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The state-of-the-art of organic waste to energy in Latin America and the Caribbean: Challenges and opportunities

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A B S T R A C T

Organic waste to energy (OWtE) technologies have been developed and implemented in Latin America and the Caribbean (LAC) countries. However, they are still far away to significantly contribute not only to treat the ever-increasing waste volumes in the region but also to supply the regional energy demand and meet national carbon emission goals. The technical complexity of these technologies aligned with lack of research, high investment costs and political deficiencies have not allowed for an appropriate implementation of OWtE in the region, where the applicability of large-scale plants remains to be demonstrated. This research presents the state-of-the art of OWtE technologies in the context of the LAC countries based on archival research method. In addition, it presents challenges and opportunities that the region is facing for an adequate implementation of these technologies. The main findings show that OWtE have the potential to improve waste and energy systems in the region by reducing environmental impacts along with a series of social and economic benefits, such as increasing access to a sustainable energy supply. Diverse researches indicate principally anaerobic digestion, fermentation (e.g. 2G bioethanol, etc.), microbial fuel cells, gasification and pyrolysis as efficient technologies to treat solid organic wastes and produce bioenergy.

1. Introduction

Throughout the world, several studies and actions have been successfully carried out to apply Organic Waste-to-Energy (OWtE) technologies for managing and treating solid organic residues.[1] In the specific case of the Latin America and the Caribbean (LAC) countries, these practices have already been developed and implemented. However, there is still a long way to significantly contribute, not only to manage and treat the ever-increasing waste volumes in the region, but also to supply the regional energy demand and meet national goals for carbon emissions. Hence, biowaste (i.e. household organic wastes and forest and agricultural residues) is still not sufficiently recognized as a valuable energy source with significant potential and. As a result, it is largely underused in the region.

OWtE technologies in the LAC countries differ from one country to another. For the last 40 years, local experiences have varied regarding implementation strategies and sectorial applications due to political contexts and technological changes in the period. High upfront costs, deficiency in access to sophisticated technology, lack of participation of stakeholders, and public policy deficiencies have not allowed for an appropriate implementation of relevant technologies for biowaste treatment, resulting sometimes in serious environmental and health impacts due to lack of proper final disposal [1]. In addition, the continuing increase of electricity

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[1] As a result, the research does not cover biodiesel production, especially from waste streams.

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demand in the region have forced local stakeholders (e.g. farmers, waste managers, researchers, etc.) to look for ways to optimize existing waste treatment options, which could allow energy recovery [2]. Thus, the idea of searching for and implementing affordable waste to energy (WtE) strategies has been lately gaining momentum and fostering debate on whether specialized technologies, such as thermochemical or biochemical, can assist on supplying local energy demands. Other important benefits, such as improving nutrient recycling and avoiding the consumption of conventional fossil fuels, are encouraging the adoption of these technologies. Local projections expect biomass (e.g. biofuels) and biowaste to significantly contribute for energy production, but the applicability of such projects for large-scale production remains to be demonstrated in most of the cases in the region [3].

Although the preliminary examination of the body of knowledge shows that diverse literature related to OWtE in LAC, such as publications from the Network for Biodigesters in Latin America and the Caribbean (RedBioLac), academic papers from distinguished international journals, etc., exists, a *state-of-the-art* literature review and a broad frame of literature reference have not been adequately developed. Hence, the overarching goal of this research article is to contribute to the development, adoption and diffusion of technologies that generate social, economic and environmental values from the use/treatment of organic residues in the LAC region, by building a *state-of-the-art* of the regional and current technological context. In order to advance towards this goal, the present study has a twofold aim: On the one hand, it aims at systematizing the current state of knowledge about the technological and environmental situation of OWtE in the LAC context. On the other hand, it targets to identify knowledge gaps, challenges, and opportunities for further development and promotion of these technologies as tools for achieving the sustainability goals in the region, such as reducing carbon emissions under the Paris Agreement. It is important to mention that this in-depth and descriptive literature review attempts to cover all aspects and facets of the matter from a regional context.

2. Literature review strategy

The research methodology used is the Archival Research Method (ARM), which was implemented as a method to conduct and evaluate the existing literature and domain files. The ARM is regarded as a research strategy for the examination of previously recorded facts, which depend on the originality of the documents, primary and secondary official files and records gathered by other investigators and researchers [4].

In order to accomplish an exhaustive literature review, it was necessary to cover an in-depth and wide range of publications. The ARM comprises the following steps:

i. *Defining database source:* the review covered well-established scientific databases (i.e. *Scopus*, *ScienceDirect*, *Web of Science*, etc.) and publications from renowned international institutions (i.e. United Nations Economic Commission for Latin America and the Caribbean (ECLAC), United Nations Environment Program (UNEP), World Energy Council (WEC), etc.). The data collection was conducted in three languages: English, Portuguese, and Spanish.

ii. *Delimitation of the scope:* the timeframe covered almost two decades, from 2000 until 2019, in order to include recent and historical publications.

iii. *Defining unit of analysis:* the review included single research papers, reports, books, and Internet articles. Given the large number of academic articles, the selected research articles are from the top 25% international scientific journals, according to the SCImago Journal Rank (SJR) indicator, based on the research topic related to waste, environment, and energy themes. The SJR rank is an indicator to measure scientific influence of academic journals and it accounts for both the number of citations received by a journal and the importance or prestige of the journals where such citations come from. Other sources were Institutional websites, academic databases containing reports, MSc theses and PhD dissertations, among other sources of scientific publications.

iv. *Sampling:* the first sample of documents was defined by searching the selected keywords and Boolean connectors: *lignocellulose** OR *organic* OR *biowaste* AND *waste** OR *residues** AND *energy** OR *biogas**. The first sample contained 21,024 publications.

v. *Applying regional filtering:* collected documents were filtered according to the region of interest and considered all countries and sub-regions in LAC: North, Central and South America and Caribbean Islands. This step reduced the number of publications from 21,024 to a second sample with 482 documents.

vi. *Conducting a general compilation:* the documents from the second sample were then stored and organized to discard repeated information and avoid duplicity. As a result, the second sample was reduced to 342 publications.

vii. *Defining final sample:* the third sample was classified by geographical scope and through deductive analysis was categorized into two main topics: thermochemical and biochemical technologies, following by a sub-categorization on the specific type of technology (i.e. combustion, gasification, pyrolysis, anaerobic digestion, fermentation, landfilling, and microbial fuel cells). After reading all abstracts and conclusions of each one of the documents within the third sample, documents containing very technical information (i.e. documents fully describing biochemical process) and/or specific research articles (i.e. documents describing budget details) were discarded. The fourth and final sample contains 199 documents and it was organized by country of interest. Fig. 1 illustrates the sampling steps and the number of selected publications for each one of the steps.

Once the relevant documents were selected, a deep and detailed content analysis was carried out. Content analysis (CA) is a research technique used to make replicable and valid interpretations by systematically evaluating texts (e.g. academic articles, reports, and other publications) and converting them into valuable information that allows researchers to examine nuances of organizational behaviors, stakeholder perceptions, and societal trends [5]. The aim of using CA in this case was to collect information that was useful for understanding the current state, viability and the potentials of the thermochemical and biochemical technologies in the given geographical context; as well as observations about research gaps, opportunities and challenges. To achieve this, each document was read and analyzed, and coded, highlighting and selecting relevant pieces of information. The goal was to search for patterns and cluster observations into related subtopics to finally compare and synthesize their state in each subregions and country. After gathering relevant information from selected publications, they were organized into a summary table (see Table 1).

