asia Region (SAR).*

Countries belonging to the Organization for Economic Co-operation and Development (OECD) are responsible for ca. 35% of the world's waste. In 2016, 673 Mt of MSW were generated in these countries with an average rate of 1.43 kg/capita/day (OECD, 2018). Highest waste generation rates in the region were observed in countries with a high GNI, such as Australia, Canada, Denmark, or the United States. The extremely high variation of ranges from 0.87 to 4.35 kg/capita/day is attributable to a variety of factors, including the heterogeneous rate of development in these nations and different rates of urban sprawl. Although the Middle East and North Africa (MENA) is one the regions with lowest MSW generation in absolute values, it has the second highest waste generation rate per person and day, with an average value of 1.12 kg/capita/day, ranging from 0.55 to 1.83 kg/capita/day.

In contrast, Sub-Saharan Africa (AFR) is the region with the lowest generation rate, representing 6% of global waste (Hoornweg and Bhada-Tata, 2012), with an average rate of 0.47 kg/capita/day. South Asia (SAR) shows similar trends (0.54 kg/capita/day), with a waste generation rate per person and day that ranges from 0.17 to 1.44 kg/capita/day. However, this region represents around 17% of global waste generation due to the contribution of India (84%), and to a lesser extent, Pakistan (9%).

An intermediate group of regions, with generation rates ranging from 0.87 to 1.04 kg/capita/day, includes East Asia and the Pacific (EAP), Europe and Central Asia (ECA), and LA&C. These results are consistent with the premises discussed above: higher income and development levels are correlated with higher waste generation rates. Of all these intermediate regions, EAP and LA&C nations represent the highest proportion of global waste, ca. 19% and 12%, respectively (see Figure 1b).

When comparing waste generation per capita for OECD and LA&C countries data shows that, on average, OECD countries have higher waste generation rates

however the dispersion within countries in the same regions have similar trends to those in LA&C. In fact, the dispersion of the average rate in LA&C is very high, ranging from 0.41 to 3.79 kg/capita/day (Hoornweg and Bhada-Tata, 2012). Nevertheless, these values should be interpreted with care, given the fact that most LA&C countries do not have integral waste generation studies. Hence, waste generation per capita is determined, in many cases, in waste transfer plants or disposal sites. This procedure implies an important source of uncertainty, since the amount of waste generated and waste treated is not always the same. The rationale behind this discrepancy in LA&C nations is linked to the amount of waste that is segregated and recovered by informal recycling workers, which, according to some estimates, could be as high as 5% of the waste weighted in transfer and disposal plants. In addition, small cities and towns in LA&C lack scales in transfer and disposal plants, augmenting further the difficulty to determine accurate national waste generation rates (Tello et al. 2010).

In line with worldwide trends, Figure 2 shows that high income (HI) and upper-middle income (UMI) LA&C countries produce the highest amount of MSW per capita, whereas low income (LI) and low-middle income (LMI) countries (e.g., Haiti, Bolivia, Guatemala and Honduras) present the lowest generation rates. However, the exponential correlation between income level and waste generation is relatively low ($r^2=0.53$), suggesting that MSW does not increase at the same pace as economic growth.

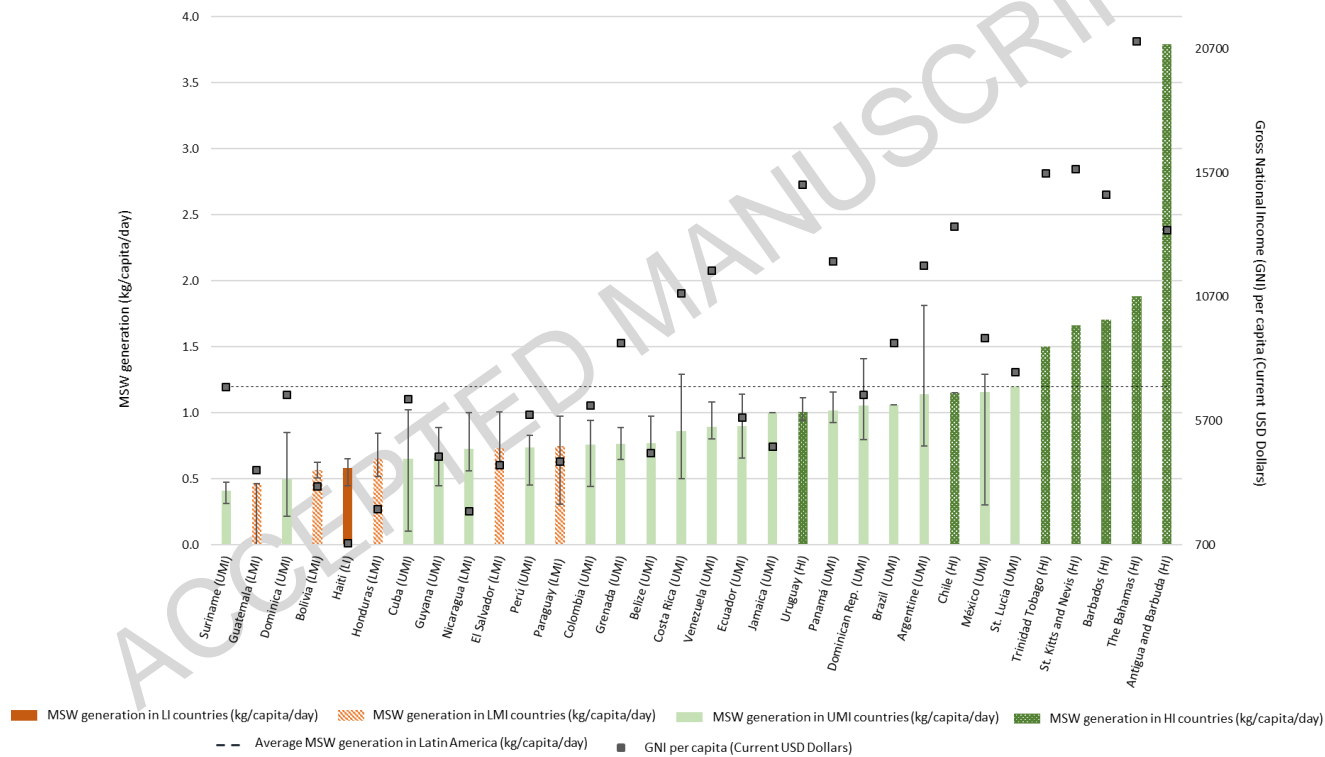


Figure 2. Waste generation per person per day and GNI in Latin American and the Caribbean nations. HI: high income countries; UMI: upper-middle income level countries; LMI: low-income level countries; LI: low income level countries (Hernandez- Berriel et al., 2016; Hoornweg and Bhada-Tata, 2012; IDB, 1998; Kaza et al. 2018; Kawani and Tasaki 2016; Tello et al. 2010; UNWTO, 2018; WB, 2018).

The generation rate of MSW in several member states of the Commonwealth of Nations in the region was found to be remarkably high. In fact, 6 of these countries (all of them islands) are in the top 10 countries in terms of waste generation per capita in LA&C. Mohee and colleagues (2015) state that Caribbean Islands possess higher generation rates as compared to other small island developing states (i.e., Pacific, Atlantic, Indian Ocean, Mediterranean and South China) due to the higher standards of livings and economic growth. However, we hypothesize that the tourism industry accounts for an important portion of the very high waste rates identified in some of these nations for a number of reasons. On the one hand, many of these islands absorb high volumes of waste that are disposed of by cruise ships. In fact, recent research studies have determined at which ports cruise ships should dispose of the waste generated onboard to minimize economic costs (Wang et al., 2018). On the other hand, when the data on waste are crossed with that of the World Tourism Organization (UNWTO, 2018), there is a high correlation between island states with a daily per capita MSW generation rate above 1.71 kg (i.e., Antigua and Barbuda, The Bahamas or Barbados) and receiving over 1.8 annual overseas visitors per resident (see Figure S2 in the SM). Considering that most of these islands are small in territory, but heavily populated, they face important waste management challenges in the near future.

2.2 Municipal Solid Waste Characterization

The determination of waste composition is essential in the development of adequate waste management strategies, since the proportion of different waste fractions will determine waste collection protocols and waste treatment technologies that should be used in each particular case (Powell and Chertow, 2018). Unfortunately, however, high quality and consistent data are in many cases hard to retrieve (Hernandez- Berriel et al., 2016). For the purpose of the current study, MSW is broadly classified into

organic and inorganic. Moreover, inorganic residues were subdivided in the following flows: cardboard and paper, plastic, glass, metals and other and inert materials (see Table S1 in the SM). It is important to note, however, that hazardous waste generated in the residential, commercial, institutional and industrial sectors (excluding waste generated to the industrial process) is usually included in the MSW classification. Hazardous waste separation at landfill facilities is not common but has been reported in some cases (Joel Inga, Municipality of Loreto-Nauta, personal communication, May 2017).

According to Hoornweg and Bhada-Tata (2012), the composition of average global waste consists mainly of organic fraction (51%), followed by paper (14.1%), plastic (10.4%), glass (4.10%) and metals (3.3%). Other undefined materials account for ca. 17% of the total volume (see Table 1). The most up-to-date data estimate that currently the amount of organic matter and other materials has dwindled slightly to 44%, whereas the amount of inorganic fractions has increased: paper (17%), plastic (12%), glass (5%) and metals (4%) and other and inert materials (18%). However, huge differences depending on geographical location, climate energy source and income level are noticeable, as shown in Table 1 and Figure S1 in the SM (Hoornweg and Bhada-Tata, 2012).

OECD nations constitute interesting outliers when observing differing waste composition patterns around the world. These countries present a low organic fraction in MSW as compared to other regions, where organic matter is the prevalent waste fraction. In contrast, OECD countries have a high percentage of recyclable materials in their waste. One of the main reasons that explain this difference is the fact that citizens in OECD countries tend to consume more pre-packed multi-ingredient food products, whereas other countries throughout the world, such as those as those in LA&C, tend to

consume a higher proportion of food products with less processing involved (Mohee et al., 2015). Moreover, another factor that should be taken into consideration is the fact that households in many emerging and developing nations destine approximately 50% of the monthly revenue to purchase food products, whereas the proportion in OECD countries is lower (Vázquez-Rowe et al., 2017). Consequently, this leads to a higher rate of consumption of nonfood items that ultimately leads to higher inorganic waste fractions.

When observing the average values for OECD countries, the organic fraction (27%) is substantially lower than for AFR, EAP and MENA countries, where average values ranged from 57% to 62%. Nevertheless, in all regions throughout the world important fluctuations in terms of the proportion of the organic fraction can be observed when analyzing individual nations (see Table 1).

In contrast, OECD presented the highest generations of paper and cardboard (32%), glass (7%) and metals (6%) and relatively high values for plastic (11%). These data confirm that HI and UMI countries contain less organic matter (45-53%) and more paper and cardboard, plastic, glass and metals (42-34%) than LI and LMI countries, with 75-53% of organic matter content and 15-23% of recyclable materials, respectively.

However, plastics show an independent trend as compared to other recyclable materials. In this sense, average plastic content in waste in AFR, EAP and LA&C showed higher average values than those observed in OECD. There is not a clear cause for this phenomenon. However, it was observed that in AFR and LA&C a small pool of countries were the main contributors to increase average values. For instance, in the case of LA&C, Trinidad and Tobago (24%) surpassed the average value (12%). Some reasons for this could be probably linked to rapid urbanization and economic

development (Gu et al., 2017) and tourism activity mainly in Caribbean, Pacific and African islands, and on the other hand, to the influence of waste generation in China. Another factor that can influence waste composition is the energy source, especially in LI countries or regions where energy for cooking, heating, and lighting might not come from district heating systems or the electricity grid.

