Chapter

Review Chapter: Waste to Energy through Pyrolysis and Gasification in Brazil and Mexico

José Antonio Mayoral Chavando, Valter Silva, Danielle Regina Da Silva Guerra, Daniela Eusébio, João Sousa Cardoso and Luís A.C. Tarelho

Abstract

Millions of tons of forest residues, agricultural residues, and municipal solid waste are generated in Latin America (LATAM) each year. Regularly, municipal solid waste is diverted to landfills or dumpsites. Meanwhile, forest and agricultural residues end up decomposing in the open air or burnt, releasing greenhouse gases. Those residues can be transformed into a set of energy vectors and organic/chemical products through thermochemical conversion processes, such as pyrolysis and gasification. This book chapter provides information on current examples of gasification on large scale in the world, which typically operate at 700°C, atmospheric pressure, and in a fluidized bed reactor. The produced gas is used for heat and energy generation. Whereas pyrolysis at a large scale operates around 500°C, atmospheric pressure, and in an inert atmosphere, using a fluidized bed reactor. The produced combustible liquid is used for heat and energy generation. The decision of using any of these technologies will depend on the nature and availability of residues, energy carries, techno-socio-economic aspects, and the local interest. In this regard, the particular situation of Brazil and Mexico is analyzed to implement these technologies. Its implementation could reduce the utilization of fossil fuels, generate extra income for small farmers or regions, and reduce the problem derived from the accumulation of residues. However, it is concluded that it is more convenient to use decentralized gasification and pyrolysis stations than full-scale processes, which could be an intermediate step to a large-scale process. The capabilities of numerical models to describe these processes are also provided to assess the potential composition of a gas produced from some biomass species available in these countries.

Keywords: Gasification, Pyrolysis, biomass, MSW, RDF

1. Introduction

LATAM has a rising renewable energy market, where more than a quarter of its primary energy is generated from renewable sources, twice the world average [1]. Across the continent, hydropower plays a pivotal role in the energy sector. However, LATAM has also access to biomass resources, which may enable the production of bioenergy, providing the opportunity to exploit a domestic, low carbon, and

Region	Total Renewable energy		Hydropower		Wind Energy		Solar Energy		Geothermal Energy		Bioenergy	
	Cap.(MW) 2019	Prod. (GWh) 2018	Cap.(MW) 2019	Prod. (GWh) 2018	Cap. (MW) 2019	Prod. (GWh) 2018	Cap.(MW) 2019	Prod. (GWh) 2018	Cap.(MW) 2019	Prod. (GWh) 2018	Cap.(MW) 2019	Prod. (GWh) 2018
BR	141,933	495,945	109,092	388,971	15,364	48,489	2485	3987	0	0	14,992	54,498
MX	25,648	54,770	12,671	32,526	6591	12,877	4440	1363	936 o	5375	1010	2628
VE	16,598	25,278	16,521	25,183	71	88	5	6	0	0	0	0
CO	12,375	58,433	11,927	56,661	18	43	90	14	0	0	340	1715
AR	12,776	42,501	11,314	39,957	1609	1413	441	108	40 o	214	298	1846
CL	11,488	38,515	6679	23,367	1620	3588	2648	5218	0	0	502	6128
PY	8822	59,912	8810	59,211	0	0	0	0	0	0	22	701
PE	6640	33,483	5715	30,731	372	1502	326	797	0	0	186	452
EC	5279	21,224	5079	20,678	21	80	28	38	0	0	152	428
UY	3772	14,234	1538	6557	1521	4732	258	415	0	0	425	2529
BO	1036	2967	736	2612	27	59	120	127	0	0	154	169
CAM*	15,691	47,658	8147	29,160	1942	5838	2218	2625	722	3969	2663	6066
Lat	262,058	894,920	198,229	715,614	29,156	78,709	13,059	14,698	1698	9558	20,744	77,160
EU	497,267	1,052,187	156,412	379,820	191,277	377,494	132,500	128,358	916	6765	41,179	188,053
W**	2,532,866	6,586,124	1,307,994	4,267,085	622,408	1,262,914	584,842	562,033	13,909	88,408	124,026	522,552