3. The current technological context in Latin America and the Caribbean

Every year millions of tonnes of agricultural, forest, and urban waste are generated in LAC. Their potential as alternative energy sources has been identified. In fact, several studies in recent years

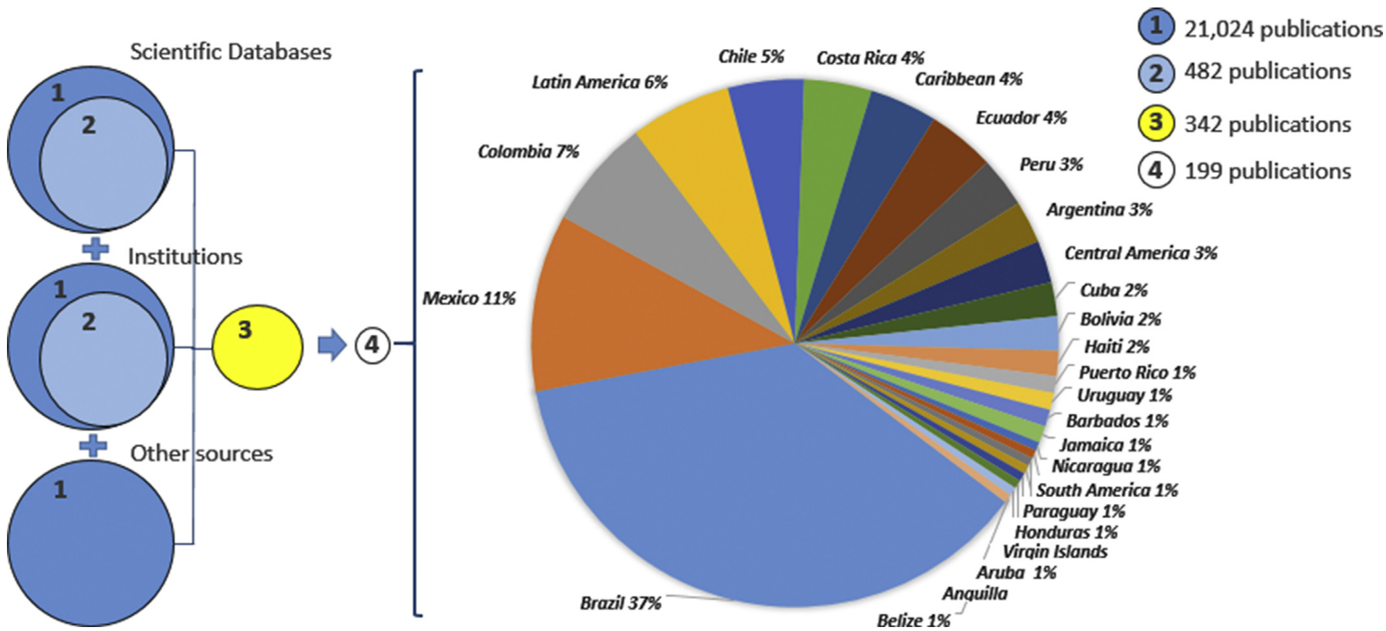

Fig. 1. Sampling steps and number of documents for each one of the steps.

have presented technical, environmental, and economic analyses of different OWtE technologies as well as their comparative performances for bioenergy production. However, they are not fully explored in the region.

In order to facilitate the analysis and presentation of results, this review follows the technological classification established by the WEC [6] to present the compiled information in two main technological classifications and their subcategories: a) thermochemical and b) biochemical processes.

Thermochemical technologies include combustion or incineration, gasification and pyrolysis. Among them, incineration is the most commonly practiced in the region [7,8]. Nevertheless, there is an ongoing debate on whether this is the right organic waste treatment method, considering the negative environmental effects and the low process efficiency these technologies portray when compared to other treatments such as pyrolysis and gasification systems.

Biochemical technologies comprehend anaerobic digestion, fermentation, landfilling gas capture, and microbial fuel cell (MFC) technologies [6]. Research and Development (R&D) in the region has been mostly focused in small-scale anaerobic digesters (AD) [9] and landfilling. In addition, R&D has studied fermentation to a lesser extent. Nonetheless, interest in large-scale biodigesters, second-generation (2G) biofuels, and MFCs has been gaining ground in countries such as Argentina, Brazil, Chile, Colombia, and Mexico.

3.1. Thermochemical technologies

Existing thermochemical technologies (e.g. incineration, gasification, and pyrolysis) use heat to promote chemical transformations of biomass into energy and chemical products. On the one hand, these technologies follow similar processes to create three main products: solid (e.g. char and/or ash), liquid (e.g. bio-oil or tar), and gas (e.g. syngas or producer gas). On the other hand, each process uses different reaction conditions such as temperature, pressure, heating rate, residence time, reactive or inert atmosphere, purge gas flow rate, and so forth [6].

Currently, incineration is the most used technology in the region, but gasification and pyrolysis present some advantages over it such as being a more thermally efficient and flexible system regarding the utilization of downstream products (e.g. biofuels, chemicals or fertilizers) [10]. The decision for selecting any of these technologies is related to:

- The type of residues or lignocellulosic materials being treated;
- What energy carries are being developed; and
- The local interest.

For example, direct combustion can produce steam to generate electricity. Gasification produces a lower heating value gas, which can be used to power gas turbines [8]. Furthermore, Parascanu et al. (2017) concluded that for pyrolysis processes, the desirable characteristics of biomass are high volatile matter with a low ash content, and for combustion processes, the biomass has to show high low heating value (LHV) combined with a low ash content. In the case of gasification processes, the biomass ought to have high fixed carbon[2] [11]. The implementation of thermochemical technologies might be crucial in the upcoming years because they present a promising pathway for taking advantage of urban residues in various countries of the region. Especially, the development of small-scale commercial systems (e.g. gasification) for the production of power in rural areas and small municipalities [8].

3.1.1. Combustion or incineration

Combustion technologies, also referred as incineration, have been implemented in the LAC region as an alternative for waste or residue treatment. In the Caribbean Islands, biomass from agricultural and forest residues is utilized to produce electricity through combustion techniques. In countries like Dominican Republic [12] or Cuba, combustion is practiced to produce energy from organic residues such as sugarcane straw and bagasse, rice husk, coffee husk, and firewood [13]. In the British Virgin Islands most of the urban waste are incinerated, despite the high costs

[2] Fixed carbon is the final calculation of the amount present in a biomass sample after the percentages of moisture, ash, and volatile matter have been determined.

Table 1
Summary of the content analysis and its coded references.

Country or subregion		OWtE technologies						
		Combustion	Gasification	Pyrolysis	Anaerobic digestion	Fermentation	Landfilling gas capture	MFC
Caribbean	Caribbean	[7]	[7]	[7]	[7,83]	[7,154]	[7,176,179,181]	[192]
	Anguilla			[58]				
	Aruba		[39]					
	Barbados		[40]		[83]			
	The Bahamas						[179]	
	British Virgin Islands	[7]						
	Dominican Republic	[35]						
	Cuba	[13]	[13,41,42]		[74]			
	Grenada						[181]	
	Haiti			[56]	[85,86]			
	Jamaica			[57]		[153]		
	Puerto Rico				[87,97]			
	Santa Lucia						[179]	
	Saint Kitts and Nevis			[59]				
	Vincent & Grenadines						[180]	
	US Virgin Islands						[178]	
Central America	**Belize**				[84]	[154]		
	Central America	[8]	[8,43]	[8]	[8]	[8,12]	[12,15]	
	Costa Rica	[22,32]			[73,74,89–93]			
	El Salvador		[8]					
	Guatemala	[15]						
	Honduras	[15]			[74,142]			
	Mexico	[11,17,28,35,46]	[11,46]	[11,60]	[1,2,74,103–105,107–110]	[17,168–171]	[188,191]	[193]
	Nicaragua	[16]			[74,96]			
	Panama		[8]					
South America	**South America**					[150]		
	Argentina				[79,98,99,137]	[152]	[189]	
	Bolivia				[70,75,95,135]			
	Brazil	[18,19,21,23–25, 27,30,53,120]	[50–54]	[53,62–67]	[18,24,71,78–80,107, 115–125,125,126,128–134]	[52,156,162–167, 173,195]	[18,19,24, 183–187,190]	[194]
	Chile	[31,35,44]	[44]		[77,100,136]	[150]	[182]	
	Colombia	[33,36]	[45,47,48]	[55,68]	[74,101,102,139–141,143]	[149,158]		
	Ecuador	[49,112]	[49]	[69]	[49,74,112]	[145,148, 159–161,172]		
	Guyana			[61]				
	Paraguay				[79,111]			
	Peru	[34]			[72,76,94,113]			
	Suriname	[26]	[26]		[26]		[26]	
	Uruguay				[79,111]			
Latin America		[20,29]			[1,9,144]	[3,144,146,147, 155,157]	[174]	
Others		[4–6,10,37,38,43, 50,54,69,151, 155,175,177,197]						

involved [7]. Conversely, in Puerto Rico for example, there is no incineration plants and urban waste is landfilled or recycled [7].