Table 1. Upper and lower limit of waste composition per region (Hoornweg and Bhada-Tata, 2012). *LL: Lower limit, UL: upper limit, AV: average. Sub-Saharan Africa (AFR), East Asia and the Pacific region (EAP), Europe and Central Asia region (ECA), Latin American and the Caribbean (LA&C), Middle East and North Africa (MENA), Organization for Economic Co-operation and Development countries (OECD) and South Asia Region (SAR).*

	Waste composition (%)																	
	Organic			Cardboard and paper			Plastic			Glass			Metals			Other and inert		
Region	LL	AV	UL	LL	AV	UL	LL	AV	UL	LL	AV	UL	LL	AV	UL	LL	AV	UL
AFR	18.0	57.0	88.0	2.00	9.00	21.0	1.00	13.0	20.0	1.00	4.00	5.00	1.00	4.00	5.00	1.00	13.0	57.0
EAP	4.00	62.0	71.0	2.00	10.0	31.0	2.00	13.0	24.0	3.00	3.00	9.00	1.00	2.00	20.0	2.00	10.0	63.0
ECA	5.00	47.0	65.0	10.0	14.0	37.0	3.00	8.00	12.0	1.00	7.00	13.0	3.00	5.00	9.00	11.0	19.0	43.0
MENA	40.0	61.0	70.0	9.00	14.0	25.0	4.00	9.00	16.0	1.00	3.00	5.00	2.00	3.00	9.00	2.00	10.0	16.0
OECD	14.0	27.0	56.0	8.00	32.0	68.0	1.00	11.0	22.0	2.00	7.00	13.0	2.00	6.00	13.0	5.00	17.0	63.0
SAR	35.0	50.0	80.0	3.00	4.00	17.0	2.00	7.00	18.0	1.00	1.00	4.00	1.00	1.00	1.00	5.00	37.0	59.0
LA&C	14.0	54.0	77.0	6.00	16.0	32.0	4.00	12.0	36.0	1.00	4.00	8.00	1.00	2.00	16.0	3.00	12.0	59.0
Average	18.6	51.1	72.4	5.70	14.1	33.0	2.40	10.4	21.1	1.40	4.10	8.10	1.60	3.30	10.4	4.10	16.8	4.10
Global composition 2016	NA	44.0	NA	NA	17.0	NA	NA	12.0	NA	NA	5.0	NA	NA	4.0	NA	NA	18.0	NA

When LA&C countries are analyzed in further depth, these follow the global trends for LI and LMI countries, with a high percentage of organic matter (ca. 50%). One of the major reasons for this rate is the high food loss that occurs during the food production process. Usually, developed countries show higher per capita food waste than developing countries due to lifestyle and socio-economic reasons (Gustafsson et al., 2013). In contrast, LA&C has the highest per capita food loss in the world associated to the early and middle stages of the supply chain (Hettiarachchi et al., 2018). Figure 3 presents waste composition in LA&C based on several data sources and temporal frames whereas the lower and upper limit values are provided in the SM (see Figure S3).

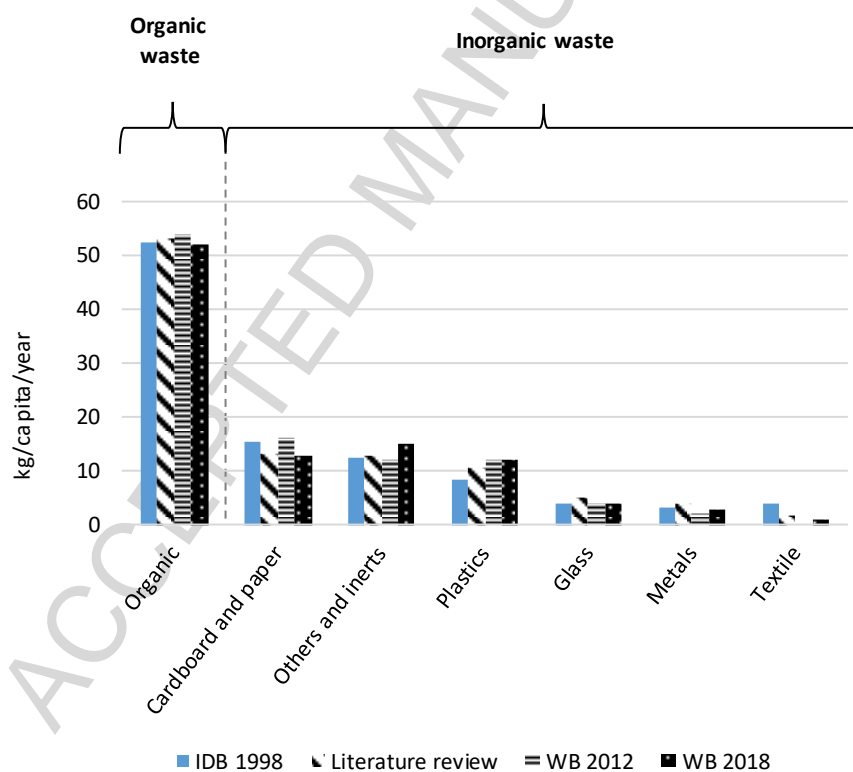


Figure 3. Average waste composition in Latin America and the Caribbean according to the world bank data in 2012 (Hoornweg and Bhada-Tata, 2012) and 2016 (Kaza et al., 2018), IDB data in 2012 (IDB, 1998) and the Literature review (Acurio et al., 1997; Aguilar-Virgen et al., 2010, 2013, 2014a, 2014b; Bezama et al., 2013; Duran et al.,

2013; Hernandez- Berriel et al., 2016; Massukado et al., 2012; Mohee et al., 2015; Moreira and Cardiani, 2016; Valencia-Vázquez et al., 2014).

The results suggest minimal variability in terms of waste composition regarding data source and temporal representativeness. However, when the results are analyzed from an urban/rural perspective, some authors found that rural areas were likely to have a greater amount of vegetable, fruit and garden waste than inner city areas (White et al., 2017). Nevertheless, most of the data show a global average without any information concerning these variables, making it difficult to assess their influence. When the results for LA&C are evaluated from a national perspective, as shown in Table 2 (see also Figure S4 in the SM), Haiti, the only LI country, displayed the highest generation share of organic matter (75%). This is not surprising, as higher organic fractions are linked to lower purchase power, which ultimately implies a higher proportion of food purchase in household expenditures (Vázquez-Rowe et al., 2017). In contrast, Trinidad and Tobago, an HI nation, showed the lowest value (26.7%). This can be explained by the high import rates of consumer products, including high levels of packaged food. (Atlas of Economic Complexity, 2019). Only one other nation, i.e., Cuba (34%), presents an organic fraction below 40%, with a great majority of countries ranging from 41% to 62%. Although the lowest generator of organic waste is an HI nation, and the highest an LI country, when the entire pool of nations in LA&C are examined there is no clear tendency that suggests that there is a direct relation between average waste composition and GNI.

Table 2. Average relative waste composition in Latin American and the Caribbean (LA&C) countries according to their Gross National Income (GNI). Income levels in brackets were based on the classification reported by World Bank (2018). Waste

composition were obtained from an aggregation of Literature review (Acurio et al., 1997; Hernandez Berriel 2016; Bezama et al. 2013 ; Massukado et al. 2013; Moreira et al. 2016; Observatorio nacional de gestión de residuos; WB 2012; Mohee et al. 2015)

Country (income level)	GNI per capita 2016 (USD\$)	Organic	Cardboard and paper	Metals	Glass	Plastics	Others and inert
Trinidad Tobago (HI)	3,070	26.70	19.70	10.40	10.50	19.90	12.60
Cuba (UMI)	6,570	34.00	11.00	17.00	22.00	11.00	5.00
Bolivia (LMI)	3,070	41.75	6.10	1.65	2.75	6.15	41.60
México (UMI)	9,040	43.68	15.19	1.88	4.02	12.05	23.93
Panamá (UMI)	12,140	44.00	25.00	5.00	8.00	11.00	7.00
Argentina (UMI)	11,960	48.51	14.14	1.95	3.83	14.36	17.35
Guyana (UMI)	4,250	50.53	14.90	3.40	3.90	14.40	12.87
Chile (HI)	13,530	52.00	14.60	2.60	3.33	9.40	18.03
Costa Rica (UMI)	10,840	54.00	20.00	2.00	2.00	14.50	7.50
Peru (UMI)	5,950	54.77	6.86	1.23	2.68	6.22	28.65
Uruguay (HI)	15,230	55.00	14.00	6.00	3.50	12.00	10.00
Guatemala (LMI)	3,720	55.45	15.95	2.90	4.10	10.55	11.05
Suriname (UMI)	7,070	56.80	6.80	2.50	5.80	11.00	17.30
Brazil (UMI)	8,840	58.93	13.92	2.17	2.47	14.94	8.50
Belize (UMI)	4,410	60.00	20.00	5.00	5.00	5.00	5.00
Paraguay (LMI)	4,070	60.53	8.13	1.23	3.60	5.63	21.07
Colombia (UMI)	6,320	61.50	10.39	1.41	4.05	10.67	12.67
Jamaica (UMI)	4,660	62.20	14.70	2.40	2.80	12.20	5.70
Ecuador (UMI)	5,820	62.70	9.10	1.35	2.40	8.05	16.45
Haiti (LI)	780	75.00	3.00	3.00	2.00	7.00	10.00

An interesting case is that of Guayaquil in Ecuador (UMI), which ranks second position in terms of organic matter content (62.7%). Approximately 20.7% of this fraction corresponds to banana peels (Von Buchwald, 2017). In fact, this country is one of the world's top banana producers and consumers, producing in 2016, 6.5 million metric tons of bananas (ESPAC, 2016).

2.3 Waste management systems

Unsuitable collection and disposal of solid waste can result in problems that endanger human health and affect economic and environmental issues (Taghipour et al., 2016). Therefore, it is imperative for local and regional authorities throughout the world to provide adequate, site-specific and innovative strategies to improve the management of MSW. In this section, waste management systems are analyzed dividing them into two main phases. On the one hand, activities involving collection, sorting and recycling are described. On the other hand, waste treatment technologies are analyzed.

2.3.1 Waste collection and sorting

Waste collection preserves public health in cities and towns around the world and creates opportunities for waste valorization. In this sense, the way that waste materials are collected is essential for waste valorization options as it will significantly influence the quality of recovered materials, compost or fuel that can be produced (White et al., 1997). The key variables of waste management include waste picking, containerization and collection frequency, in order to guarantee a good quality of life in urban and rural environments.

Regarding waste picking, several classifications can be found in the literature based on the availability of collection services (e.g., communal system, block collection, curbside collection or door to door), the location of the collection point (e.g., in the street at a short distance from the generator's property, in the street at the property boundary or inside the property), the mode of operation (hauled systems that move the container to the disposal site and stationary systems in which the container remains at site), the type of waste collected (selective or non-selective collection), the type of load (rear, side and front) or lifting (manual or automatic) (UNHABITAT, 2010).

For instance, at the location of the collection point, two main levels are distinguished: kerbside (also referred to as curbside) and bring. In the former, users leave their garbage directly outside their homes following a garbage pick-up schedule set by local authorities (Hoorweg and Bhada-Tata, 2012), whereas in the bring system users have to cover a certain distance to dispose of their garbage in different types of containers. Other household disposal systems include civic amenity sites (i.e., faraway containers), drop-off sites (less than 250 meters to the container), street collection (50-60 meters) and door to door collection (minimum distance). Drop-off sites are used in high density areas and are widely applied in Europe for the collection of paper and cardboard, glass and lightweight packaging. In street collection, high volume containers are located close to the households both for indiscriminate and selective collection. This system enjoys great acceptance among citizens due to the fact that it is an easy and quick disposal method (Gallardo-Izquierdo et al. 2009). In this type of collection above- and underground containers, as well as pneumatic collection can be applied. In the case of a door to door system, the main peculiarity is that it does not use containers situated in the street permanently: citizens leave their waste outside their house according to a pre-established collection schedule (Iriarte et al., 2009). This is the most common waste collection system in urban areas of LA&C (Kaza et al., 2018).