Note: Numbers followed by the letter "o" are figures that have been obtained from official sources such as national statistical offices, government departments, regulators, and power companies. The letter "u" follows figures that have been obtained from unofficial sources, such as industry associations and news articles. The letter "e" follows figures that have been estimated by IRENA from a variety of different data sources. All figures from the IRENA questionnaire are presented without any indicator.
In refers to central America and the Caribbean area.
**World.*

Table 1.
Renewable Energy in LATAM [2].

sustainable energy source, strengthening the renewable energy sector, and generating profits in rural areas. **Table 1** shows the renewable power capacity, considering the maximum net generating capacity of power plants and other installations that use renewable energy sources to produce electricity in LATAM. This information is also available for the European Union (EU), and the world to highlight where LATAM is in terms of renewable energy. It is interesting to notice Brazil's share of renewable energy production in LATAM is ~55%, from which ~78% comes from hydropower and ~10% from bioenergy. In contrast with the EU, whose hydropower represents ~36%, and bioenergy ~18%. On the other hand, Mexico's renewable energy in LATAM share is 6%.

Renewable energy production in Brazil accounts for ~82.63% [3]. Brazil relies on hydroelectricity for 65% of its electricity, and it plans to expand the ~6% share for biomass and wind energy [4]. While renewable energy production in Mexico is around 16.92% [3]. Without a doubt, Mexico has lagged in the development of renewable energy, comparing with other LATAM countries.

Although LATAM has been a remarkable positive development in renewable energies, the energy demand is increasing at the time, similarly to the impacts of climate change derived from the overconsumption of fossil fuels. Thus, it makes

Region	Total Solid Biofuels and Renewable Waste		Renewable Municipal Solid Waste		Bagasse		Other Solid Biofuels	
	Cap. (MW) 2019	Prod. (GWh) 2018	Cap. (MW) 2019	Prod. (GWh) 2018	Cap. (MW) 2019	Prod. (GWh) 2018	Cap. (MW) 2019	Prod. (GWh) 2018
BR	14,670	53,364	0	0	11,462 o	35,435 °	3195	17,928
MX	811	2368	0	0	791 e	1770	21	598
VE	0	0	0	0	0	0	0	0
CO	336	1711	0	0	336 e	1711	0	0
AR	254	1701	0	0	56 o	351	198	1350
CL	442	6059	0	0	0	0	442	6059
PY	20	700	0	0	20 e	700	0	0
PE	175	402	0	0	175	402	0	0
EC	144	382	0	0	144 o	382 o	0	0
UY	423	2482	0	0	10 e	18	413	2464
BO	149	168	0	0	149 o	168 o	0	0
CAM*	2620	5937	6	23	2509	5599	10	315
Latam**	20,044	75,274	6	23	15,596	46,536	4279	28,714
EU	26,051	122,078	4664	22,969	155	318	21,228	98,680
W***	101,426	426,830	14,518	62,148	19,070	55,355	67,702	309,214

Note: Numbers followed by the letter "o" are figures that have been obtained from official sources such as national statistical offices, government departments, regulators, and power companies. The letter "u" follows figures that have been obtained from unofficial sources, such as industry associations and news articles. The letter "e" follows figures that have been estimated by IRENA from a variety of different data sources. All figures from the IRENA questionnaire are presented without any indicator.
In refers to central America and the Caribbean area.
**World.*
***From Martinique.*

Table 2.
Solid Biofuels and Renewable Waste [2].

sense today more than ever to take advantage of LATAM's potential for producing bioenergy. **Table 2** shows the production and capacity of the different solid biofuels and renewable waste to produce bioenergy, where bagasse is the main solid biofuel source to produce bioenergy. Brazil is a key player having a 70% share of the total bioenergy production from solid biofuels and renewable waste, occupying first place in LATAM. Regarding renewable municipal waste as a source to produce bioenergy, Martinique is the only one that utilizes them. This situation can be seen as a wise and potential solution to deal with the problems that municipal solid waste (MSW) in landfills and open dumps areas bring out. Therefore, it could be produced a refuse-derived fuel (RDF) to produce bioenergy through gasification or pyrolysis as some developed countries are already doing it at a large-scale, adding value to a material that has no other valorization option and is disposed of in landfills.