In the case of Central America, currently sugarcane bagasse and straw are the only agricultural residues to produce energy at large scale [8]. Almost half of the existent sugar mills in the subregion produce heat and power through combustion processes (e.g. combined heat and power (CHP) plants), supplying electricity to the region [8]. In Belize, there is cogeneration powerplant using sugarcane bagasse as fuel, with an installed capacity of 31.5 MW [14]. In Guatemala and Honduras, these treatment processes play a major role for electricity supply [15]. Around 67% of sugar mills in Guatemala and 100% in Honduras are already operating under CHP schemes firing bagasse [8]. Regarding scale, one of the largest sugar mills in the region is located in Nicaragua; The San Antonio sugar mill (NSEL), is the top electricity producer from sugarcane bagasse in the region, currently with an installed capacity of around 79 MW [16]. In Mexico, there are around 59 projects for self-power supply through combustion processes using biomass residues (i.e. mostly sugarcane bagasse) with an installed capacity of 500 MW [17].

In the case of South America, particularly in Brazil, bagasse from sugarcane is an important source of electricity with an operating power potential of more than 9 GW [18], considering that burning bagasse is still by far the least cost option in comparison with other thermochemical routes [19]. Additionally, being Brazil one of the largest agricultural producers globally with large generation of agricultural residues [20], it has also already a considerable number of biomass combustion power plants running on different feedstock beyond sugarcane bagasse. For example, black liquor (1.7 GW), wood residues (371 MW), rice husk (36 MW), charcoal (35 MW), elephant grass (32 MW) and palm oil (4 MW) [18]. In addition, the first thermoelectric plant for eucalyptus residues was already authorized, with a capacity of 50 MW in the State of Mato Grosso do Sul and should start operation by 2021. The owner of the thermoelectric plant, is also planning to install two more plants in the near future [21].

Other countries in LAC have identified their potential for application of local agroindustrial and forest residues as alternative energy sources in direct combustion processes. In Costa Rica, for example, the agricultural sector produces approximately 1.5 million tonnes of residues per year mainly from banana, coffee, sugarcane, pineapple, and oil palms. However, these residues are currently also in demand as supplement for fodder. Therefore, a potential exists in using some percentage of these residues to generate heat by direct combustion of raw residues [22], without affecting the fodder demand.

Incineration can be also used as an energy recovery alternative to reduce the impacts of household solid waste (HSW), which are usually landfilled in LAC without any pretreatment (e.g. sorting, recycling, and so forth). Various studies [23–25] have demonstrated HSW energy potential and technical and economic feasibility of incineration process as an efficient way to treat it. Furthermore, a study by Nordi et al. (2017) demonstrated that removing the organic fraction of the HSW increase efficiency of energy production [25]. Therefore, they suggest that incineration should not be a solution for treating the organic fraction of municipal solid waste (OFMSW). It is important to mention that the costs (e.g. upfront and operation costs) of incineration plants for HSW as an appropriate solid waste management technology [24] are still far too high in most of the countries in the region. For example, incineration in Suriname is not feasible due to its high costs and high humidity contents in the wastes [26].

3.1.1.1. Densification. To promote better and faster combustion processes, diverse densification techniques exist and have been applied in the region such as pelletizing, briquetting and torrefaction, which are useful for achieving adequate properties and a higher calorific value of original materials. These pretreatment technologies also provide advantages such as increase of bulk density, reduction of transportation, and storage costs, which in turn facilitates material handling [27]. For example, pelletizing wood residues can have economical attractive opportunity for areas with conifer plantations because densification can increase the heating value to 22.13 MJ/kg and meet the requirements for high-quality pellets [28].

Even though the pellet industry is developing in LAC, there is still large potential to pelletize agricultural and wood residues. Nowadays, Argentina [20,29], Brazil [20,27,30], Chile [20,31], Costa Rica [22,32], Honduras [20], Mexico [20], and Uruguay [29] produce pellets at industrial level for national markets but their exports are still insignificant [20]. Other countries show tangible potential to produce pellets [29] such as Colombia [20,33] and Peru [34].

In the region, even though, specific policies have not yet been established for the regulation of pellets production, it is expected that the topic will advance in the years to come. Pelleting has been lately calling the attention of scientists and decision makers in the region, as an effective way of densifying the energy contained in lignocellulosic wastes and wood, and to significantly replace the direct burn of agricultural wastes that produce large amounts of gaseous pollutants harming the environment and people's health [20].

The current small number of pelletizing industries and underutilization of wood residues in the region can be attributed to undeveloped national markets for wood pellets, lack of knowledge on technical and economic advantages of pellet production, competition with cheap natural gas, and costly transportation that creates a challenging environment for residual biomass logistics [20].

Studies from Gaitán-Álvarez & Moya (2016) [32] and Sánchez et al. (2017) [35] show that local potential for producing pellets from torrefied biomass (e.g. wood residues, avocado seeds, and husks) presents adequate properties and high calorific value. In the Dominican Republic there has been governmental support for the production of briquettes for their use in small and medium size industries [12]. Furthermore, in Colombia, researchers such as Marrugo et al. state that using biomass residues in the form of pellets, provides an opportunity to successfully incorporate a high quality biofuel to the national agroindustry chain [36].

Noteworthy stating that Refused-Derived Fuel (RDF), which consists largely of combustible components (e.g. non-recyclable plastics not including PVC, paper cardboard, labels, and other corrugated materials) of various types of waste such as municipal solid waste, industrial waste or commercial waste, are not covered by this analysis. The reason is RDF has neglectable values of degradable organic residues in its composition.

3.1.2. Gasification

Gasification is the thermochemical conversion of an organic material (e.g. biomass) into a valuable gaseous product, called syngas, and a solid product, called char [37]. Different types of gasifier configurations have been developed: downdraft (DG) gasifiers, which are the most often offered commercially, followed by fluidized beds (FB), updraft and other gasifier types [38].

In the Caribbean islands, Mohee (2015) [7] points out the following facts: In Aruba, the company *WastAway* patented a new technology for the conversion of unsorted HSW into a sub-product, which is consequently gasified for steam and electricity generation [39]. In Barbados, Cahill Energy is planning to implement gasification in order to meet the country's target of replacing 29% of its oil-based electricity with renewables by 2029 [40]. In the case of Cuba, the first gasification plant was installed in 2010 using biomass as feedstock [41], producing electricity for 96 households, a bakery, a primary school and for the water supply system. With a power capacity of 6.5 kW, this small scale gasification plant currently saves more than 18 tonnes of diesel fuel [42]. Gasification is an emerging technology in the Caribbean islands due to various benefits associated with it [7]. Furthermore, aside of agricultural and wood residues, gasification offers efficient energy outputs for the treatment of other wastes such as medical, used oil, among others [7].

In Central America, there are no operating gasification plants and no plans to develop this type of project in the coming years [43]. On the one hand, the successful case in Cuba, is seen in the subregion as a valuable experience for future transfer of technologies for design, start-up and operation of small scale gasification systems [8]. On the other hand, barriers such as financial, institutional, technical and human resources should be surpassed to make these technologies technical and economically feasible [42]. According to Cutz et al. (2016), the subregion has a capacity to produce between 96 and 175 MW by implementing DGs and FBs gasification systems running with logging residues in Central America, and up to 31 MW from agroindustrial residues. By combusting these residues, up to 150 MW could be produced [8].

Looking at South America, diverse experimentation indicates that gasification has the ideal characteristics for producing energy. For example in the case of Chile, the potential of FBs gasifiers was found for the electricity production from wheat, but these technologies have not been commercially used, due to the fact that they do not have a competitive price yet [44]. García et al. (2017) [45], in Colombia, also suggests that gasification production costs should be improved in order to be competitive with traditional technologies. This study also declares that gasification is the best technical scenario for hydrogen production along with ethanol and electricity. In Mexico, the study by Rincón et al. (2014) [46] shows gasification as the most advantageous system to generate important contributions of electricity and heat. In other countries such as Guyana, gasification has been proposed as a waste management technology, while in Suriname, gasification of rice husk was investigated as a potential solution to the energy and waste disposal problem [7].