Based on the previous description, it is evident that there is no unique universal model valid for all towns and cities (Bertanza et al., 2018). In fact, there are huge differences in waste collection methods between countries, as well as between rural and urban areas. These differences depend on collection cost, type of MSW collected, geographical conditions, degree of mechanization, existence of transfer stations, among others (Gallardo-Izquierdo et al., 2009).

Regarding costs, HI level countries tend to have collection costs that represent less than 10% of the waste management budget. However, these countries, using mechanized, efficient and frequent collection methods, are capable of achieving very high collection rates, ranging from 76% to 100%. This is the case of OECD countries, which present the highest collection rates, 98% (see Table S2 in the SM). In contrast, collection services in LI countries make up more than 80% of the budget assigned to waste management. Despite this higher preponderance in budgetary expenditure, collection rates in these nations tend to be much lower, from 11% to 55%, leading to lower collection frequency and efficiency. SAR and AFR presented the lowest average collection rates with 65% and 46%, respectively. Similar values were observed for other low-middle and upper-middle countries with a collection coverage ranging from 50% to 95% (Tello et al., 2010; Hoornweg and Bhada-Tata 2012; United Nations, 2014).

For LA&C countries there are some discrepancies between data sources. The World Bank Report of 2012 compiled the most up-to-date and available collection rates per country for 2001. An average coverage of 78% was reported, although a considerable range from 11% to 100% is observed, as shown in Figure 4 (Hoornweg and Bhada-Tata, 2012). Nevertheless, according to Tello and colleagues (2010), collection coverage in LA&C underwent a notable increase in the first decade of the century, reaching a rate of 93.4% by 2010. These data are consistent with the new World Bank Report of 2018 that indicates a rate of 85% of waste collection at an urban level and 30% in rural communities (Kaza et al., 2018).

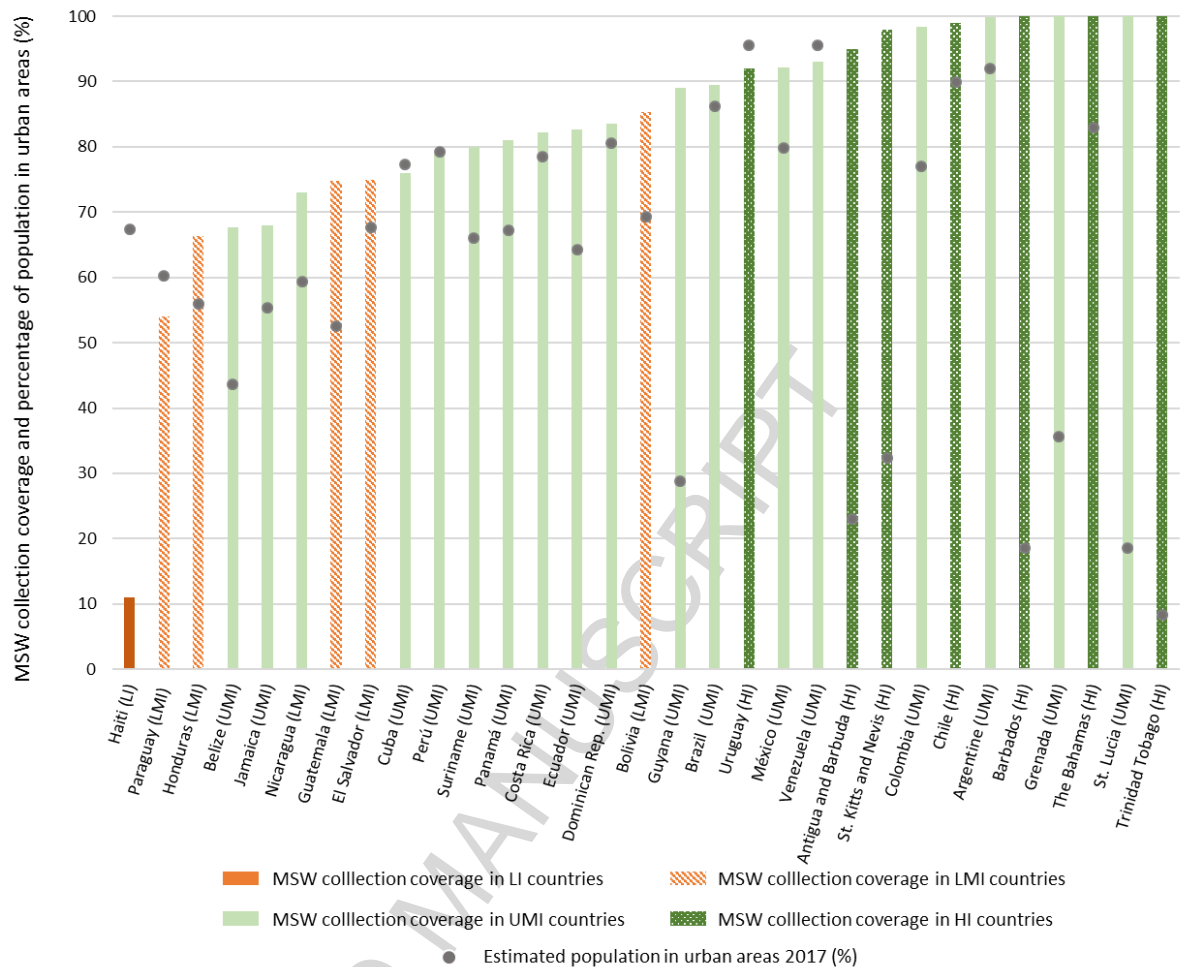


Figure 4. Relative urban population and municipal solid waste (MSW) collection coverage in Latin America and the Caribbean (LA&C) countries (Tello et al., 2010; Hoornweg and Bhada-Tata 2012; United Nations, 2014).

Greater collection rates were linked to high urban population and GNI. In fact, most UMI countries in LA&C presented collection rates close to or beyond 70%, whereas most HI countries, such as Chile and some Caribbean islands, displayed full coverage. Countries with lower coverage are, in most cases, rural low-income nations, although some HI Caribbean islands are also characterized by a low percentage of urban population, suggesting that income level is a more determining parameter than population distribution when it comes to having high waste collection coverage in the region.

An outstanding percentage is that of Bolivia (85%), despite being a low-medium nation in terms of income, and with a relatively high rural population as compared to neighboring countries. It is important to note, however, that since 2007, Bolivia started collaboration with the Catalan Agency for Development and Cooperation (ACCD) to improve the management of waste and water. This cooperation allowed the analysis of the current waste management situation, the development of a national waste management program, several technical guidelines and educational materials and the elaboration and passing of the national MSW Law (ARC, 2016). All these measures, which intent to replicate the Catalan waste management system, have significantly improved the situation in Bolivia.

Regardless of the collection coverage attained in a specific geographical context, service quality should also be analyzed in detail. For instance, Tello et al. (2010) suggest that there is erratic planning and information linked to containerization in urban environments in LA&C. In fact, location, capacity and maintenance of these containers is of particular interest in residential areas since the disposal of waste in closed containers avoids disturbance by vermin and other animals and prevents water-log or waste burning (Hoorweg and Bhada-Tata). Lack of information and capacity building ultimately affects the citizen awareness, leading to waste disposed of in inadequate places (Tello et al., 2010).

Another indicator linked to service quality is collection frequency. Most small towns in LA&C (<50,000 inhabitants) conduct waste collection services once per week due to the lack of resources, the poor maintenance of vehicles, as well as the low volume of waste and the high distance between households, whereas frequency increases for bigger settlements. Low collection frequency is intimately related to high

percentage of open burning, disposal of waste in water bodies and use of waste as animal feed (Tello et al., 2010).

In Argentina and Mexico, around 72% of waste is collected on a daily basis, presenting the highest rates in LA&C. In a second group, Ecuador, Peru and Dominican Republic show a daily collection rate above 50%. However, in general terms, most LA&C countries collected more than 35% of waste between 2 to 5 times per week, showing low rates of weekly collection. Jamaica and Costa Rica displayed the highest weekly collection, 65% and 31%, respectively (see Table S3). In these cases, an improvement in collection frequency is recommended, since normally low frequency collection is linked to high rates of uncontrolled combustion and unappropriated disposal both in water bodies and as animal feed (Tello et al., 2010). Poor coverage and collection frequency, collection of only a fraction – in many cases below than 50% of generated MSW, and inadequate disposal of MSW constitute an important source of pollution and pose significant risks to human health and the environment in many cities (Medina, 2005). Nonetheless, one of most important challenges in LA&C, but also in many low and low-middle income countries of Asia and Africa, is the informal waste collection and management strategy, and its link with the formal sector and official waste management plan (Katusiimeh et al., 2013; Gutberlet, 2010). In fact, the number of people linked to the informal collection system in China is twice higher than in the formal collection system (Mian et al. 2017). In contrast, most HI and UMI countries have developed formal waste collection systems, which consist of public service providers and private companies (Katusiimeh et al., 2013). Waste collection by formal workers can be sent to a variety of venues, including transfer plants, sorting plants or landfills, where they may undergo different levels of segregation. After the sorting,

recyclable residues arrive to collection points that will sell these materials to national processing industries or that will export it (FOMIN, 2013).

However, formal collection conducted by large companies is not always possible in low-income or isolated areas (Medina, 2005). In these cases, informal collectors provide the service, collecting and sorting individually or collectively paper and cardboard, plastics, metals and glass, among other recyclable materials with carts drawn by horses, bicycles or three-wheeled motorcycles (Zapata and Zapata, 2014). Thereafter, recyclable materials are transported to intermediate or final collection points for subsequent sale to national processing industries or international markets. Nevertheless, it is important to note that in many LA&C locations there is a blend between activities performed by formal and informal actors. While the formal actors are responsible for the overall waste management system, informal actors play an important role in the recovery of recyclable goods, from the street, waste containers, open dumps or landfills, (Kahhat and Williams, 2009; Estrada-Ayub and Kahhat, 2014).