Other materials that need better valorization are the biomass residues from agricultural and forestry activities (agroforestry residues) since they are sometimes burnt in the field, causing a range of health issues and significantly raise pollution levels [5]. Similar to Municipal Solid Waste (MSW), agroforestry residues can turn into alternative products. For example, briquettes and pellets made from those residues can partially replace coal in thermal power plants.

Together, RDF and agroforestry residues can be used to generate a set of energy vectors and organic products in LATAM, implementing pyrolysis and gasification at a large-scale, like some countries in the world are already doing. Those products can be used in distinct applications to partially replace fossil fuels. This strategy can add value to the solid waste management sector and the agriculture sector. In this regard, Section 2 presents how some companies in the world utilize pyrolysis and gasification on a large-scale, and Section 3 shows the feedstock availability in Brazil and Mexico, as well as a brief analysis of the current situation in bioenergy in these countries. Section 4 shows an Experimental and Numerical Analysis of two important biomasses in Brazil and Mexico (Wood and coffee husk). Section 5 analyzes the viability of these technologies in Brazil and Mexico. Finally, the conclusion will present, highlighting the main remarks.

2. Large-scale pyrolysis and gasification process

Pyrolysis and gasification are thermochemical conversion processes like combustion, where biomass is broken down into smaller hydrocarbon chains by applying heat and chemical interactions. Unlike combustion that only produces heat, pyrolysis and gasification produce components that can be turned into higher-value commercial products, for example, transportation fuels, chemicals, and fertilizers [6]. Below is a brief description of each technology.

- Combustion: it burns biomass directly with excess oxygen at 800 to 1000°C. It generates heat to be transformed into mechanical power and produce electricity. It is already a well-known commercial technology and broadly accessible at domestic and industrial scales [7].

- Gasification: it transforms biomass into a combustible gas mixture throughout partial biomass oxidation. It operates normally at temperatures from 700 to 900°C [7].

- Pyrolysis: it is the thermal destruction of biomass in the absence of air/oxygen. Pyrolysis of biomass starts at 350 to 500°C and can go to 700 °C, producing bio-oil, gases, and char [7].

These three technologies have not only different operating conditions but also different products, as is described in **Figure 1**.

The oldest thermochemical conversion process to produce energy is certainly biomass combustion. Besides, it is the most dominant process in the thermochemical conversion field. However, pyrolysis and gasification are two promising technologies since their products can be transformed into multiple energy vectors and some chemicals. In fact, some companies already commercialize these technologies on a large-scale to produce power and heat mainly. The following section presents some of those companies and their general process to transform different kinds of biomass into power and heat.

2.1 Large-scale fast pyrolysis

The main objective of fast pyrolysis is to produce bio-oil, which can be utilized as a replacement for fossil fuels in energy production, and transport. Bio-oil is a complex mixture of organic fuels containing some water and a small amount of fine carbon [10]. It aims to mobilize biomass into the energy sectors (heat, power, and transport). It is more manageable to transport and handle, and more cost-effective than solid wood-based fuels or biomass, to be successfully commercialized, its characteristics should follow the ASTM D7544–09 and EN16900/2017 standards. **Table 3** presents the main physical and chemical requirements for bio-oils produced from biomass [12].

Bio-oil production on a large-scale involves multiple processes, working together to set up a functional bio-oil refinery. The heart of bio-oil production is in the fast pyrolysis process, where pre-treated biomass is converted into bio-oil. Pre-treated biomass has basically (1) appropriate particle size (<5 mm) and (2) proper moisture content (<10% w) [13]. Then it is fed into the reactor (approximately 500°C), causing the biomass to become a gas. This process occurs in nearly oxygen-free conditions to prevent combustion. The resulting gas enters a cyclone, where carbon