A research group at the *Universidad Nacional de Colombia* has designed and built a system for biomass gasification involving a fixed-bed parallel flow reactor. The results show good production of quality syngas from biomass such as wood, cocoa waste, coconut and coffee husk [47]. Lastly, the authors point out that it is expected that projects in the future would allow commercial gasification systems in Colombia to produce low-cost energy; for this, also further research is necessary. In line with this, Martínez et al. (2020) analyzed the gasification of corncobs for power generation in an 18 kW pilot-scale fixed bed system under various conditions and concluded that this residue is suitable for power generation, even with a content of up to 15% of fines [48]. Also, García et al. (2017) analyzed the production of hydrogen through gasification of coffee cut-stems and argue that the process has the potential to produce high H_2/CO ratios, but it needs to be benchmarked with other technologies and evaluated in the context of integrated biorefineries [45]. In Ecuador, Narvaez et al. (2013) [49] compared several WtE technologies that can be applied for the management of solid wastes, highlighting gasification as the most promising in terms of potential power generation.

In Brazil, technologies have been developed for converting biomass into syngas through gasification in downdraft gasifier systems. According to Panwar et al. (2012) [50] this is the most appropriate system for industrial applications such as heating and drying of agricultural and industrial products. For example, in the Amazon, the electricity needs of isolated communities and small towns can be satisfied through gasification systems [51]. Moreover, in other parts of the country this technology already gained ground in the business sector, although no project has been operated long enough to reveal real data useful for assessing performance and costs [52]. Besides, researchers have also been conducting a complementary study in which the gasification potential of rice husk is being evaluated [53]. Market potential for gasification technologies was also detected for the agricultural residues in Brazil [54].

Conclusively, gasification is one of the most promising technologies for its mitigation and generation of energy such as heat, hydrogen, ethanol and electricity. Among the potential benefits of biomass gasification are: its use for waste treatment, reducing greenhouse gas emissions, fostering regional socioeconomic and agricultural developments, and offering a regular supply of energy, especially for isolated communities [51].

3.1.3. Pyrolysis

Pyrolysis is an effective and efficient thermochemical process in which the chemical constituents of the biomass are thermally degraded and transformed into bio-oil and an inert gas. It is the previous stage of combustion and gasification [55] and comprises the thermal decomposition of material in absence of oxygen. The major benefit of pyrolysis as compared to other technologies, is that this bio-oil can be then transformed into fuels for the transport sector (e.g., diesel and gasoline), or as feedstock for chemical industries [52].

In the Caribbean Islands, even when pyrolysis is the least thermochemical technology practiced according to Mohee et al. (2015) [7], there are tentative cases being discussed such as in the implementation of a plant in Haiti, from which the produced biochar from agricultural residues could be employed to improve the soil quality, as well as to stimulate the plant growth, and produced bio-oil to supply fuel in rural areas [56]. Also, pyrolysis has been proposed in other countries of the region such as Jamaica and Puerto Rico for managing used tires [57], or in Anguilla, where a pyrolysis plant was proposed to reduce the amount of wastes being landfilled by 90% and supply 30% of the Island's energy [58]. Also in Saint Kitts a plant with a capacity of 5 MW was proposed as a renewable energy alternative [59].

With respect to Central America, no discussion has been developed, as pyrolysis is reasoned to be the least preferable technology in the region because of the high investments and operation costs associated with it [8]. In addition, according to Cutz et al. (2016) [8] there are currently no plans to build any pyrolysis plants in the region. However, in the case of Mexico, a study by Gracida-Alvarez et al. (2016) [60] support the implementation of this technology to produce renewable fuels in the country. The study results show that this technology has the potential to displace up to 7% of the current annual fossil fuel consumption in transportation.

In South America, pyrolysis is employed for the production of charcoal from wood in Guyana, [61]. Slow pyrolysis techniques have been used since ancient times in the Brazilian Amazonia to produce biochar, which is an energy-dense solid product [62]. Nowadays, other cases have occurred in Brazil. For example, “Bioware Tecnologia” which is supported by the University of Campinas (UNICAMP), promotes fast pyrolysis [63]. Other studies have demonstrated the great potential and efficiency of pyrolysis treatments in countries like Brazil [64–67], Colombia [33,55,68], and Ecuador [69]. However, these studies point out that further research is necessary to understand its feasibility and logistical processes.

3.2. Biochemical

Biochemical organic waste treatment technologies are based on the decomposition of organic matter under microbial action to produce biogas and digestate (e.g. biofertilizers). The conversion technologies utilize microbial processes to transform degradable waste such as food, forest and agricultural residues [6] into biogas under anaerobic conditions. In recent years, these technologies have been developed and implemented in the region in various extents. Interest in large-scale biodigesters, second generation (2G) biofuels and MFC's have been gaining ground in the region.

3.2.1. Anaerobic Digestion

The R&D of anaerobic digestion (AD) of organic residues in LAC has mainly covered small-scale digesters, which are typically used to produce biogas for heating and cooking purposes [9]. The main reasons are the low investment cost and the low maintenance these technologies require, which in turn has resulted in multiple successful biodigesters designs and adoption of small-scale technologies [1]. Since 2009, the regional coordination of R&D programs in LAC is promoted and assisted mostly by the Network for Biodigesters in Latin America and the Caribbean (RedBioLAC), which was established by the non-governmental organization Green Empowerment with support from the US Environmental Protection Agency (US EPA) and from the Wuppertal Institute for Climate, Energy and Environment (WISIONS).

It is important to mention that interest in large-scale biodigesters has been gaining ground in the last years in some countries (i.e. Argentina, Brazil, Bolivia, Chile, Colombia, Costa Rica, Mexico, Paraguay, Puerto Rico, and Uruguay). In the last decade, research on treating residues via large-scale AD has been carried out in the region with some interesting results on biomethane potential and techniques [70,71].

3.2.1.1. Small-scale digesters. Most small-scale digesters are mostly based on agricultural residues. Hence, this study assumes as a small-scale digester, biogas plants with installed capacity below or equal to 100 kW while the large-scales digesters are above this threshold.

The first small-scale biodigesters were installed in LAC in the early 1970s. In the following decade, most of the countries in the region had developed experiences with these technologies. This process was accelerated on the 1990s and early 2000s [1] and small-scale ADs have spread successfully in rural zones of Latin America. These low-cost anaerobic digesters are considered an appropriate technology that helps expanding modern energy services in developing countries, especially increasing households' access to energy [72]. Additionally, the implementation of these digesters has proven to be an efficient way to improve sanitation and decrease illnesses and environment impacts such as soil contamination [73].

The main types of small-scale biodigesters installed in the region are the fixed dome digester and the tubular Taiwanese model. However, the low-cost and non-mechanized AD designs of the Taiwanese-model digester replaced the fixed dome on the late 1990s. Hence, Latin American countries have been successfully treating agricultural residues, especially manure, since the first plastic tubular digester was introduced in Colombia in the late 1970s. Since then, the technology has spread in rural areas of the region, especially in Colombia, Costa Rica, Cuba, Ecuador, Honduras, Mexico, and Nicaragua [8,74]. Lately, this technology was adapted to harsh climate conditions of some Andean countries such as Bolivia [75], Peru [76], Chile [77], Ecuador, and Argentina [1]. In Brazil, small scale digesters, known as "Sertanejo" biodigester, were based on the Indian model and implemented in the northeast region of the country [78]. Unfortunately, due to operational problems many farmers had abandoned this technology [79]. There are however a considerable number of small size biodigesters, mainly in the south and southeast regions of the country [80]. Currently there are 406 biogas plants in Brazil, from the majority are small-scale plants using animal residues – mostly pig's manure – as feedstock and producing electricity under the distributed generation system[3] [81,82].

The Caribbean Islands present potential for implementation of small-scale AD technologies because the organic fraction of OFMSW in the region averages around 44% [7]. Small-scale AD was introduced first in the English-speaking Caribbean countries by the German organization *Deutsch Gesellschaft für Technische Zusammenarbeit* (GIZ) [83]. In Jamaica, around 200 biogas small-scale digesters were installed between 1988 and 1993. In the case of Cuba, small-scale AD was introduced as early as 1940, and today there are hundreds of digesters installed in the country [7]. In Belize, a polyethylene digester for converting manure into biogas was installed in 2009 [84]. In Haiti, where the lack of basic sanitation services and inadequate waste treatment largely contributed to the ongoing cholera epidemic [85], small-scale AD is a well-established technology for biogas production and is used for treating agricultural wastes, domestic wastewaters, and manure [86]. In Puerto Rico, benefits from using manure and residues from local dairy farms have motivated interest in using small-scale AD technologies [87].