Moreover, these under-valuated activities are carried out by men, women, children and old people that work under harsh conditions (i.e., weather conditions, long distance walks, existence of insects, rats and other vectors, high rivalry level among workers to find valuable materials, etc.). Nonetheless, the economic incentive of this activity is higher than other jobs that are socially better recognized, such as working in rural areas (Ávila et al., 2013). Nevertheless, despite the health impacts and work conditions, the informal sector contributes to waste reduction, promoting a circular economy system, reduces costs related to municipal waste management, and recovers valuable materials which otherwise would be lost (WBCSD, 2016). In fact, in many under-developed countries informal collectors provide the only alternative for urban

waste management. Figure 5 presents the classification of informal workers based on a set of criteria:

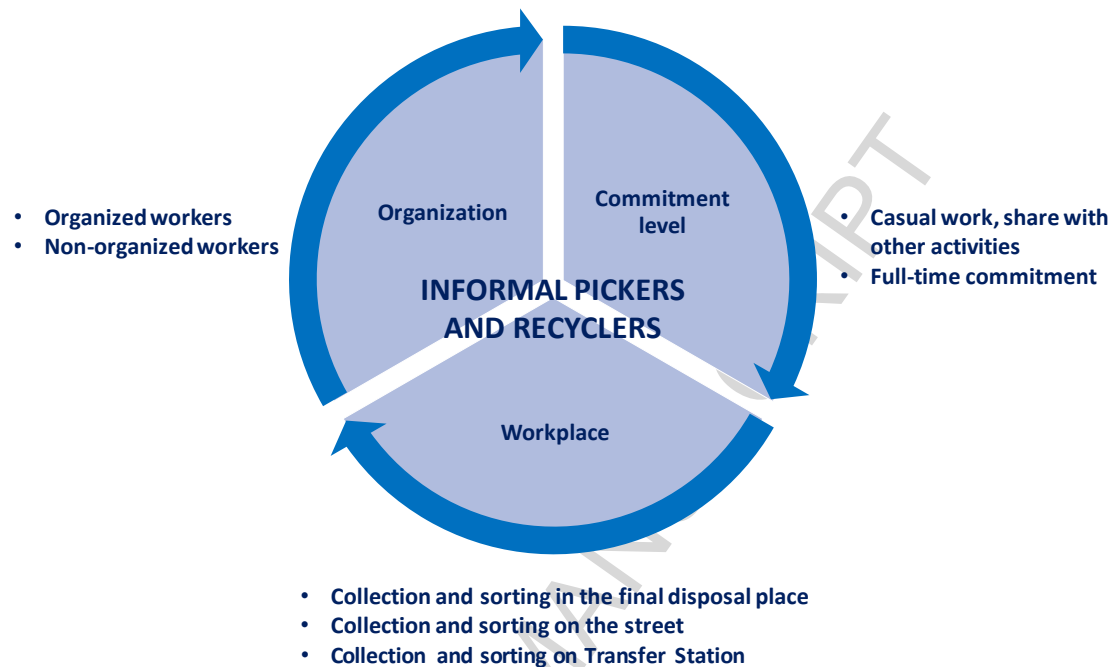


Figure 5. Classification of informal workers (Adapted from Terraza and Sturzenegger, 2010).

In 2005 the Pan-American Health Organization (PAHO) estimated that, in LA&C there were approximately 500,000 informal workers. In 2010, Tello et al. (2010) determined a ratio of 8.57 informal pickers per every 10,000 LA&C inhabitants (i.e., slightly above 400,000 informal workers). Nevertheless, this group constitutes a volatile population, making its quantification challenging. Thereby, other authors state that this sector consists of around 3.8 million workers (FOMIN, 2013). As compared to other regions of the world, the organization of the informal sector is considerably advanced in LA&C, with their recognition and inclusion as workers in MSW systems more common than elsewhere (Ezeah et al., 2013). Indeed, different levels of advancements have been achieved in LA&C countries concerning regulations, formalization and acceptance of the informal sector, as well as their connection with the formal sector. For example, a

group of countries, such as Brazil, Colombia and Peru, show certain level of formal activities, which include the development of regulations for the informal sector or the application of some type of incentive to formalize these activities. The challenge of these countries is to implement effectively these regulations. A second group of countries, such as Bolivia, consider the informal sector as a marginal activity outside the law (FOMIN, 2013).

Moreover, it is estimated that LA&C counts with ca. 1,000 recycling organizations linked with informal recyclers (IDB, 2017), finding the highest levels of organization in Brazil and Colombia, with special attention to the *National recycling movement* in Brazil and the *National association of recyclers* in Colombia. In certain Brazilian cities, such as Recife, Porto Alegre, Londrina or Belo Horizonte, informal pickers (named *catadores*) are organized in associations and cooperatives that work hand by hand with the municipalities in collection recycling programs. Moreover, the city of Curitiba is famous for its role in the development of recycling strategies and social growth issues, managing as early as the 1990s a 70% recycling rate (Kenchucuritiba, 2018). Since the city lacked a budget for a standard recycling plant, complementary currencies to reward people for separating their organic and non-organic recyclable wastes and taking them to waste stations were created, where these coupons could be exchanged for bus tickets, food or school books (PANDA, 2018).

In the case of Colombia, more than 100 cooperatives are active, particularly in the capital city, Bogota (Terraza and Sturzenegger, 2010). Recycling work has begun to be recognized, and some programs have been designed to increase recycling rates through separation at source, generating a recycling culture. Moreover, recycling associations have achieved consolidated alliances with the industrial sector to sell recycled materials (Pardo Martinez and Piña, 2017).

Interestingly, Paraguay also shows a high level of organization, with at least one third of informal pickers organized in cooperatives named *carretilleros* or *gancheros*. Nevertheless, most LA&C countries, such as Chile and Nicaragua, do not have this level of organization. Legislation, however, is being introduced at national or municipal levels to dignify informal recycling.

2.3.2 Waste treatment

Landfilling is the only waste disposal method that can deal with all types of materials in the solid waste stream. Other alternatives such as biological or thermal treatment technologies produce waste residues that subsequently need to be landfilled (White et al., 1997). Landfills can be classified according to their location, topography, type of waste received and the technology employed in the operation of the landfill (Bilitewski et al., 1994). Beyond these classifications, it is particularly important to establish the significant differences existing between sanitary landfills, controlled landfills and open dumpsters. For instance, prior to World War II throughout the world most municipal waste was disposed of in open dumps or tips. It was only in the 1930s that the need for improved methods of MSW disposal started to raise concern in Europe. Thereafter, in 1959, the American Society of Civil Engineers (ASCE) provided the first recognized definition of sanitary landfilling as “a controlled operation in which MSW is deposited in defined layers, each layer being compacted and covered with soil before depositing the next layer” (Trevor and Vallero, 2011). This compaction, as well as the daily cover allows minimizing fires, odors and disease vectors. Moreover, sanitary landfills include an adequate management of leachate and gases and a site access control, which helps to discourage waste scavenging and properly define the facility’s boundary through fencing or similar means (Townsend et al., 2014). Similar to a

sanitary landfill, controlled landfills include a series of control measures, but lack some of the technological infrastructure present in sanitary landfills.

On the contrary, in open dumps (so called “botaderos”, “basureros” or “tiraderos” in Spanish-speaking areas of LAC) waste is disposed of without or limited measures to control operation and to protect the environment and, thus, the chemical and biological contaminants in waste will find their way back to humans to affect health and quality of life (Rushbrook, 1999; Oakley and Jimenez, 2012). In fact, the available literature demonstrates that groundwater pollution in the vicinity of open dumps is usually significantly above environmental standards (Aiman et al., 2016; Ziegler-Rodriguez et al., 2019), whereas pollution near adequately managed landfilling sites tends to be limited as compared to baseline concentrations (Han et al., 2016; Gworek et al., 2016). Open dumping is considered as the simplest, and in many areas, the cheapest of all existing disposal methods. Unfortunately, it is still one of the most common practices for the disposal of MSW in the LI and LMI countries, mainly in less developed regions of Africa, Asia and LA&C (Oakley and Jimenez, 2012; Munawar and Fellner, 2013).

In other areas, such as the EU, open dumpsters have been close to eradicated, while sanitary landfilling is the main waste disposal method (Figure 6), although the increase of land prices and the application of the European regulation, which establishes landfilling as the least preferable option (European Commission, 2008), is starting to limit its use considerably. Moreover, the European Commission has adopted an ambitious circular economy package to stimulate Europe's transition towards a circular economy, setting for 2030 a target for recycling 65% of municipal waste and 75% in the case of packaging waste, as well as reducing landfill to a maximum of 10% of municipal waste (European Commission, 2015). In 2015, the landfilling share in the

EU-28 was 26% (see Figure 6), whereas several EU-28 countries and candidates and potential candidates to the EU still presented rates beyond 50%: 53% in the case of Czech Republic and above 99% in Turkey and Kosovo. In fact, whilst the landfilling rate in Greece, Turkey or Montenegro (candidate) surpassed 300 kg of waste per capita, north and central Europe presented rates of landfilling below 10% (EUROSTAT, 2017). However, waste policies have been successful in increasing alternative waste treatments. In fact, in 2015 EU-28 had reached a high rate of incineration (27%), recycling (29%) and composting (17%) (EUROSTAT, 2017).

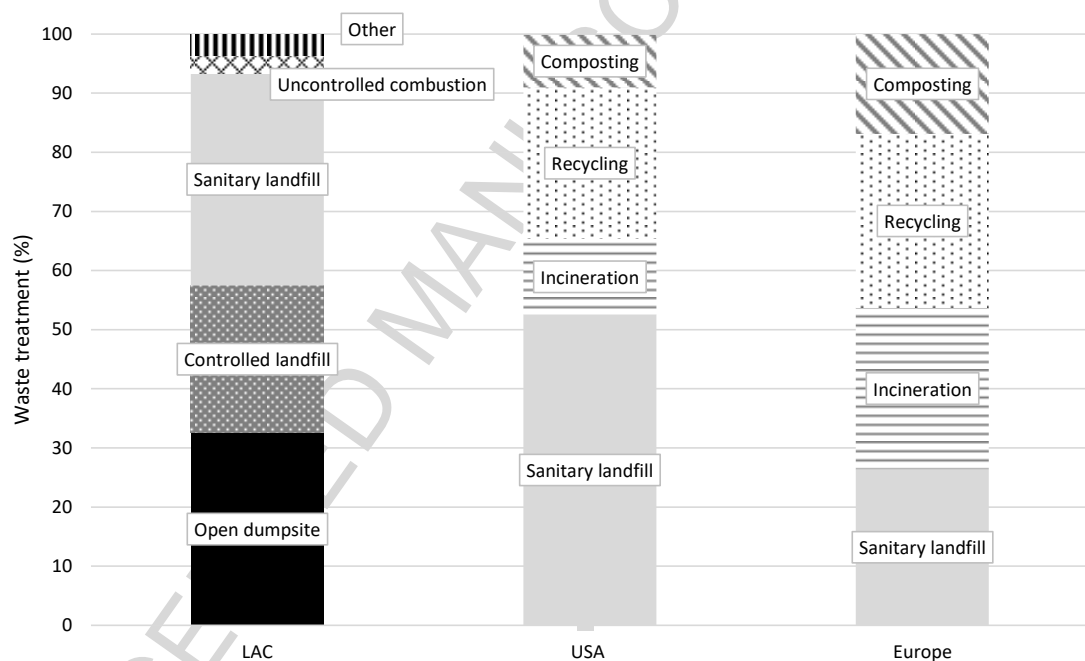


Figure 6. Relative importance of different waste treatment options in Latin America and the Caribbean (LAC), USA and Europe. Data obtained from: Tello et al. (2010), Hoornweg and Bhada-Tata (2012), USEPA (2012), and EUROSTAT (2017).

In the case of the US, landfilling was still the most preferable waste treatment option in 2014 (53%), followed by recycling and composting (35%) and incineration (13%) (EPA, 2014). Despite the importance of landfilling, a substantial decrease in the amount of waste entering landfills has been identified in the past 15 years (from 140 to

136 metric tons per person and year) and a growth in composting and recycling (from 69.5 to 89.4 metric tons). Lack of policies and incentives that promote alternative practices, land availability, and opposition towards incineration based on past environmental impacts are, perhaps, the main reasons behind landfill prevalence in the United States.

In LA&C, the main final waste disposal option is landfilling: 36% of waste is disposed of in sanitary landfills and 25% in controlled landfills. Overall, 33% of waste is still disposed of in uncontrolled dumpsters (see Figure 6). For instance, in the case of Peru, the Ministry of the Environment has identified over 1400 dumping points throughout the nation as of May 2018 (Technical staff, Ministry of Environment, personal communication, May 2018). Although the number of sanitary landfills has significantly increased in the region over the past decade, many of these face significant operation and environmental issues (Hettiarachchi et al., 2018). On the one hand, the operation of these landfills in most cases lacks of leachate treatment and LFG treatment and recovery. Leachate recirculation is a common practice in well-managed landfills in the region. On the other hand, best available technologies for landfills have been implemented in the region, such as in Brazil (Costa et al., 2019). Other treatments such as incineration, anaerobic digestion, composting but also formal recycling are emerging techniques for waste treatment, presenting relatively low rates as compared with other regions of the world (Hoornweg and Giannelli, 2007). For instance, in the case of anaerobic digestion, the development of this technology is considerably high in countries such as Chile (Martínez et al., 2012), Brazil (dos Santos et al., 2019) and, to a less extent, Colombia (Alzate-Arias et al., 2018). Although a significant potential to foster anaerobic digestion in the region exists, only timid efforts have arisen in other countries such Nicaragua, Peru and Costa Rica (Garfí et al., 2016).