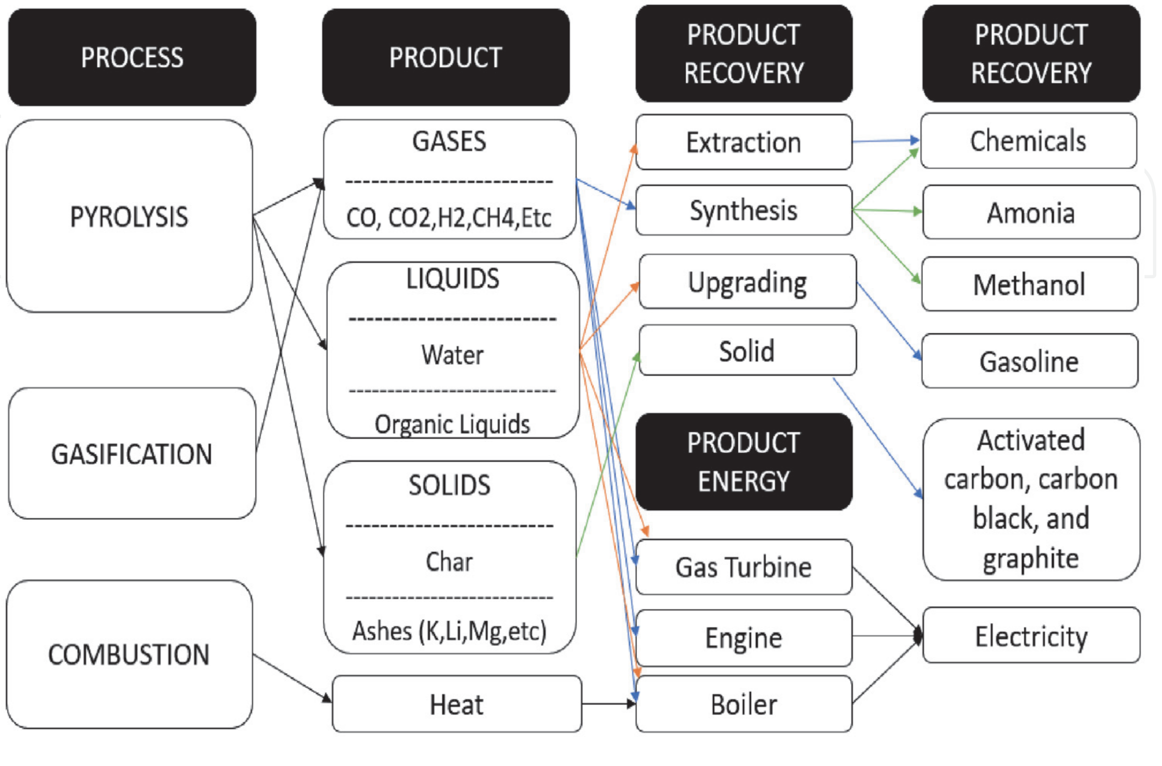

Figure 1.
Biomass thermal conversion adapted from [8, 9].

Property	Unit	Test Method	Requirement
LHV	MJ/kg	ASTM D240	15 minimums
Solid content	Mass %	ASTM D7544	2.5 maximum
Water content	Mass %	ASTM E202	30 maximums
Acidity	pH	ASTM E70	4.1
Kinematic viscosity	cSt (40 °C)	ASTM D445	125 maximums
Density	kg/dm^3 (20 °C)	ASTM 4052	1.1–1.3
Sulfur	Mass %	ASTM 4294	0.05
Ash content	Mass %	ASTM 482	0.25

Table 3.
Main physical and chemical requirements for bio-oils produced from biomass [11].

and other solids are mechanically separated from the gas flow. Then, the gas passes through a condenser system, where it cools down and condenses into bio-oil, then it is filtered. Finally, non-condensable gases are used to produce heat [13].

According to The Green Fuel Nordic company, Bio-oil can be used as a replacement for fossil fuels in the energy production, and transport sector [11]. Furthermore, bio-oil can be transformed into high value-added products like chemical compounds, food ingredients, cosmetics compounds, etc. **Table 4** presents large-scale fast pyrolysis examples in different countries, where the produced bio-oil is used to produce transport fuels, electricity, and heat or to be refined, as appropriate in each case.

A successful example of a bio-oil refinery is Green Fuel Nordic company, whose business model is based on utilizing pyrolysis technology to produce an advanced bio-oil. Then this bio-oil is commercialized and send to its customers like the Savon Voima heating plant to produce heat [16]. Another successful and profitable example is Fortum company, which is a Finnish company that invested €30 million in its bio-oil plant in Joensuu, receiving about €8 million in government investment subsidies for new technology demonstration [13]. This company signed a contract to supply bio-oil produced in Joensuu to Savon Voima, which uses bio-oil to replace the use of heavy and light fuel oil in its district heat production in Iisalmi [13]. In December 2019, Fortum signed an agreement to sell its district heating business in Joensuu Finland to Savon Voima Oyj. The contract concluded in January 2020, registering a tax-exempt capital gain of €430 million in the City Solutions segment's first-quarter 2020 results [28].