Noteworthy is that waste streams from other sources such as elephant grass, lemon grass, pig manure, poultry droppings, sugarcane leaves and bagasse, banana leaves presents an important feedstock potential throughout the subregion [88], not just for small scale projects but also for large OWtE technologies given their volumes.

In the case of Central America, biogas is commonly produced from manure and these small-scale biogas plants can range in size between 12 and 100 cubic meters (m^3) [8]. Their upfront cost vary from US$ 675.00 to US$ 4000.00 per plant, which means production costs ranging from US$ 40.00 to US$ 57.00 per m^3 of biogas [8]. Hence, economy of scale plays an import role even in small-scale technologies when it comes to production cost. The larger a plant is, the lower its production costs are. Besides the numerous Taiwanese-model digesters installed in Central America, research has been developed in various areas of biogas production such as co-digestion experiments [89–93], especially in Costa Rica. In Mexico, the International Institute of Renewable Source (IRRI-México) initiated in 2012 a biogas program in the country, which installed 265 biodigesters in the state of Yucatán, beneficiating more than 2000 people [1].

In South America, low-cost tubular digesters have been also adapted to Andean countries during the last years [72]. They were adapted to work at 3000–4000 m above sea level, where extreme weather conditions and temperature fluctuations prevail [94,95]. International organizations such as the Netherlands Development Organization (SNV) and the Dutch International Humanist Institute for Cooperation with Developing Countries (Hivos) developed national programs with the objectives of developing national markets for biodigesters to further diffusion/adoption of household digesters in Bolivia and Peru so called "*Programa Nacional de Biodigestores*" [75]. In addition, there are also some non-governmental organizations (NGOs) in Peru carrying out integrated projects covering segregated MSW collection and treatment in small waste treatment plant [76]. From 2006 to 2011 more than 30 digesters were implemented in rural Andean communities of the country [94]. Also in Chile, in diverse parts of the country there are biodigesters applied for households to treat wastes of domestic animals [77].

3.2.1.2. Large-scale digesters. Unlike small-scale digesters, large-scale anaerobic digesters have not been widely implemented in the region mainly due to their high investment costs, technical complexity, high maintenance, among other reasons [1]. However, countries like Argentina, Brazil, Chile, and Mexico have implemented various large-scale ADs based on Continuous Stirred Tank Reactors (CSTR), Up-flow Anaerobic Sludge Blanket (UASB), and cover lagoons.

According to Cutz et al. (2016) [8] in Central America, the theoretical biogas potential of biomass-based feedstock in the region is 1817 Mm^3/year [8]. If this theoretical potential is used in CHP applications, the region could produce 373 MW of electricity and 746 MW of heat [8]. On the one hand, even when decision makers acknowledge the theoretical biogas potential, production has not been yet adequately exploited in the subregion. On the other hand, advances in research have been achieved. For example, in Nicaragua the potential of implementing full-scale digesters was found economically viable when combining anaerobic digestion with ethanol fermentation for coffee wastes. Using fermentation by-products (i.e. wash and yeast) acquired during ethanol fermentation as feedstock for the anaerobic digester [96]. There is also an AD plant at the University of Costa Rica, which is able to generate biogas from crop residues, animal manure and food wastes [8].

In the case of the Caribbean, there is currently a large-scale plant under construction in Puerto Rico for the treatment of urban waste mixed with Napier grass feedstock. This plant will have a power capacity of 2 MW [97].

In Argentina, biogas technologies have been fairly well implemented for over 20 years [79], with a list of 105 digesters in 16 provinces of various sizes and technology levels. These plants belong to the public and private sectors, production cooperatives and NGOs [98] and just a small portion of them are used to produce energy. Several plants belonging to municipalities present operational and management problems [99].

Today around 74 large-scale biodigester exist to treat residues from meat industry (mostly from pig farming), dairy waste and wastewaters in Chile. Some of the outstanding cases are the treatment plant "La Farfana" in Santiago, which produces around 24 Mm^3 of biogas annually; the plants "Santa Irene" y "Las Pampas",

[3] In April 2012, the Normative Resolution No. 482/2012, issued by ANEEL, came into force and established the initial rules for the development of electricity distributed generation in Brazil.

with a combined installed capacity of 800 kW and supplying electricity for approximately 2500 families [77]. Chamy and Vivanco (2007) [100] estimate biogas presents a power generation potential of approximately 3.5% of the installed capacity of Chile.

Colombia is one of the greatest producers of vegetable oils in the world from oil palm, soybean, colza and sunflower. Palm oil mills are characterized by the availability of considerable amounts of by-products of high-energy such as empty fruit bunches (EFB), fibers and shells, and Palm Oil Mill Effluent (POME), which is particularly contaminating and a potential biogas source [101]. A study by Arrieta et al. (2007) [101], demonstrates huge potential for increasing the power efficiency of palm oil mills; mainly by the use of these by-products in cogeneration plants; by generating biogas from the anaerobic treatment of wastewater and its conversion into electricity with CHP systems. Systems. Yet, Ramirez-Contreras et al. (2020) argue that few mills carry out biogas capture and only some of them generate electricity from biogas [102].

In Mexico, in the last decade some programs have emerged to provide financial and technical support for the implementation of AD systems throughout the country. Manly through the state agency SAGARPA (Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food), now SADER (Secretariat of Agriculture and Rural Development), which has supported several agribusinesses to install AD units (mostly anaerobic lagoons) [103]. However, this has been limited to treat mainly manure for electricity generation. Rios and Kaltschmitt (2016) [104] suggest that biogas production from other organic residues should be carried out to produce energy over the next decades. In this context, on May 2017, an AD plant was inaugurated in México City (Milpa Alta), for the treatment of cactus and vegetable waste, generating almost 106 m^3 per day of biogas [105,106]. Since late 2016, the city of Culiacan installed the first large-scale dry anaerobic digestion plant (DAD) for treating 4500 tonnes per year of agricultural residues. The plant has an installed capacity of 100 kW [107]. Another project is the AD plant in Atlacomulco, which co-digest OFMSW and wastewater [106]. Other studies have obtained positive results using nejayote, which is the primary by-product of the nixtamalization [108]; banana peel [109] and vinasse from tequila production [110].

In other countries, such as Uruguay and Paraguay, the potential of full-scale AD plants has been planned. As mentioned in Moreda (2016) [111], forest and agricultural residues in Uruguay are better off treated in a centralized facility receiving waste from other sources to generate electricity and digestate. Currently, there are two projects in Uruguay, in which energy is generated from biogas [79]. Despite presenting an adequate regulatory framework for biogas deployment, there are still few planned large-scale projects in Uruguay [79]. Local potential for biogas is estimated between 52 and 84 Mm^3 per year, which is equivalent to 1.3–2.1% of total primary energy of the country [111].

In Ecuador, in the "Social Urban Metabolism Strategies" for cities, implemented in Quito, biogas technologies were found to be the optimal technology for the conversion of OFMSW into electricity [112]. Besides electricity, biogas production presents other important services such as heat and biofertilizer [112,113]. However, these technologies are not yet in place.

Biogas production in Brazil has been increasing but its contribution to the country's energy matrix is still marginal (e.g. almost 0.1%) despite Brazil's large biogas potential [114]. The Brazilian Biogas Association (ABiogas) estimates that biogas can supply around 40% of Brazil's electricity demand or replace 70% of its diesel consumption [81]. Hence, biogas has a pivotal role on guaranteeing energy security.

Brazil could generate approximately 85 billion cubic meters of biogas per year. If translated into energy equivalence, this amount of biogas could supply one third of the country's electricity demand and decarbonize the national energy matrix even more, especially in during peak demand. Biogas is a clean and renewable biofuel, distributed throughout the national territory, in three sectors of great investment and public policy attraction: sanitation with 7% of the biogas potential, agriculture with 44% and sucroenergetic industry with 49% [81].

Large-scale projects are based in vinasse from sugar mills with 2 plants and landfills with 38 WtE plants. There are 14 WtE plants using sewage to produce energy – mostly thermal and/or electricity – but only 1 plant producing biogas as vehicle fuel in Franca, São Paulo State. The plant treats an average of 500 L of sewage per second and produces around 2500 Nm^3 of biogas per day, enough to replace 1500 litters of common gasoline daily [79,81,115–117].