Incineration provides several advantages such as the reduction in waste mass and the energy recovery; however, this technique has a poor reputation related to environmental impacts because of its emissions of GHG, acidifying gases, dioxins or furans (PCDD/F) (Margallo et al, 2014). In addition, the implementation of an MSW incineration facility or a Waste-to-Energy (WtE) plant in a developing or poorly developed waste management system without proper planning can lead to environmental and economic failure. Therefore, a complete evaluation of technical and economic aspects of the incineration site is required. In fact, the key risks and limitations of incineration are the minimum requirements in terms of lower calorific value, the need of skilled staff for operation and maintenance, financial support and appropriate choice of technology (Kamuk and Haukohl, 2013; Kahhat et al., 2018). In LA&C the Energy Recovery Unit (URE) at Barueri (Brazil) is expected to be one of the first WtE plants when it opens in 2020 (Citvaras, 2016). The plant will treat more than 800 metric tons of waste per day and will produce energy and heat (Kahhat et al., 2018).

Recycling presents a variety of environmental, sanitary, social, economic and educational benefits. This approach reduces the use of raw materials and the amount of waste landfilled, creating new job opportunities and income. However, recycling has not been fully spread yet in LA&C (Conke, 2018) and only few countries have sorting plants. Therefore, most recyclable materials end up in landfills and dumpsites, creating a window of opportunity for informal sector (Hettiarachchi et al., 2018), which reduces the waste inflow into the landfill, providing a service to the community (Ferronato et al., 2018). Only 2.2% of MSW are formally recovered and recycled in LA&C (Grau et al., 2015). Therefore, most efforts currently focus on improving recycling to reduce informal waste picking and upgrade pickers into community-based organizations (Hoornweg and Giannelli, 2007). Nonetheless, some countries such as Mexico have

reached a recycling rate of 10%, whereas in the metropolitan area of Santiago de Chile the recycling rate increased to 12% in one decade. The best recycling rates were observed for paper and cardboard, steel and aluminum cans, glass bottles and PET packaging (Tello et al., 2010). The main barriers to waste recycling development are the lack of knowledge about recycling programs, the competition between the formal and informal sectors, deficient infrastructure and a shortfall of professional management (Conke, 2018; Hoornweg and Giannelli, 2007).

Regarding organic matter, the high content of this waste flow in MSW of LA&C, around 50%, is ideal for composting. However, waste separation at source is not a common practice in the region, so MSW streams contain increasing quantities of glass, plastics, metals and hazardous materials, which can contaminate the finished compost, diminishing its quality (Hoornweg et al., 1999; González-Martínez et al., 2012).

Table 3 analyses waste management practices in LA&C countries. However, it is important to highlight that waste disposal data are challenging to collect considering that in most cases there are no databases at a national level. Furthermore, in those cases in which data are available, the methodology of how disposal is calculated and the definitions used for each of the categories is often either unknown or inconsistent (Hoornweg and Bhada-Tata, 2012). Some of the highest sanitary landfilling rates are observed in Colombia and Chile (82%), El Salvador (78%), Costa Rica (68%), México (66%) and Argentina (55%). El Salvador banned open dumpsters in 2007, although the eradication is yet to be completed (MARN, 2018), and Colombia enforced a governmental plan named “Colombia without open dumpsite” (El Colombiano, 2008). Both initiatives allowed reducing this practice drastically. In Mexico and Brazil the approach has been somewhat different, with several open dumpsites being converted

into controlled landfills. This perspective also allowed achieving high reduction levels in terms of open dumping. In the particular case of Peru, the government is currently investing in an ambitious plan to transition from open dumpsters to sanitary landfills. Interestingly, this initiative has been coupled to the nation's GHG mitigation objectives within the Paris Agreement (Ziegler-Rodríguez et al., 2019). In other countries, such as Suriname, Haiti, Belize, Guatemala or Nicaragua, the use of open dumpsters is still overwhelming, whereas uncontrolled combustion and other practices such as disposal into water bodies and the use of waste as animal feed are alarming in Bolivia, Belize, Honduras and Panama (Tello et al., 2010).

Table 3. Relative values of final disposition or treatment of waste in Latin America and the Caribbean (LA&C) nations. Income levels in brackets were based on the classification reported by World Bank (2018). Data adapted from Tello et al. (2010)

Country (income level)	Sanitary landfill	Controlled landfill	Uncontrolled landfill	Uncontrolled combustion	Others treatments
Colombia (UMI)	81.8	4.1	12.5	1.2	0.3
Chile (HI)	81.5	13.8	4.0	0.0	0.7
El Salvador (LMI)	78.2	0.0	13.8	7.3	0.6
Costa Rica (UMI)	67.5	23.5	9.1	0.0	0.0
México (UMI)	65.6	12.1	12.4	5.9	4.0
Argentina (UMI)	64.7	9.9	24.6	0.8	0.0
Guyana (UMI)	59.0	37.0	0.0	0.0	4.0
Brazil (UMI)	55.0	20.2	24.5	0.0	0.3
Bolivia (LMI)	44.7	16.4	10.6	1.9	26.3
Perú (UMI)	43.5	10.6	45.3	0.6	0.0
Panamá (UMI)	41.7	16.0	23.4	4.7	14.2
Paraguay (LMI)	36.4	40.2	23.4	0.0	0.0
Dominican Rep. (UMI)	33.7	24.5	31.6	10.0	0.2
Ecuador (UMI)	30.2	46.3	20.5	0.8	2.1
Average LCR	56.0	19.6	18.3	2.4	3.8
Guatemala (LMI)	15.4	9.6	69.8	0.0	5.1
Venezuela (UMI)	12.9	40.9	45.6	0.5	0.0
Honduras (LMI)	11.3	59.9	15.0	13.8	0.0
Uruguay (HI)	3.8	68.2	18.1	0.0	9.8
Haiti (LI)	0.0	0.0	100	0.0	0.0

Suriname (UMI)	0.0	0.0	100	0.0	0.0
Belize (UMI)	0.0	0.0	85.2	14.8	0.0
Nicaragua (LMI)	0.0	19.6	59.3	7.5	13.6
Jamaica (UMI)	0.0	100	0.0	0.0	0.0
Barbados (HI)	No data available				
Cuba (UMI)	No data available				
Trinidad and Tobago (HI)	No data available				

To sum up, multiple actions are required in LA&C to improve the current waste management system. The development of selective collection, segregation at source and waste management plans will increase recycling rates and will reduce the amount of waste that ends up in landfills. Moreover, the cooperation between formal and informal pickers and recyclers, and the inclusion of the latter in integrated waste management systems will increase the amount of recycled materials, reducing the environmental impact. Regarding final treatment, the reduction of open dumpsites, the conversion to sanitary landfills if possible with energy recovery and the application of novel techniques are the challenges of this region.

3. Environmental impact considerations in municipal solid waste (MSW) management

LCA is an internationally-standardized environmental management method that aims at tracking the environmental impacts that are attributable to a particular product or process from a life-cycle perspective (ISO 2006a; 2006b). This implies that after a clear and concise definition of the goals of the study conducted, material and energy flows in the different stages of the product or process under evaluation are gathered in what is named the Life Cycle Inventory (LCI). The LCI is structured in such a way that it represents a mathematical formulation of the function of the system. For instance, in agricultural production this mathematical formulation, named functional unit (FU)

could be 1 hectare of land, or 1 mass unit of harvested product. The LCI is then crossed with impact assessment methods, which classify the substances depending on their potential environmental impacts. In other words, dinitrogen monoxide (N_2O), for example, is a GHG, but also has ozone-depleting properties. Thereafter, substances with a common environmental impact are converted to common impact units to make them comparable (Hellweg and Milà i Canals, 2014), allowing a more understandable interpretation of results.

As exposed throughout the manuscript, landfilling of solid waste in its different types constitutes the backbone of MSW treatment in LA&C. Therefore, it is evident that it plays an imperative role in both the material and economic flows in the region, considering that almost all anthropogenic interventions imply a certain amount of waste generation. For instance, it is a challenge for this region to finalize the full transition from open dumpsters to landfilling MSW (Guerrero et al., 2013). Nevertheless, it is desirable for this process to be part of a more complex transition in which other, more sophisticated and environmentally sustainable options, which may include waste recovery, incineration or waste-to-energy pathways (Kahhat et al., 2018). Consequently, it is important to have a holistic idea of the environmental performance of landfills, independently of their type, for policy-makers and MSW stakeholders to take informed decisions that can actually improve the current status. In this context, LCA is viewed as one of the most useful environmental management methodologies to assess final disposition environmental profiles (Laurent et al. 2014a). Hence, the elaboration of a literature review regarding this MSW treatment method has been considered critical. Throughout the following subsections, a more extensive analysis of this idea is carried out.

3.1 Scope of Included Studies

The concept “solid waste” can be defined in multiple ways. In this review, however, it has been defined as all the waste, which excludes liquid residues and airborne emissions (Christensen, 2011; Laurent et al., 2014a). Therefore, environmental management studies focusing on wastewater treatment and flue gases have not been included in this review.

The studies included in this analysis were limited to those in which landfilling assessment constitutes the core aim of the study. Moreover, studies aimed at analyzing integrated solid waste management systems, which can include different treatment combinations along its stages (e.g., incineration followed by landfilling of ash; combining recycling, composting and landfilling) have not been considered, as waste treatment in LA&C emerging economies is based almost exclusively on landfilling. However, articles comparing landfilling with other treatment technologies have been included as they can show to what extent management strategies can be improved in the future.

Laurent and colleagues (2012, 2014a) recommend not to include LCA studies focusing on climate change exclusively, disregarding other environmental impact categories, as they are not compliant with the requirements of the ISO 14044 standard. This standard advocates for the inclusion of a wide range of impact categories in life-cycle modelling to minimize the risk of biasing the conclusions and recommendations due to hidden trade-offs between environmental compartments (Laurent et al., 2012). However, despite this suggestion, it was decided to include these single indicator studies that focus on climate change exclusively in the current review, as it is still important to have a wide overview of the different case studies conducted throughout the world.

3.2 Identification of Studies

Only English-written literature from peer-reviewed scientific journals was included in the scope of this study. The article-choosing criteria applied were based on several steps. In the first place, the Scopus database, combined with the authors' expertise in both waste management and LCA, was used to identify up to 10 journals that met the required characteristics. Secondly, journals were explored considering keywords such as "landfill", "LCA" and "waste management". The best hits were analyzed in order to identify whether their inclusion in the review would be appropriate. Moreover, these studies were then revised, and relevant cited and citing literature was identified and cross-checked. Only papers published after 1997 were considered for this review. This criterion was chosen considering that landfilling is one of the oldest waste management technologies and its application has not evolved much in recent years in developing and emerging economies in LA&C. Despite the fact that some of the oldest studies have outdated impact assessment models, the authors of this review consider that the assumptions and considerations made in these studies are still valid and worth including. These steps were also supported by the use of the Google Scholar search engine. Finally, as abovementioned, included studies were those in which their primary focus was landfilling, either by itself or by comparing it to other technologies, and that necessarily had a life-cycle perspective.