The integrated Coal handling plant (CHP) in Joensuu was constructed in 2012 and began full operation in 2015, producing heat, electricity, and 50,000 tons of bio-oil (maximum planned capacity per year). The process consists of a fluidized bed boiler that supplies heat for the pyrolysis reactor and burns the coke, biochar, and non-condensed gases produced during the pyrolysis process to produce electricity and heat (See **Figure 2**). In such a way, high efficiency can be reached for the pyrolyzed fuel production process. Additionally, when a fluidized bed boiler is integrated, pyrolysis is a cost-efficient way of producing bio-oil to replace fossil oils.

It is also interesting to notice that Brazil has already taken a leading role in LATAM with the partnership 50/50 between Ensyn and Suzano to produce 2 million gallons/year of Ensyn biocrude. The project is located at Suzano's pulp facilities at Aracruz city, in the State of Espirito Santo, Brazil. The company derivated from this partnership (NYSE: SUZ) is now the world's largest eucalyptus pulp company in America Latina [25].

Country	REF	Company/entity	Technology/Information	Product	Biomass	For Producing	Feed rate/Production	Status
SE	[14]	Pyrocell-Setra	BTG-BTL Rotating cone	Bio-oil	Sawdust	Transportation fuels	40,000d ton/year of biomass	Construction Start:2021
FI	[15, 16]	Green Fuel Nordic	BTG-BTL Rotating cone	Bio-oil	Wood	Electricity and heat	24,000 ton/y of bio-oil	Operational 2020
CA	[17]	Ensyn	Ensyn Fluid bed/riser	Biocrude	Wood	Heat & refinery	65,000d ton/y of biomass	Operational
NL	[18]	Twence / Twence / EMPYRO	BTG-BTL Rotating cone	Bio-oil	Wood	Electricity 450 GWh	-	Operational
USA	[19]	Ensyn and Renova Capita	circulating fluidized bed reactor	Bio-oil	Wood residues	To refinery	76 ML/y	To Start-up
USA	[20]	Biogas Energy	Ablative reactor	Bio-oil	Wood and agricultural residues	Intermediate fuels	500 kg /h of biomass	Operational
IE	[21]	Kerry Group PLC	RTP (Ensyn)	Biocrude	Wood residues	Food ingredients	30–40 tons/d of biomass	Operational
DE	[22]	KIT	Twin-screw mixing reactor	Biosyncrude	Wheat Straw	Intermediate fuel	500 kg/hr. of biomass	Operational
FI	[23] [24]	Fortum - Valment	Fluid bed (VTT)	Bio-oil	Wood residues	Electricity and heat	50,000 ton/y bio-oil	Operational
BZ	[25]	Ensyn, Suzano S.A	circulating fluidized	Bio-oil	Eucalyptus forest residues	—	83 ML/y	Detailed engineering underway
CH	[26]	Shanxi Yingjiliang Biomass Company	circulating fluidized bed reactor	Bio-oil	Rice Husk	—	2–6 ML	Operational
IN	[27]	MASH Energy	—	Bio-oil	Waste materials	—	—	—

d: dry.

Table 4.
Large-scale Fast Pyrolysis Examples.