The development of biogas in Brazil has the potential to avoid CO_2 emissions, which may be up to 19.8 $MtCO_{2eq}$ per year, approximately 5% of the National emissions [117]. At the same time, several other studies have been carried out in the country to test the potential of anaerobic digestion from various sources [118–121]. In addition, several more studies specifically on vinasse from the sugar and ethanol industrial sector have found out that biogas produced from vinasse through AD technologies has great energy potential for large scale projects in the short- and medium-terms [71,122–129]. In addition, these studies benefit other sectors such as vinasse from corn-based ethanol plants and wastewater from cassava mills [130].

In 2016, the Brazilian government launched an auction call aimed at contracting electricity for new generation projects. The winning project was the first commercial scale biogas plant in the world using by-products of sugarcane (e.g. filter cake and vinasse) as raw material for biogas production. The project is located in the northwestern region of the São Paulo State, which is famous for its sugar and ethanol production in the country. The biogas plant enters in operation in 2021 and focuses on electricity generation, with an installed capacity of 21 MW [131]. Another important region for sugar and ethanol production is the western region of São Paulo, in which a new commercial scale biogas plant aiming at not only generate electricity (i.e. installed capacity 5 MW) but also biomethane (i.e. 67,000 m^3/day, which can replace about 17 million liters of diesel per year) [132]. The plant enters in operation on December 2020 and biomethane will be distributed by dedicated pipeline for two cities, Pirapozinho and Presidente Prudente. It is estimated that 230 thousand people in these cities will benefit from this project through their local gas grid. Another important feature of this project is the commercial destination to nearby chemical plants of the CO_2 captured during the fermentation process in the ethanol production and during the biogas upgrading process.

Regarding DAD technology, Brazil has only one pilot project located in Rio de Janeiro State, which is a joint project between the company "*Methanum Resíduo e Energia*" and The Federal University of Mina Gerais (UFMG). The project developed a dry anaerobic digester for the treatment of the 50 tonnes per day of OFMSW, initial installed capacity of 250 kW and designed to scale up in the future. This national technology is adequate to the particular conditions of Brazil and is denominated "sequential batch methanization tunnels" [133,134].

As for biogas production based on DAD, and considering the successful experiences in Europe, these technologies have lately attracted the attention of some LAC countries, in particular Mexico and Brazil. However, there are still some structural characteristics in the region that inhibit its implementation. For example, the lack of waste sorting systems (e.g. selective collection), that generate large volumes of unsorted waste with mixtures of un-degradable materials, is one of these barriers to disseminate DAD technologies in the region [133].

3.2.1.3. Co-digestion & Biochemical Methane Potential (BMP). Research in the region has also shown the importance of co-digestion to improve performances of biodigestion processes. For example Alvarez and Lidén (2008) [135], found out mixing residues such as quinoa stalk residues, totora (*Schoenoplectus californicus* subsp. *Tatora)* and aquatic flora from Lake Titicaca, with manure from llama, cow and sheep improved the biogas generation in Bolivia. The use of totora resulted in a considerable increase up to 130% in methane yields. A research by Santibañez et al. (2011) [136] estimates the potential of residual glycerol from biodiesel as feedstock for anaerobic co-digestion processes around 10%, 1 L of residual glycerol for every 10 L of biodiesel produced.

In Argentina, co-digestion of poultry manure with vegetable and fruit waste was tested in a continuous stirred tank (CSTR) at a bench scale. The research outcome shows that presence of food waste improved the biogas and methane yield by more than 31% and increased not only the C/N ratio but also the dilution of nitrogen compounds [137].

In Brazil, the first large-scale co-digestion plant is located in Paraná State. The plant produces biogas from 600 m^3 of sewage sludge and 150 tonnes of OFMSW per day. The installed capacity is 2.8 MW, which is enough to supply electricity to 2100 households or 8400 people [138]. Unfortunately, the plant is currently not on operation and undergoing maintenance due to operational problems with the digesters.

In Colombia, co-digestion of a mixture of cocoa industry residues (CIR), pig manure (PM) and organic fraction of municipal solid waste (MSW), resulted in high methane production (2485.91 mL CH4/gr Vs) according to the experiments developed by Rodríguez et al. (2017) [139]. In addition, Martínez-Ruano et al. (2019) analyzed the effect co-digestion of milk-whey and potato stem on heat and power generation using biogas as an energy vector. They concluded that the process might be feasible [140]. However, Garfi et al. (2011) [72] has demonstrated that co-digestion not always promotes higher biogas production rates. For example, in their experiment conducted in Peru, co-digestion of guinea pig manure and cow manure did not improve biogas yields [72].

Several other works [141,142] confirm the importance of Biochemical Methane Potential (BMP) test, for the evaluation and selection of residues to be treated via Anaerobic Digestion; however as stated by Cárdenas Cleves et al. (2016) [143] it is a priority to define an standardize methodology to measure BMP in the region. This would increase reliability and reproducibility of experiments.

3.2.2. Fermentation

Fermentation is the process by which organic material is converted into alcohol, gas or acids (e.g. bioethanol, lactic acid, etc.), in the absence of oxygen and based on selective cultures of anaerobic microorganisms. Fermentation industries that produce biofuels (e.g. bioethanol), have recently shown continuous growth in various countries in the American continent [144]. The growth is based on the fact that LAC region has great potential to increase this share and become one of the major global producers of bioenergy [145]. However, Argentina, Brazil and Colombia are the only countries in the region with established biofuel markets [146]. Bioethanol, for example, is Brazil's one of the most prominent biofuels [147]. Furthermore, there are also various other countries in the region that have shown interest or have already implemented, in less extent, projects on the production of biofuels [147]. For example, in Uruguay, the goal of incorporating 5% of liquid biofuels into gasoline was recently achieved in 2016 [111]. In Ecuador, a recent governmental mandate has fostered a bioethanol production of 80 million liters [148].

Contrastingly, even when first generation (1G) biofuel production represent a viable and convenient alternative for the substitution of fossil fuels in the region, there are recent concerns related to their economic, social and environmental viability as energy sources [149,150]. The more preeminent concern is the fact that biofuel production compromises food security by using arable and fertile lands. Hence, the efficient utilization of agricultural residues as raw material for second generation (2G) biofuels is becoming increasingly important not only for minimizing socio-environmental impacts but also for increasing economic profitability [151,152].

3.2.2.1. 2G Bioethanol. In the Caribbean Islands, bioethanol production from waste materials is still undeveloped [7,153]. In the rest of the islands, these technologies are practically non-existent at industrial scales [7]. In Belize, the Organization of American States (OAS) has executed an assessment to identify waste streams within the forestry, agricultural and waste management sectors to evaluate their potential as feedstock for 2G bioethanol production. The results envisioned a considerable potential for a cellulosic ethanol market [154].

LAC is the region with the most production of coffee worldwide, with Colombia and Brazil being the leading producers [155]. These result as potential candidates for biofuel production due to their high cellulose and hemicellulose content [156,157].

Large amounts of banana residues (skin, stalks and steams) are also generated in the region. Being Brazil, Ecuador, Costa Rica, México and Colombia some of the largest producers of this fruit, there is an important potential of using these residues as a bio-energy source to produce 2G bioethanol in the region [156,158–161]. However, Rambo et al. [156] declare that these residues are not entirely suitable for biofuel production due to the high moisture content that prevents their transportation. Velásquez-Arredondo et al. (2010) [158] confirm the need for further research on variables affecting the process performance, such as temperature, reaction time, the water used in hydrolysis before discarding these residues for 2G bioethanol production.

Currently, in 1G bioethanol plants, large amounts of sugarcane bagasse are produced when the juice is separated from the fiber. In LAC countries, this bagasse is usually burnt in low efficient cogeneration systems to produce steam and electricity for the plant and in some cases generate surplus electricity to be sold, thus improving the revenues of the enterprises. Diverse studies [159,162–166], have concluded that 2G bioethanol can compete with 1G production in LAC only if low cost enzymes become commercially available. In fact, Wang et al. (2014) [166], state that the 1G + 2G bioethanol pathway remains less favorable economically than business as usual because current technical and economic conditions of sugar mills in LAC are more favorable to use sugarcane bagasse and trash for generating electricity via combustion.