3.3 Review Scheme

A set of characteristics were identified in the studies reviewed. These were divided in general features and LCA-related features. General features included geographical location, technologies assessed and the focus given to the respective studies, as shown in Table 1. LCA-related features consisted of components essential for the development of LCA studies and constitute an integral part of the methodology

(i.e., functional unit, allocation type, assessment method and others). The latter are displayed in Table 5 in the SM.

As of June 2019, 37 scientific articles fulfilled the requirements and selected criteria. The main characteristics and methodological concerns of these studies will be addressed and discussed in the following sections.

3.4 Geographical Location

When referring to landfilling, venue location is critical in terms of waste degradation (Henriksen et al., 2018). Landfills located in areas with warm tropical climates will have a higher generation of landfill gas (LFG) and leachate, as temperature has a direct effect on the anaerobic decomposition rates of waste, as well as other parameters (Visvanathan et al., 1999; Machado, 2009; Lee et al., 2017). The rationale behind this trend is linked to the fact that LFG generation follows a first order decay model according to the US Environmental Protection Agency (USEPA) and the Intergovernmental Panel on Climate Change (IPCC) (USEPA, 1998, 2005a; IPCC, 2006). Bearing this in mind, it has been considered to be a relevant issue to address in this review.

Out of the 37 articles, 15 focus on studying landfills spread out throughout Europe: 13 of them with country-specific information and 2 using a non-specific landfill with generic European waste characterization (Manfredi et al., 2009; Manfredi et al., 2011). Out of the remaining studies, 3 were located in North America, 15 in Asia, and only 3 in Latin America and 1 in Oceania. In Asia, 3 studies were located in the Middle East (Iran and Lebanon), 2 in China (Yang et al., 2014; Zhou et al., 2019), 2 in India (Sharma and Chandel et al., 2017; Yadav and Samedder et al., 2018), 1 in Kazakhstan (Noya et al., 2018), 2 in Asian Russia (Starostina et al., 2014; 2018) and 1 in Pakistan

(Ali et al., 2017). Moreover, additional studies analyzed landfills in Southeast Asia: Indonesia (Aye and Widjaya, 2006; Wanichpongpan and Gheewala, 2007), Thailand (Liamsanguan and Gheewala, 2008), and Singapore (Khoo et al., 2012). Meanwhile, one of the studies identified in Latin American corresponded to one performed for the city of São Paulo, Brazil (Mendes et al., 2004), while the remaining are more recent ones: one carried out for a generic Brazilian scenario (Lima et al., 2018) and for specific Peruvian case studies throughout different geographical contexts (Ziegler-Rodriguez et al., 2019). Further information regarding the studies is depicted in Table 4. A map shown in Figure 7 shows the worldwide distribution of the studies selected.

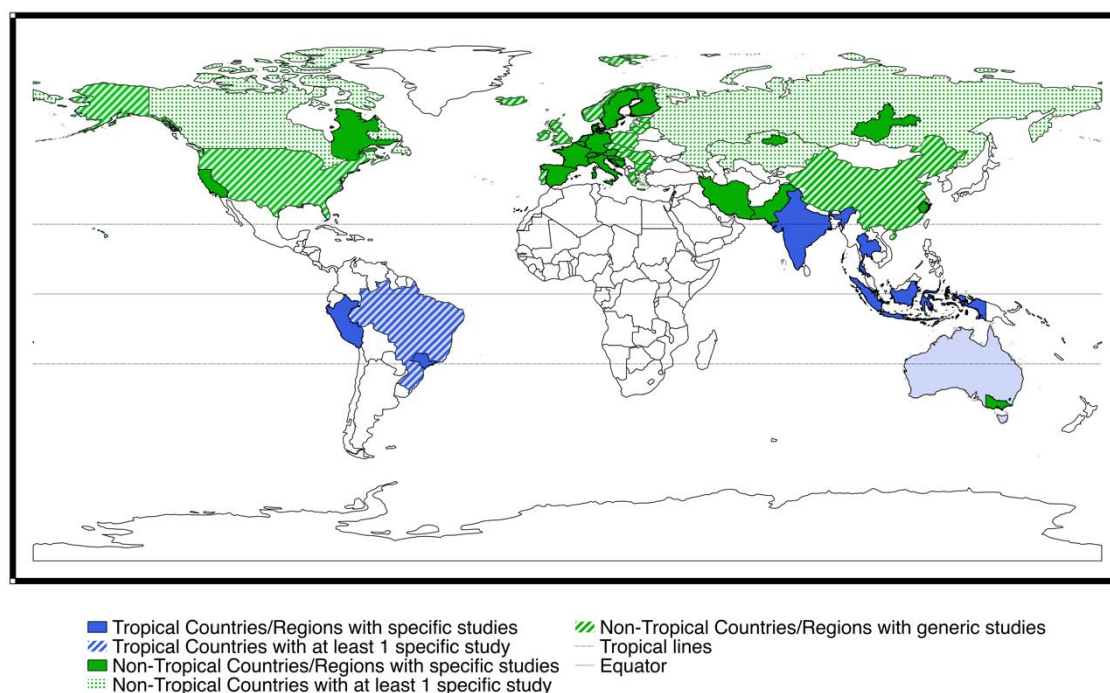


Figure 7. Geographical location of landfill LCA studies retrieved from the scientific literature.

Table 4. List and main characteristics of the landfill-related LCA studies selected in the review.

Authors	Geographical Location	Functional Unit	LCA perspective (Atributional/ Consequential)	System Expansion/ Allocation	Model/ Tool	Assessment method
Abduli et al. (2011)	Tehran (Iran)	1 tonne of MSW	A	n.s.	LandGEM	Eco-Indicator 99
Ali et al. (2017)	Lahore (Pakistan)	1 tonne of MSW generated annually	A	System Expansion: Substitution	EASETECH	ILCD recommended
Aye and Widjaya (2006)	Indonesia	1 tonne of traditional market wastes in Jakarta	A	System Expansion: Substitution	IWM2	n.s.
Belboom et al. (2013)	Belgium	Treatment of 1 tonne of MSW	A & C	System Expansion: Substitution	n.a.	ReCiPe
Beylot et al. (2013)	France	The biogas management at a landfill site for a 100 year life-time perspective, considering 1 tonne of French average residual MSW	A	System Expansion: Substitution	EASEWASTE	IPCC 2007, ReCiPe, USEtox

Bjelić et al. (2015)	Banja Luka (Bosnia & Herzegovina)	Landfilling of 1 tonne of wet waste in a 20 m deep landfill considering a time horizon of 100 years	A	n.s.	EASETECH	EDIP97, USEtox
Camobreco et al. (1999)	United States	Treatment of 1 short ton of MSW	A	System Expansion: Substitution	SWANA & EPA emission models	n.a.
Cherubini et al. (2009)	Rome (Italy)	1460 kt of waste contained in the so-called “black sacks” (i.e. pre-sorted and recycled wastes not included)	A	Allocation: Exergy content	n.a.	MFA, GER, & SPI
Demetrius and Crossin (2019)	Victoria (Australia)	Treatment of 1 kg of each individual material, mixed paper and mixed plastic	A	System Expansion: Substitution	SimaPro based	IPCC 2007, CML

Finnveden et al. (2005) and Moberg et al. (2005)	Sweden	Treatment of the amount of the included waste fractions collected in Sweden during one year (1.2 million tonnes)	A	System Expansion: Substitution	n.s.	EDIP97, USES-LCA
Fernández-Nava et al. (2014)	Asturias (Spain)	Management over a period of one year of 480,000 tonnes of MSW generated in Asturias	A	n.s.	SimaPro based	Impact 2002+
Hadzic et al. (2017)	Zagreb (Croatia)	1 tonne of wet MMW produced in households in a 100 year time-horizon	A	System Expansion: Substitution	EASETECH	EDIP97

Khoo et al. (2012)	Singapore	Per year of Singapore-generated landfill material, comprising a mixture of both incineration ash and non-incinerable MSW in variable proportions.	A	n.s.	EASEWASTE	EDIP 2003
Kong et al. (2012)	California (United States)	Treatment of 1 tonne of wet organic matter	A	System Expansion: Substitution	LACSD model	n.a.
Liamsanguan and Gheewala (2008)	Phuket (Thailand)	1 tonne of MSW treated	A	System Expansion: Substitution	n.s.	n.s.
Lima et al. (2018)	Brazil	Management of 1 tonne of MSW	A	System Expansion: Substitution	EASETECH	ILCD recommended
Maalouf and El-Fadel (2019)	Beirut (Lebanon)	Management of 1 tonne of waste generated in the test area	A	System Expansion: Substitution	EASETECH	ILCD recommended

Manfredi et al. (2009)	Europe	1 tonne of wet waste landfilled	A	System Expansion: Substitution	EASEWASTE	EDIP97
Manfredi et al. (2010a)	The Netherlands & Denmark	Landfilling of 1 tonne of wet waste in an up-to-date low-organic waste landfill considering a 100-year life-cycle time horizon	A	System Expansion: Substitution	EASEWASTE	EDIP97
Manfredi et al. (2010b)	Denmark	1 tonne of mixed wet MSW	A	System Expansion: Substitution	EASEWASTE	EDIP97
Manfredi et al. (2011)	Europe	Treatment of 1 tonne of wet individual waste fraction	A	System Expansion: Substitution	EASEWASTE	EDIP97
Manfredi and Christensen (2009)	Denmark	Landfilling of 1 tonne of wet household waste in a 10 m deep landfill for 100 years	A	System Expansion: Substitution	EASEWASTE	EDIP97

Ménard et al. (2004)	Quebec (Canada)	Stabilization of 600 tonnes of MSW in a landfill and the production of 2.56E8 MJ of electrical energy and 7.81E8 MJ of heat energy	A	System Expansion: Substitution	n.a.	EDIP97
Mendes et al. (2004)	São Paulo (Brazil)	Treatment of 1 tonne of MSW	A	System Expansion: Substitution	Integrated Solid Waste (ISW)	EDIP97
Niskanen et al. (2009)	Finland	Landfilling of 10 million tonnes of waste considered for 100 years, from 1987 to 2087	A	System Expansion: Substitution	EASEWASTE	EDIP97
Noya et al. (2018)	Astana (Kazakhstan)	1 tonne of treated MSW	A	System Expansion: Substitution	SimaPro based	IPCC 2013, ReCiPe
Obersteiner et al. (2007)	Europe, Austria, Germany & Switzerland	1 tonne of waste sent to the landfill and lying in place for 30 years	A	System Expansion: Substitution	Measurements, empirical data and multi-input inventory tools	n.s.
Sharma and Chandel (2017)	Mumbai (India)	1 tonne of MSW	A	System Expansion: Substitution	Gabi 6.0 & IPCC	CML 2001

Starostina et al. (2014; 2018)	Irkutsk (Russia)	Handling 500 000 tonnes of municipal waste yearly in the municipal waste management system	A	System Expansion: Substitution	EASETECH	IPCC 2007, EDIP97, ReCiPe, CML, USEtox
Wanichpongpan and Gheewala (2007)	Indonesia	1 tonne of collected MSW	A	System Expansion: Substitution	LandGEM	IPCC 2007
Yadav and Samadder (2018)	Dhanbad (India)	1 tonne of MSW	A	System Expansion: Substitution	SimaPro based	CML 2 2000
Yang et al. (2014)	China	1 tonne of landfilled MSW	A	n.s.	EASETECH	EDIP 2003
Zarea et al. (2019)	Ahvaz (Iran)	Disposal of 292,000 tonnes of municipal wastes	A	n.s.	IWM	TOTAL 4.0 (CML 2002 based)
Zhou et al. (2019)	Hangzhou (China)	1 tonne of MSW	A	System Expansion: Substitution	Gabi 8.0	CML 2001
Ziegler-Rodriguez et al. (2019)	Peru	1 tonne of landfilled MSW in 100 years in three different cities: Lima, Cusco and Nauta	A	System expansion: Substitution	EASETECH	IPCC 2013, ReCiPe

On the one hand, it is imperative to mention that European and North American case studies may not be representative for LA&C due to their technological and geoclimatic conditions (Henriksen et al., 2018), as well as MSW generation patterns (Hoornweg and Bhada-Tata, 2012). However, given the absence of LCA studies focusing on landfilling in LA&C, and the fact that the countries in this region tend to replicate policies and technologies already established in these developed countries (Kahhat et al., 2018; Ziegler-Rodríguez et al., 2018), results in these areas may still be relevant either as a benchmark or as a screening of how current scenarios could be improved in the future.