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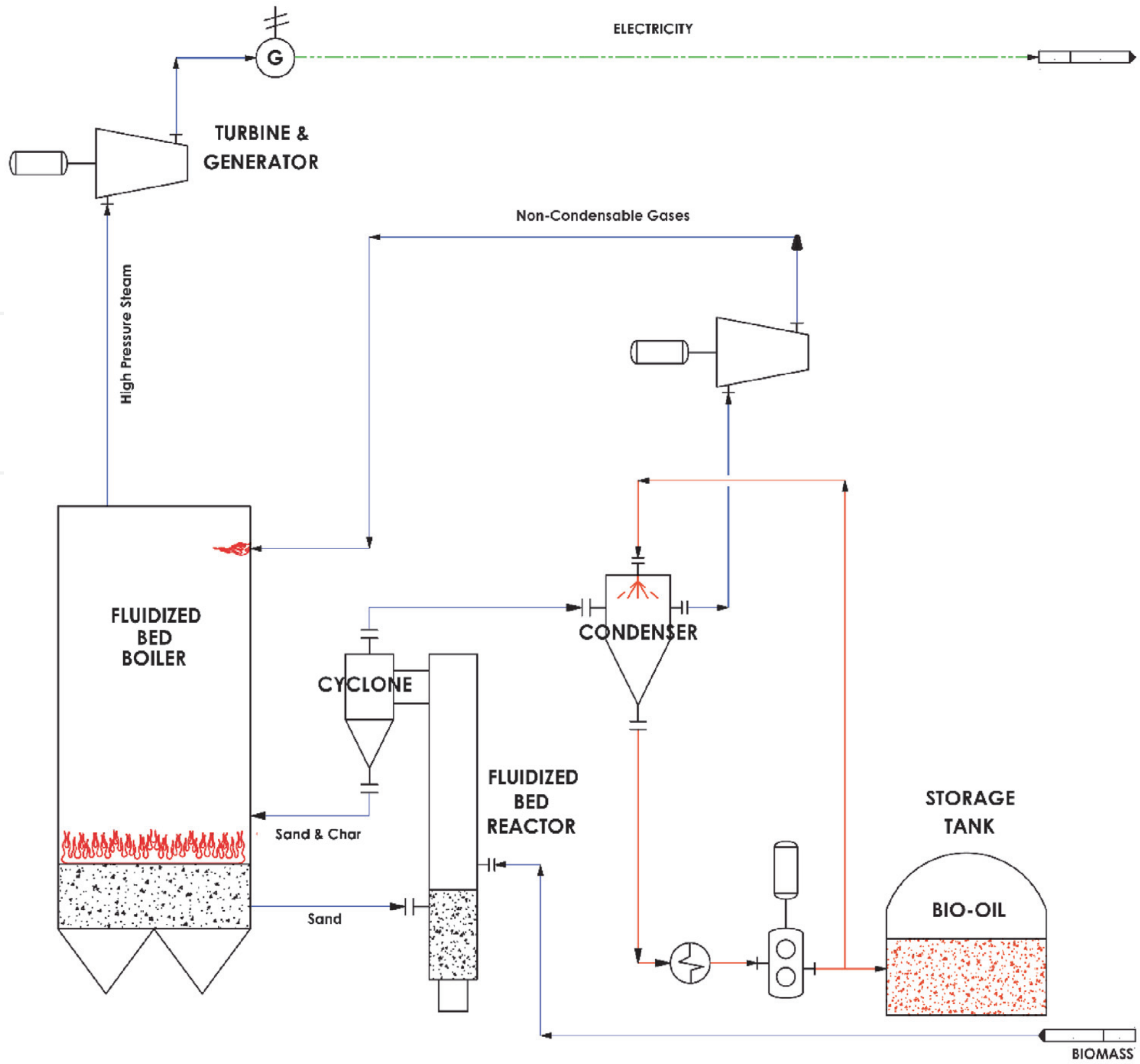

Figure 2.
Large-Scale Fast Pyrolysis Process (Valmet) adapted from [13].

These success cases seem to support the pyrolysis of biomass as a wise way to reduce the use of fossil fuels, adding value to biomass and contributing to mitigate the impact of greenhouse gases without losing sight of profitability. Applying technologies might make sense to countries with a bast biomass availability. However, as in any process, it is necessary to evaluate the performance of the process to look for continuous improvements. The following section contains some of these performance parameters.

2.1.1 Pyrolysis performance

Pyrolysis is a thermochemical cracking process in which organic material is transformed into a carbon-rich solid and volatile matter (gas and liquids) by heating in the absence of oxygen as Eqs. (1)-(4) describe [29].

$$Biomass \rightarrow Char + Ash + Moisture + Volatile\ (C0, CO_2, CH_4, C_2H_4, H_2O) \quad (1)$$

$$Biomass_{Molecule} \rightarrow 2R^*\ (\text{Initiation}) \quad (2)$$

$$R_n^* \rightarrow O_j + R_{n-j}^* (\text{Propagation}) \quad (3)$$

$$2R^* \rightarrow Products\ (\text{Termination}) \quad (4)$$

Eq. (1) is the general pyrolysis reaction. The other reactions represent the thermal cracking process, where R_n^* is a free radical with a chain length n. O_j is an alkene from olefins with a chain length j [29].