In Brazil, there are two plants evidencing viable production of cellulosic bioethanol from sugarcane bagasse and straw. They are: GranBio power plant installed in São Miguel dos Campos, Alagoas, and Raízen in Piracicaba, São Paulo. However, only Raízen is already successfully producing 2G bioethanol on commercial scale [167].

There are also expanding research efforts in Mexico to use bagasse residues from the tequila industry for the production of biofuels, at the same time propitiating their correct disposal [168–170].

3.2.2.2. Biohydrogen and biomethanol. Other technique that seems to be attractive for the proper treatment of organic wastes and clean energy generation in the region is biohydrogen (H_2) production via dark fermentation. Results of various studies demonstrated fermentation of agricultural wastes as an attractive and feasible technique to generate biohydrogen. For example in Mexico

[171], H_2 production was analyzed in batch fermentation of a substrate that consisted of a mixture of sugarcane bagasse, pineapple peelings, and sewage sludge. Posso et al. (2017) in Ecuador proposed the use of the H_2 derived from the OFMSW as an energy source for transportation [172].

As for the production of biomethanol in the region from organic residues, being CO_2, an inevitable residue from fermentation processes, recently attention has been put into the option of hydrogenating CO_2 into biomethanol. In Brazil, this option is attractive and relatively easy to implement in the short-to-medium terms in pilot plants [173]. However, the low reactivity of CO_2 remains a challenge to be overcome in order to achieve commercial deployment [173].

3.2.3. Landfilling with gas capture

In LAC most of the solid waste is destined to landfills and dumpsites. More precisely, 83% of the total waste produced in the region in 2011 [174] were collected and disposed. Landfilling is the common practice for disposal in the region due to its low-cost management technique. In addition, it is a well-established disposal method and presents fairly structured building guidelines which are easier to be applied by municipalities, when compared to other management alternatives [175]. Yet, many of them are poorly sited and improperly managed [176].

Until 2011, more than 99 landfills projects adopted WtE techniques and were approved and financed through carbon markets associated with the Clean Development Mechanism (CDM) in the region [174], resulting in the reduction of more than 19 million tonnes of CO_{2eq} from 2007 to 2012 [177]. Brazil and Mexico are amongst the top five countries worldwide that receive more income from mitigation projects. Most of the Certified Emissions Reductions (CERs) were the result of biogas capture projects in landfills [17].

Regarding the Caribbean Islands, some successful cases and proposals were detected. In the US Virgin Islands there is a landfill with gas capture infrastructure, which supplies biogas to an electricity generation plant. The plant has an installed capacity of 815 kW and supply electricity to around 900 households in the island [178]. Other countries like Bahamas, St. Lucia [179], St. Vincent and the Grenadines [180] and Grenada [181] have also demonstrated interest to implement landfill gas capture projects. The implementation of efficient technologies for waste treatment and volume reduction is becoming increasingly important in these islands, considering the lack of locations for solid waste disposal and the pollution caused by traditional disposal methods, which in turn affects the tourism sector [7].

In Mexico, the city of Monterrey, implemented the first landfill gas capture project in 1990 and its success have been replicated in other municipalities. Nowadays, landfills with gas capture infrastructure in Mexico receives more than 19 million tonnes of waste annually, amounting to an installed capacity of 16 MW. The biogas from waste is converted to electricity that moves subways and provides safer streets through public lighting. At the same time, these projects cut down municipalities' operating costs and reduced GHG emissions [174].

Other cities in LAC have also installed similar systems. For example, in Uruguay, the city of Maldonado uses the biogas captured from landfills to run a plant with an installed capacity of 550 kW [174]. Economy of scale it is an important factor for municipalities. The Uruguayan Ministry of Environment detected that gas capture technologies are a heavy financial burden for small populations. Hence, cities with a population over 100,000 inhabitants seem to be the most appropriate for implementing gas capture systems [174]. In Chile, an important share of biogas produced in the country comes from landfills [77,182]. In Colombia, the landfill of "Doña Juana" runs a biogas-based powerplant with an installed capacity of 1,7 MW. Another powerplant is being constructed in the landfill of Guayabal, located in Cúcuta, Colombia. The project is estimated to supply electricity for 25,000 people.

In the case of Brazil, the use of biogas from landfills is well implemented for electricity production and increasing. Currently, there 39 projects in operation in the country. In São Paulo, for example, there are nine landfills where gas capture has been used to produce electricity [24]. The first experience in the region used landfill biogas as fuel gas for the urban bus fleet have in Campinas [183,184]. Since July 2017, the use of biomethane obtained from landfill is already regulated for its commercialization as a vehicle fuel [185]. It is expected that in the upcoming years biogas and biomethane will play a major role in the energy matrix of the country [186]. For example, the Gas State Company of the Ceará State (CEGAS) is already injecting 15% of biomethane from landfill biogas in its commercialized natural gas system [187].

Landfilling is still seen as a viable option for waste disposal because of its low operation costs, especially because land is not an issue for its implementation. However, there is an ongoing debate on whether landfilling should prevail in the country in comparison to other thermal and biochemical treatment technologies [24]. In the long-run, landfilling is expected to be replaced in Brazil by environmentally sound management options [188].

In line with this, some countries in LAC are already closing their dumpsites, for example in Buenos Aires, an open air dumpsite occupying an area of 8 ha for 20 years was recently closed [189]. In Brazil, the dumpsite in Brasilia, which served between 4 and 5 million people, has been already partially closed and MSW is now diverted to a new sanitary landfill. The city is also currently building a number of sorting and recycling plants, where urban waste is intended to be properly sorted and treated [190]. In 2011, Mexico closed its largest open air dumpsite [191]. Hence, even when several studies and projects in LAC have demonstrated the benefits of MSW landfilling with gas capturing in the region, just in the last decade there have been some perception changes towards the implementation of thermochemical or anaerobic digestion in view of the technical and environmental advantages they can offer for being more efficient energy recovery options.

3.2.4. Microbial fuel cell (MFC)

In the LAC countries, the development of Microbial fuel cell (MFC) projects is at research level, with some studies highlighting the potential they may have in the region, especially in the Caribbean context [192]. In Mexico, another study [193], concluded that the application of MFC for municipal wastewaters and landfill leachate is promising for effluent depuration and bioenergy generation. In Brazil, Rachinski et al. (2010) [194] describe MFC as a favorable technology for electricity and fertilizer production based on animal and vegetable solid wastes and as an alternative to waste remediation.

4. General challenges and opportunities

4.1. Challenges

In general, according to our literature review, the identified challenges LAC region is facing for an adequate implementation of OWtE technologies are classified mainly as institutional, financial, technical and educational, as hereafter mentioned:

- Dearth or ineffectiveness of waste management strategies, which require the balancing of optimized waste reduction practices, recycling, recovery, and landfilling [7,154], together with educational and technical programs;

- Lack or deficient institutional frameworks, environmental legislation [52] and business models [117].
- Need for fostering new markets for biogas and the creation of public incentive policies for technology implementation [195].
- High technology costs for the equipment and maintenance.
- Low or no financial incentives to facilitate energy generation from wastes and the implementation of modern waste management strategies [154];
- Lack of reliable and relevant information on urban waste (i.e., amount of waste, waste composition, and potential uses of collected waste), or agricultural residues (i.e., quantities, types, BMP's, etc.) according to the situation in each country [154];
- In many countries of the region there is a dearth of engineering companies, manufacturing equipment, and a prevailing low state of technology that has limited the region's capacity to implement OWtE [8].
- Other of the major problems in the region is the absence or limited knowhow, capabilities and expertise on the existing technologies [7]; and furthermore research and development for new and appropriated technologies.
- Lack of research to prove the competitiveness of bioenergy production as compared to fossil fuels [52]; and
- Low prices of fossil fuels are slowing the development of renewables in LAC, hence waste-to-energy alternatives may become less attractive throughout the region.

In LAC, one of the main challenges identified, and pointed out by various authors [45,112,185] is to find the economic feasibility of the projects, considering the high technology, production and maintenance costs involved. The costs from generating biofuels or biogas in the region from residues are, in general, still higher than the fossil fuels resources tariff currently in the market [117]. The development of technologies that are economically feasible for the region is transcendental for OWtE to thrive.