On the other hand, it is important to bear in mind that most of the LCA case studies in India and Southeast Asia are located in tropical (i.e., Indonesia, Thailand and Singapore) or subtropical (i.e., China) zones. Therefore, the environmental impacts analyzed in these studies present different implications with respect to the studies located in the temperate nations. It is also important to take into consideration that because of the climatic and geographical conditions, waste decay in landfills in tropical Asia may resemble that of LA&C landfills when taking into account that most of Latin America is located in tropical areas – Af, Am, As or Aw equatorial climates according to Köppen-Geiger classification (Kottek et al., 2006). Moreover, in both regions the amount of organic material present in MSW is high (Hoornweg and Bhada-Tata, 2012). The results of these articles reinforce the conclusions reached by the few studies addressing the Latin American reality, specifically in Peru and Brazil. They show that generation, management and most importantly decomposition patterns are greatly comparable to LA&C's current situation (Mendes et al., 2004; Lima et al., 2018). For instance, as shown in Ziegler-Rodríguez et al., (2019), a series of case studies and scenarios in a wide range of geoclimatic realities in Peru were analyzed. Waste decay in

areas under tropical conditions, such as the Amazon Rainforest, occurs at a faster rate as compared to arid or highland climatic conditions. Considering these patterns while designing waste management strategies is crucial to develop an adequate integrated waste management system with low environmental impacts.

3.5 Waste treatment emission models

LCA modelling is extremely important in the waste sector because it allows researchers to obtain indications on different types of emissions (i.e., air, leachate, soil) based on a series of known parameters, such as waste composition, treatment methods and stages, technologies and other relevant considerations (Bisinella et al., 2017). As aforementioned, solid waste decomposition and LFG generation follow a first order decay model (USEPA, 1998, 2005a; IPCC, 2006). This model considers a degradation rate, “ k ”, which is dependent on several site-specific parameters such as temperature, moisture content, waste composition or pH, among others (USEPA, 2005a; Garg et al., 2006; Park et al., 2018). In the particular case of landfilling, it is imperative that the waste degradation rates and, subsequently, the k values, are tracked in an adequate way in order to obtain robust results, modelled according to the local geographical and climatic conditions (Lee et al., 2017).

A previous review by Gentil et al. (2010) analyzed the technical assumptions performed in several waste LCA models available at the time in the literature. They identified more than 50 waste models developed in Europe alone, all with different applicability, functionality license restrictions, and costs, but also regarding functional unit, time horizon, waste composition and waste treatment alternatives included. Some of the most commonly used models are EASEWASTE, which has now been substituted by EASETECH, EPIC/CSR, IWM2 and ORWARE, among others (see Table 2 in Gentil et al., 2010 for details on each one). Other models were identified as being less

significant given their limitations (e.g., scarce information availability or limited waste treatment alternatives). The main conclusion of Gentil and colleagues (2010) was that, despite many models being developed independently, in general terms they appeared to be consistent when compared, although some contradictory results were identified, such as leachate generation per amount of waste analyzed, the distinction or not between fossil and biogenic carbon, which generated emission overestimations or the exclusion of carbon sequestration in some cases. Moreover, they discussed the benefits and deficiencies of the available models with the aim of leading the practitioner towards more feasible conclusions regarding the selection of the model according to their needs.

In the current study, up to 10 different modelling tools were identified in the literature. Once again, EASETECH, and previously EASEWASTE, appeared as the most recurrently used model. A more detailed description of the EASEWASTE model can be found in Kirkeby et al. (2006) and of the EASETECH model in Clavreul et al. (2014). These two models, developed by researchers at the Technical University of Denmark (DTU), were used in 16 of the 37 articles included in the current review. We hypothesize that this can be due a number of aspects, including the versatility of the software, its user-friendliness, or its capacity to model almost any waste management system, including energy substitution and other criteria, according to the practitioners' requirements. In addition, the database in EASETECH has experienced continuous updates and has been expanded through time, allowing the practitioner's experience and analysis capabilities to be improved.

Other relevant models include LandGEM, LACSD, or IWM2. LandGEM (Landfill Gas Emission Model) is a tool developed by USEPA aimed at estimating LFG emission rates, including non-methane volatile organic compounds (NMVOCs) and other individual air pollutants for the specific case of US landfills. It includes generic

information and allows the practitioner to estimate unavailable site-specific parameters based on both the facility's available characteristics and the software's generic data. This tool focuses on allowing landfilling stakeholders to determine whether or not their facilities are subject to the required control regulations with an LCA approach (USEPA, 2005b). Hence, it is considered an LCA-based policy support tool. LACSD is another US-based tool developed by the Los Angeles County Sanitation Districts (LACSD). However, it only includes California-specific information regarding its waste management situation with an LCA perspective. In a similar way to the LandGEM model, it is aimed at improving policy support. Nevertheless, it is not landfill exclusive, as it includes transport information and other waste management technologies (Kong et al., 2012). The IWM2 model, developed in the UK (McDougall, 2001), aims at modelling more sustainable waste management systems. In consequence, it uses the software's LCI to evaluate consumption of resources, emissions to air, water and soil, and the production of waste-based sub products. It is also aimed at being a decision support tool for waste management stakeholders, in order for them to design better systems.

3.6 Selection of assessment methods and impact categories

The assessment methods are the computational models to calculate the environmental impacts linked to the list of substances that generate impact in a particular environmental compartment. The assessment methods used in the reviewed studies vary depending on the year of publication of the study. In this sense, it should be noted that numerous assessment methods have been developed or updated in the past decade. For instance, the revised version of ReCiPe was released in late 2016 and few manuscripts in the literature have included this method in their analysis (ReCiPe, 2016). In fact, none of the studies included in the review used this updated method.

The abovementioned environmental compartments that reflect a common cause-effect environmental hazard are aggregated in what are named impact categories (ISO, 2006a). Differing assessment methods may aggregate environmental compartments into different impact categories, with specific assumptions and embedded uncertainties. Consequently, results regarding a specific impact category will be highly influenced by these assumptions and limitations. Moreover, impact categories can be divided into midpoint and endpoint categories. The former are based on reporting a direct emission to the environment caused by anthropogenic activities (e.g., kg CO₂eq). The latter, in contrast, report a damage in one of the so-called areas of protection, such as human health or ecosystems damage (Vázquez-Rowe et al., 2015). Interestingly, in the case of the selected sample of studies assessed, only Abduli et al. (2011) provide endpoint environmental impacts linked to landfilling.

On the one hand, some assessment methods, like the subsequent IPCC updates, are single issue methods that focus on one single impact category, in this case, climate change (IPCC, 2013). In fact, as shown in Figure 8, climate change is repeatedly the most used impact category in landfill-related LCA studies. However, it should be noted that not in all cases the IPCC method is applied, but that of other assessment methods (e.g., ReCiPe, CML...). Nevertheless, in most cases the latter model climate change impacts based on assumptions and criteria provided by the IPCC (Hauschild et al., 2013). On the other hand, several assessment methods provide a wide range of impact categories in different areas of protection, allowing the assessment of a wider range of impacts, but also identifying trade-offs between categories (Laurent et al., 2012). For example, LCA results analyzing the transition from open dumpsters to different landfilling technologies in Peru provided interesting insights (Ziegler-Rodriguez et al., 2019). Even though the transition to facilities without LFG treatment increased air

pollution (e.g., climate change and particulate matter formation), it reduced other impacts such as eutrophication and toxicity.

While a commonly used justification for the choice of method is the existence of previous studies in the literature using that same method, we argue that this assumption should be applied cautiously. In this sense, previous studies using a specific method should not be a barrier for practitioners to apply more updated, accurate or novel methods or impact categories when needed. For instance, GHG emissions have been identified as a critical environmental concern in landfilling. Therefore, it appears evident that an effort to use more updated methods, with revised and more accurate characterization factors and improved comprehensiveness in terms of the number of GHGs included should be prioritized ahead of comparability with past studies.

In addition, as LFG is produced by microbial activity through anaerobic degradation of organic matter, it is mainly made up by CH₄ (50-60% by volume) and CO₂ (40-45% by volume) (Beylot et al., 2013). However, up to other 200 NMVOCs add up to less than 1% of the volume of the LFG. Regardless of the low concentrations of these gases, they have considerable negative environmental consequences, both on a global and local scale. Examples of these are hydrofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs), which have elevated potential impacts in categories different to climate change, such as ozone depletion (Molina and Rowland, 1974; Ravishankara et al., 2009). In consequence, it is important for both practitioners and stakeholders to consider these trace gases throughout their assessment in order to have more accurate studies and identify better treatment options.

Linked to the discussion on selection of assessment methods and impact categories, Hauschild and colleagues (2013) performed several recommendations based on the scientific quality and stakeholder acceptance of characterization models.

Although some of the methods that were used in this assessment may seem currently outdated, such as IPCC 2007, many of the recommendations and findings may still be valid nowadays. More recently, the UNEP-SETAC Life Cycle Initiative initiated a global consensus process to agree on an updated life cycle impact assessment (LCIA) framework and to recommend a non-comprehensive list of environmental indicators and LCIA characterization factors (Jolliet et al., 2018). More specifically, this consensus framework focuses on how climate change, fine particulate matter impacts on human health, water consumption impacts (both scarcity and human health) and land use impacts on biodiversity should be reported to support UN Sustainable Development Goals – SDGs (Jolliet et al., 2018). Consequently, it is expected that this framework, which will probably be subject to periodical updates, may be a repeatedly used protocol to quantify and monitor progress towards sustainable production and consumption in developing and emerging economies, such as those in LA&C (Jolliet et al., 2018).

The selection of different impact categories by the practitioners throughout the studies assessed varies depending on their scope and objective. A large number of impact categories were identified, especially when considering that the different methods involved may have similar categories with different names. In consequence, to identify a clear trend between the several analyzed papers, some related impact categories have been grouped into less specific sections, which can be seen in Figure 8, as well as the amount of studies including them. Despite the fact that not all studies have the same impact categories, and some do not even include toxicity-related categories, what they all concur on is on the inclusion of Global Warming Potential/Climate Change. This preponderance of climate-related categories is linked to the importance that this environmental threat has developed in the current world, but also due to the importance of methane and carbon dioxide emissions in the

decomposition of organic landfilled waste. Nevertheless, we consider that the inclusion of other impact categories other than GHG-related impact categories is critical in final disposition units. For instance, eutrophication or acidification may have important impacts at a regional or local level. However, when addressing non-GHG related categories, practitioners must proceed with caution. For example, for toxicity-related impact categories (e.g. USEtox's Human Toxicity (Laurent et al., 2011) or EDIP's different Eco-Toxicity categories (Wenzel et al., 1997) the characterization of thousands of substances is still under evaluation, implying that underestimation and omissions of many toxic substances should be expected as well as high uncertainties in the characterization factors of the reported substances. Similarly, certain environmental hazards, such as the release of mismanaged macro-, micro- and nano-plastics to water bodies or soil sediments are yet to be included in life cycle methods (Sonnemman and Valdivia, 2017).