Pyrolysis temperature ranges from 350 to 600°C and it plays a critical role in the cracking process since, at higher temperatures, molecules move violently, which causes the breaking of shorter chains from the main C-C chain. Therefore, shorter hydrocarbon products are favored as in fast pyrolysis or gasification. While biochar is boosted under low temperatures and large residence times as in slow pyrolysis [29].

General measures of performance are often quoted as measures of how effective a given pyrolysis scheme may be. These parameters can be oriented to a mass balance and an energy balance.

2.1.1.1 Product yields

Some parameters can affect the product yield of pyrolysis, such as temperature, particle size, heating rate, etc. If the desired product is liquid, then producing more liquids will indicate a more effective process. While, if the desired product is solid, then producing more solids will indicate a more effective process. Eqs. (5)-(8) describe the pyrolysis yield calculations.

$$m_F = m_{solid} + m_{gas} + m_{liquid} \tag{5}$$

$$Y_{solid} = \frac{m_{solid}}{m_F} * 100 \tag{6}$$

$$Y_{gas} = \frac{m_{gas}}{m_F} * 100 \tag{7}$$

$$Y_{liquid} = \frac{m_{liquid}}{m_F} * 100 \tag{8}$$

where m_F represents the feedstock mass, m_{solid} is the solid mass, m_{gas} is the gas mass, m_{liquid} is the liquid mass, m_F is the feedstock mass, Y_{solid} is the solid yield, Y_{gas} is the gas yield, and Y_{liquid} is the liquid yield.

2.1.1.2 Lower heating value (LHV)

The lower heating value of the products is determined by the contribution of each of the compounds contained in a specific phase. This parameter is important because it indicates the amount of energy contained in the products. The LHV of the gas, liquid, and solid yield is calculated as the following equations describe.

$$LHV_{gas} = \frac{\sum y_{igas} * m_i * LHV_i}{m_{gas}} \tag{9}$$

$$LHV_{liquid} = \frac{\sum y_{iliquid} * m_i * LHV_i}{m_{liquid}} \tag{10}$$

$$LHV_{solid} = \frac{\sum y_{isolid} * m_i * LHV_i}{m_{solid}} \tag{11}$$

where y_{igas} is the mass fraction of the component "i" in the gas, $y_{iliquid}$ is the mass fraction of the component "i" in the liquid, y_{isolid} is the Mass fraction of the component "i" in the solid, m_i is the mass of the component "i", m_{solid} is the solid mass, m_{gas} is the gas mass, m_{liquid} is the liquid mass, LHV_i is the LHV of the component "i",

LHV_{gas} is the LHV of the gas, LHV_{liquid} is the LHV of the liquid and LHV_{solid} is the LHV of the solid.

2.2 Large-scale gasification

Similar to pyrolysis on large-scale, gasification on a large-scale involves other processes working together. The main product of gasification is combustible gas. But unlike pyrolysis, the main product is not stored and then transported to be used somewhere else but used in the same facilities where it was produced. Even so, gasification offers great benefits, namely reducing CO_2 emissions for replacing fossil fuels and avoiding their extraction. Another benefit is that gasification can use materials that currently have no other valorization option but to be disposed of in landfills. Waste gasification provides much better electrical efficiency compared with the direct combustion of waste [30].

A perfect successful gasification example is its integration with an existed coal-fired plant in Vaskiluodon Voima Oy, Vaasa, Finland. This integration of gasification into the coal-fired facilities had several advantages, such as the investment cost was kept to about one-third of a similar-sized new biomass plant, it was also kept the full original coal capacity, and the use of coal was cut off by 40% by using local biomasses like wood, peat, and straw [31]. The Plant generates 230 MW electricity and 170 MW district heating.