Having in mind that OWtE systems represent a part of an integrated waste management strategy and are not always the most sustainable solution, particular analysis should be carried out for the evaluation on which technology should be better. Further research is also required to proper seek for the contributions these technologies can provide to reduce emissions and for the viability to implement and diffuse WtE technologies to promote sustainable energy systems in the region.

4.2. *Opportunities*

The utilization of organic wastes to produce energy in LAC has been lately enhanced by the series of environmental, technical and economic opportunities and benefits offered by their implementation, which are plentiful and have been demonstrated by diverse research and projects. These opportunities have been lately expanding and arising interest in the region due to the benefits associated with the implementation of these technologies. Hereafter a series of identified opportunities in the region.

4.2.1. *Environmental opportunities*

- The implementation of these technologies could contribute to face the multiple problems derived from the disposal of solid waste in sanitary landfills and dumpsites [196];
- Accordingly, the countries in the region could also benefit from OWtE technologies to reduce GHG emissions and attain national goals established by the Nationally Determined Contributions (NDC's) under the new international agreement adopted in December 2015, in Paris [197].
- For anaerobic digestion, the use of resulted digestate materials as fertilizer and soil improver contributes to "close the loop" of the substrates lifecycles and foster circular economy [198]. The same can be said for biochar, which is a by-product of gasification and pyrolysis processes.

4.2.2. *Social opportunities*

- Beyond improving the sustainability on each country, the production of bioenergy with waste will also help to improve energy security, diversify their national energy mix and reduce diesel fuel imports [172].
- Harnessing the potential from residual biomass would also enhance the development and wellbeing of the rural communities, not affecting their food security [160], and further bringing the much needed employment in the rural areas.
- Public health will also be beneficiated, reducing pollutants in the environment. Especially, the use of biogas as vehicle fuel can reduce significantly air pollution (e.g. particulate matter) in cities; however attention must be payed towards undesired emissions of methane and nitrous oxide [199].
- Create new alliances between engineering companies or firms and academic units, which will allow for a mutual improvement, and gain technical experiences regarding new Technologies [8].

4.2.3. *Economic opportunities*

- Increase the revenues generated by the utilization of residues or by-products that are usually discarded by large enterprises;
- The economic use of residual biomass in rural areas could generate an extra income to the small farmers of the region and enhance their development [160].

5. Key findings and concluding remarks

In LAC, every year millions of tonnes of agricultural forest and urban solid residues are generated. Their advantages and challenges as alternative energy sources through biochemical and thermochemical processes have been identified. In recent years, various small and large-scale projects have occurred, and several studies have presented technical, environmental and economic analyses of different technologies in the region, as well as their comparative performances for bioenergy production. Hereby the key aspects and highlights identified on the state of the art of OWtE in LAC though this literature review.

5.1. *Thermochemical*

Among the main thermochemical technologies, incineration is the most commonly practiced in LAC [7,8] with a demonstrated further potential. Nevertheless, nowadays there is an ongoing debate on whether this is the right organic waste treatment method, considering the environmental drawbacks and low process efficiency these technologies portray. Gasification and pyrolysis present some advantages over combustion such as being more thermally efficient, utilization of downstream products (biofuels, chemical or fertilizers), and higher and cleaner bioenergy production, among others [10].

5.1.1. *Key findings*

- Combustion technologies have been widely applied in LAC, for agricultural and forest residues to produce electricity, considering that it is still the least cost thermochemical option [19]. Sugarcane bagasse and straw are the main combusted residues [8].

- Diverse densification techniques have been applied in the region, such as pelletizing, briquetting and torrefaction, which are intended to achieve adequate properties and higher calorific values. Today, Argentina, Brazil, Chile, Costa Rica, Honduras, Mexico and Uruguay [29] produce pellets at industrial level for national markets. LAC accounts for a large potential to palletize and export agricultural and wood residues.
- Diverse experimentation indicates that gasification has ideal characteristics for producing energy in LAC. Gasification systems have been implemented in countries like Cuba [8] and Brazil [52], which are seen as valuable experiences for further transfer of technologies. In other countries in LAC, gasification has been proposed or is in development phase as a waste management technology and generation of energy (heat, hydrogen, ethanol and electricity).
- Even when pyrolysis is the least thermochemical technology practiced in the region [7,8], various researches have demonstrated it as an efficient technology to treat OW and produce renewable fuels in the region. However in Central America, for example, pyrolysis is deduced to be the least preferable technology [8]. Further studies are necessary to understand more on the economics and logistics of the process [33].

5.2. Biochemical

Biochemical technologies comprehend anaerobic digestion, fermentation, landfilling gas capture and Microbial fuel cell (MFC) technologies. In recent years, R&D on biochemical treatment of organic residues in LAC has been focused in small-scale anaerobic digesters (AD) [9] and landfilling; and fermentation in less extent. Notwithstanding, interest in large-scale biodigesters, second generation biofuels and MFC's has been gaining ground in the last years with some countries in LAC already implementing such projects.

5.2.1. Key findings

- Low-cost household biodigesters have been successfully implemented in rural zones throughout LAC and are proved as an appropriate technology to treat agricultural residues, produce fertilizers and energy. However, according to Garfí et al., 2016 [9], there are still several barriers to overcome in order to improve and further disseminate the technology.
- Large-scale AD have not been widely implemented in the region mainly due to their high investment costs, systems technical complexity and high maintenance demands [1]. However, Argentina, Brazil, Chile and Mexico have implemented various large-scale ADs based on Continuous Stirred Tank Reactors (CSTR), Up-flow Anaerobic, Sludge Blanket (UASB), and cover lagoons. Other countries have similar experiences in less extent. Full-scale dry AD has been implemented in Brazil and Mexico.
- Significant research in the region has evaluated the benefits of co-digestion and Biochemical Methane Potential (BMP) tests to improve performances of biodigestion processes.
- Currently, the fermentation industries that produce first generation (1G) biofuels have shown continuous growth in various countries in LAC. Only Argentina, Brazil and Colombia have established biofuel markets.
- The inclusion of 2G biorefinery is lately gaining ground in LAC. R&D is developing on the potential of residues from diverse crops such as sugarcane, coffee, corn, banana, palm oil, rice, etc. However, the application of such projects has still some constraints and challenges, such as the technology readiness, or the profit-earning capacity. In Brazil, optimistic projection on the 2G paths has been shown by the two plants' GranBio and Raízen. Raízen currently produces bioethanol from sugarcane bagasse and straw.
- Biohydrogen production via dark fermentation is gaining attention in the region, with proposals to use the OFMSW and other residues as feedstock.
- In LAC, 83% of the total waste produced in the region was destined to landfills and dumps in 2011. By then more than 99 WtE landfills projects were approved and financed in the region, by the Clean Development Mechanism (CDM) [174]. Brazil and Mexico are among the five countries worldwide that receive more carbon incomes.
- Some countries in LAC are already closing their dumpsites. For example, Buenos Aires, Brasilia and Mexico City. These cities are changing towards the implementation of thermochemical or AD in view of their technical and environmental advantages.
- Microbial fuel cell (MFC) technology in LAC is at research level; with some studies highlighting the potential they may have in the region.

5.3. Concluding remarks

In recent years, various small and large-scale OWtE projects have been implemented, and several studies have presented environmental and technical analyses of different OWtE technologies in LAC. Currently, there is an ongoing debate on which of these is the most adequate technique to treat organic residues because of their energy potential. Throughout this literature review, we found out that OWtE technologies are not always the most adequate option and the benefits of keeping agricultural residues on the fields cannot be neglected.

The answer to the feasibility on the implementation of one technology over the other for each residue is not set in stone but rather depends on each country conditions and mainly on market and technological factors. Therefore, genuine analyses and studies shall be carried out for each unique case. The review of the state of the art of these technologies resulted that anaerobic digestion and gasification are deemed as the two most promising technologies; in view of the technical and environmental advantages they offer.

Furthermore, it was recognized that the implementation of OWtE technologies will be crucial for the sustainable development of LAC and to significantly contribute to improve waste and energy systems along with a number of social and economic benefits. Further works shall keep determining the bioenergy production potential for the diverse organic residues and demonstrate the applicability of small and large-scale OWtE treatment plants throughout the Latin-American and Caribbean region.

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Appendix A. Supplementary data

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