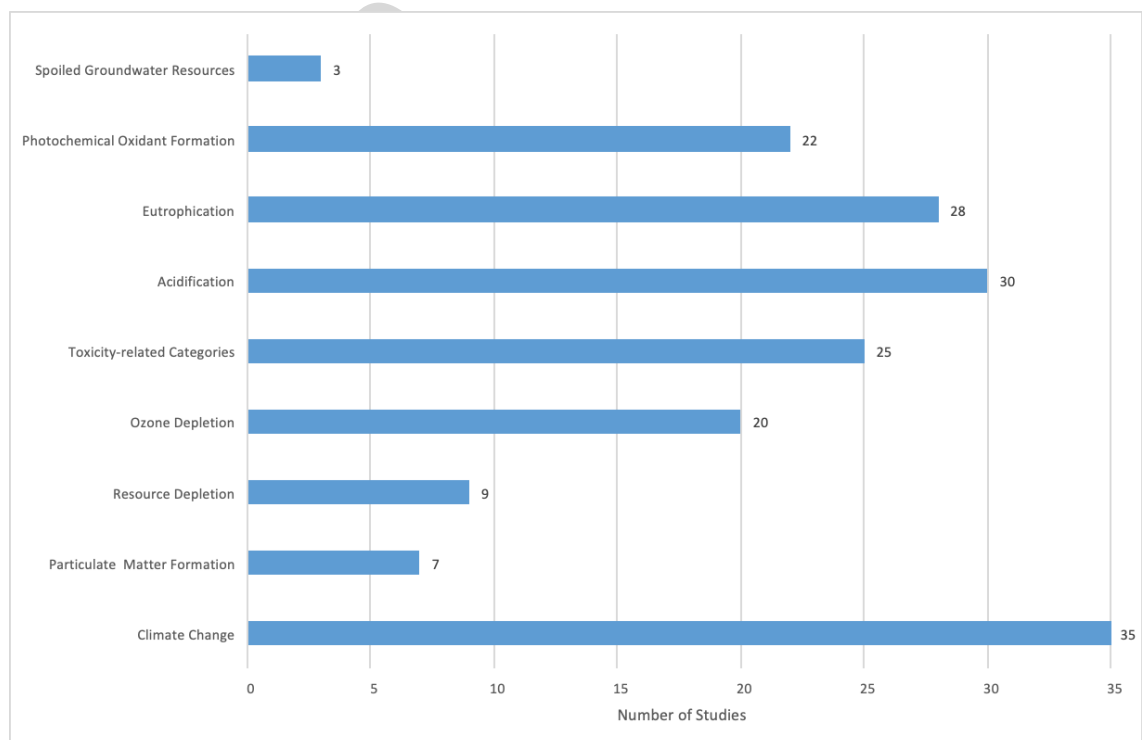


Figure 8. Total amount of studies from the sample selected that include the main impact categories available in Life Cycle Impact Assessment methods.

Further comparisons could not be carried out, not only because of the difference between methods, impact categories and assumptions, but also because some studies presented the results with normalized values rather than characterization values. This implies that impacts have been scaled based on several and different assumptions which can depend of the practitioners' criteria. Additionally, the normalization factors were only found in Starostina et al. (2014), Yang et al. (2015), Bjelic et al. (2015) and Lima et al. (2018).

3.7 Uncertainty and Data Quality

All along these studies, while modelling biodegradation, different approaches are taken: some assumptions are made due to generic emissions and the amount of biogas and products available, while others are made based on calculations regarding waste composition and technical parameters. In general terms, the deterministic LCA studies included in this review lacked a deep uncertainty analysis. This situation should be considered a considerable drawback in the robustness of the studies, since the practitioners are not accounting for epistemic uncertainty due to data gaps, or other types of uncertainty, such as variability or uncertainty linked to methodological choices (Mendoza Beltran et al., 2018).

An important source of uncertainty in waste decomposition is the variable behavior of organic matter degradation under different conditions, namely linked to climate or the existence of aerobic or anaerobic conditions. In fact, IPCC suggest that LFG should be based on a first-order decay of degradable organic carbon (IPCC, 2006). However, for some regions certain studies have been developed to address specific

decomposition rates (Garg et al., 2006; USEPA, 2011; Park et al., 2018), these represent mainly mild and cold climates, and do not apply for many areas of the world, especially those in tropical regions. Consequently, to study landfills located elsewhere, the IPCC developed a model to estimate decomposition rates according to their geo-climatic location (IPCC, 2006). Although these rates are presented in wide ranges and with important embedded uncertainties, they constitute an important reference for many areas of the planet for which rigorous on-site modeling is yet to be performed. However, as these presented ranges cover broad values, practitioners should be extremely careful while addressing them, as a slight erroneous assumption might translate into result variations of several orders of magnitude.

Other variability and uncertainty sources come from the different scenarios assumed and system boundaries analyzed (Clavreul et al., 2012). Different processes included in each assessment may vary, and each cut-off criteria might be justified according to the ISO 14040 (ISO, 2006). Having said this, it is important for practitioners to address uncertainty and data quality, as the impact assessment methods and simulation models are approximations of the reality and not a specific 'number' as many people tend to misunderstand. With this in mind, Igos and colleagues (2018) provide an analysis and recommendations of different approaches to identify, characterize, propagate, understand and communicate uncertainty for LCA practitioners, as uncertainty is present in diverse ways and at several levels throughout LCA studies.

Throughout the reviewed articles, even though some authors recognize the absence of high quality data regarding certain parameters, which lead them to use secondary data from the literature, they do not consider neither carrying out a sensitivity analysis or an uncertainty propagation analysis. This is particular true for publications prior to 2012, which on the other hand indicates that there is a tendency towards a

higher accountancy of uncertainty in LCA studies in recent years. Having said this, it is important to note that even though a great majority of studies omit uncertainty computation either with a Monte Carlo Simulation or by other methods, most studies do identify uncertainty sources in a descriptive way.

Within the group of selected studies published before 2012, only 6 out of 17 performed a sensitivity analysis. Nevertheless, some authors do not even realize the possibility of data gaps, uncertainty or low quality information. In studies published after 2012, the trend is clearly different, as most of them (13 out of 18) include sensitivity analyses regarding either scenario uncertainty or parameter uncertainty.

4. Challenges and conclusions

This review article analyzed the situation of waste generation, collection and final disposal around the world, with a special emphasis on LA&C. Current challenges and opportunities regarding LAC's waste management situation have been exposed. The overwhelming use of landfilling in the region as the main solution to the waste problem, which still widely arrives mismanaged to the natural ecosystem, the integration of the informal sector in an integrated waste management system or the inclusion of alternative waste technologies (e.g., waste to energy technologies) into the system appear as the main challenges that the sector faces in the 2030 horizon. Moreover, the need to synchronize these policies with the concept of circular economy and with the GHG emissions mitigation strategies expected within the frame of the Paris Agreement, leads us to hypothesize that the period 2020-2030 could experience substantial changes in the sector in LA&C if political stability and economic growth allow the necessary investments to make this possible.

A notable literature gap that was identified in this review was the lack of life-cycle oriented studies linked to the waste management sector in LA&C. The literature review performed on waste LCA elsewhere allowed to determine that direct comparison between studies may be complex. This is due to differing temporal and geographical conditions, but also to variable methodological assumptions. In fact, from a methodological perspective, the function and, therefore, the FUs of many study presented notable differences. Hence, they were not found to be commensurable from a temporal, geographical or waste composition perspective (Laurent et al., 2014b). Other methodological challenges that hinder comparability include the depth of the assessed inventories, their quality, and the varying assumptions in terms of selecting waste models and LCIA assessment methods. Despite all these differences, common trends can be identified regarding the environmental impacts of these technologies, as they can not only be addressed independently as a usual single-study would do, but in a collective way. Consequently, in a context in which important know-how can be obtained from studies in other regions of the world, we recommend LCA practitioners in the LA&C region to develop site-specific studies for the waste sector as a strategy towards providing policy support to local and regional authorities in the region.

In recent years the available literature, most of which has been discussed in this review, has shown that landfills, even when technologically advanced with LFG treatment or energy recovery, present higher environmental impacts than other treatment methods, such as incineration or biological treatment. In other words, in studies that included a comparison between landfilling and other treatment methods, usually the alternative treatments (e.g. incineration, recycling, biological treatment) performed better. Nevertheless, the actual implementation of these alternative technologies in LA&C is complex, especially considering that the region is struggling to

fully-transition towards landfills while eradicating open dumpsters. Despite the higher investment costs, however, a second transition to more advanced waste treatment technologies in the region will be imperative in the next couple of decades. Therefore, we also recommend that practitioner should include prospective life-cycle studies in the region to account for future alternative technologies to treat or recover waste.

Having said this, the fact that other treatment methods have better performance as compared to landfills does not mean that they perform equally in different locations or with variable MSW compositions. As previously mentioned, tropical countries, including those in LA&C, present higher organic waste fractions in their MSW, and as stated before, k decomposition rates increase with higher temperatures and moistures, generating a faster decomposition. Hence, it is important for stakeholders and policy-makers to avoid replicating policies from developed economies around the world without taking into consideration those local and/or regional scenarios may deserve site-specific modelling.

With regards to landfilling, as expected, better technologies presented lower impacts compared to uncontrolled dumping or conventional landfilling without energy recovery. However, as several studies show, the performance of specific sophisticated technologies (e.g., bioreactor Technology, semi-aerobic Technology) depend on local factors, as some may perform better in specific aspects than others and vice-versa. Nevertheless, what remains clear is that something as simple and low cost as flaring the LFG will improve the performance of a conventional landfill considerably.

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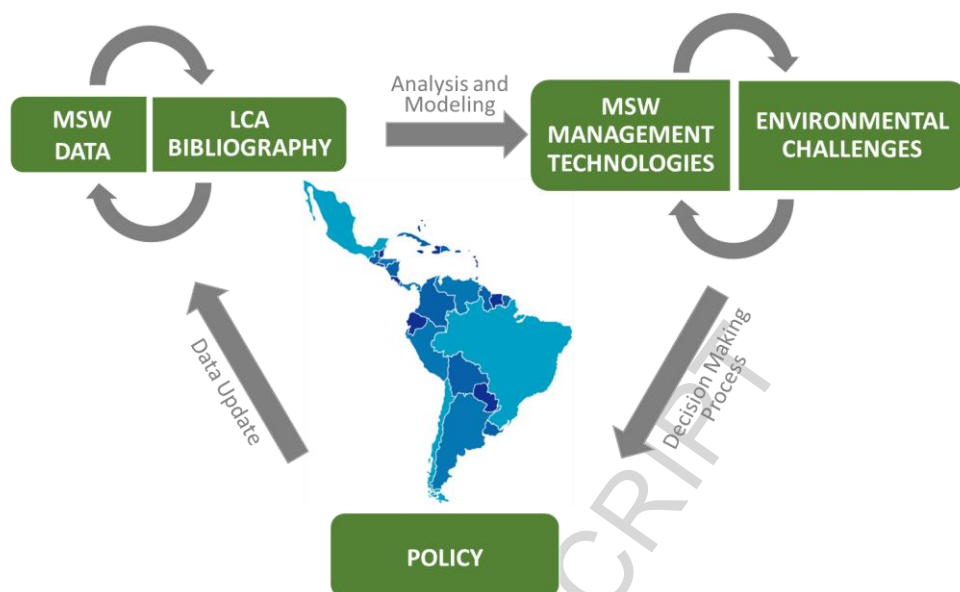
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Graphical abstract

Enhancing waste management strategies in Latin America under a holistic environmental assessment perspective: a review for policy support

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Highlights

- Waste management remains an important challenge in Latin America.
- The implementation of novel technology is still lagging throughout the region.
- Analysis on environmentally-based policy support for stakeholders is presented.
- Life-cycle methods are analyzed as key indicators to improve decision-making.
- Recommendations sustained on a holistic view to support policy are discussed.