Another example is ThyssenKrupp, whose main product is syngas, which can be used in multiple processes. While its byproducts are slags, ash, and sulfur components. These byproducts can be employed in road building, cement industry, or recovered [32]. The typical gas composition is $CO + H_2 > 85$ (vol.%), CO_2 2–4 (vol.%), and CH_4 0.1 (vol.%) [32].

More examples of large-scale gasification in the world are provided in **Table 5**, where one can notice several examples are using materials like MSW, plastics, and solid recovered fuels (SRF). The resulting gas is being used to produce heat and electricity.

ThyssenKrupp facilities have a feed dust system, so the biomass must be smaller than 0.1 mm. Then, biomass is gasified using oxygen and steam as gasification agents. The operational temperature is higher than the ash melting temperature to remove ash as slag. While the pressure is around 40 bar. The technology has multiple, horizontally arranged burners to provide heat to the gasifier and produce steam in a drum boiler (see **Figure 3**) [32].

On the other hand, **Figure 4** presents the Valmet equipment that has a screw feeder system, so it allows biomass with higher particle size, it also has a cyclone, which separates solids from the gas. After the cyclone, the gas goes through a gas cleaning system, delivering a clean gas, which enables the production of high pressure and temperature steam for the turbine without risk of boiler corrosion. In Lahti, the electrical efficiency is over 30% (540°C and 120 bar). Furthermore, this plant operates with RDF (250,000 ton/y) and wood, producing 2 x 80 MW hot gas cleaning [50]. VASKILUODON VOIMA OY (formerly Fortum) produces 230 MW electricity and 170 MW district heating, by integrating the gasification capability with the original coal-fired plant. The biomass gasification plant contributes 140 MW and a woodchip dryer. The gas produced in the gasifier and coal enters a circulating fluidized bed boiler, where hot water is transformed into steam, that goes to high-pressure superheaters and then continues to the high-pressure turbine (HPT). From HPT, the steam returns to the boiler's preheaters and ends in the intermediate-pressure turbine (IPT). Here the steam is divided into different streams (1) district heat exchangers, (2) storage water tank to preheat it, and (3)

Country	REF	Company/ entity	Technology/ Information	Biomass	For Producing	Feed rate/ Production (ton/day)	Status
USA	[33]	Energy Products of Idaho*	Bubbling bed	—	—	1040	—
DE	[34]	HTW-Plant Berrenrath / Germany	ThyssenKrupp Fluidized-Bed	High-ash coal	methanol	25 ton/h	Shut down 1986–1997
FI	[35]	Kemira Oy	ThyssenKrupp	Peat	NH_3	30 ton/h Peat	Shut down 1988–1991
FI	[36] [37]	NSE Biofuels Oy Ltd.	Sumitomo heavy industries ltd CFB	Wood residues	Heat 12 MWth	—	Start-up 2009
FI	[38]	Corenso United Ltd.	Sumitomo heavy industries ltd	Plastic Waste	50 MWth	—	Start-up 2000
BE	[39]	Electrabe	Sumitomo heavy industries ltd	Wood residues	Heat 50 MWth	—	Start-up 2002
JP	[40]	HTW-Precon	ThyssenKrupp	MSW	—	48 ton/day	Start-up 1999
FI	[41]	Lahti Energia Oy,	Valmet CFB	SRF	160 MW	250,000 ton/y	Start-up 2012
FI	[31]	Vaskiluodon Voima Oy	Valmet CFB	Wood, peat, and straw	230 MW electricity 170 MW heating	—	Start-up 2012
FI	[42]	RENUGAS	ANDRITZ Carbona Bubbling Fluidized Bed (BFB)	Wood pellets, or chip	—	100–150 ton/ day	Start-up 2013
SE	[43]	GoBiGas	Valmet CFB	Wood residues	20 MW	—	Start-up 2013
ID	[44]	OKI Pulp & Paper	Valmet CFB	Bark and wood residues	110 MW X2	—	Start-up 2017
USA	[45] [46]	Taylor Biomass Energy	Dual bed	MSW	—	300–400 ton/ day	2021
UK	[47] [48]	Amec Foster Wheeler	VESTA patented technology	Coal, biomass, waste	—	250,000 $Nm^{3/}h$ of Sin gas	—

It was bought by Outotec.

Table 5.
Large-Scale Gasification Examples.

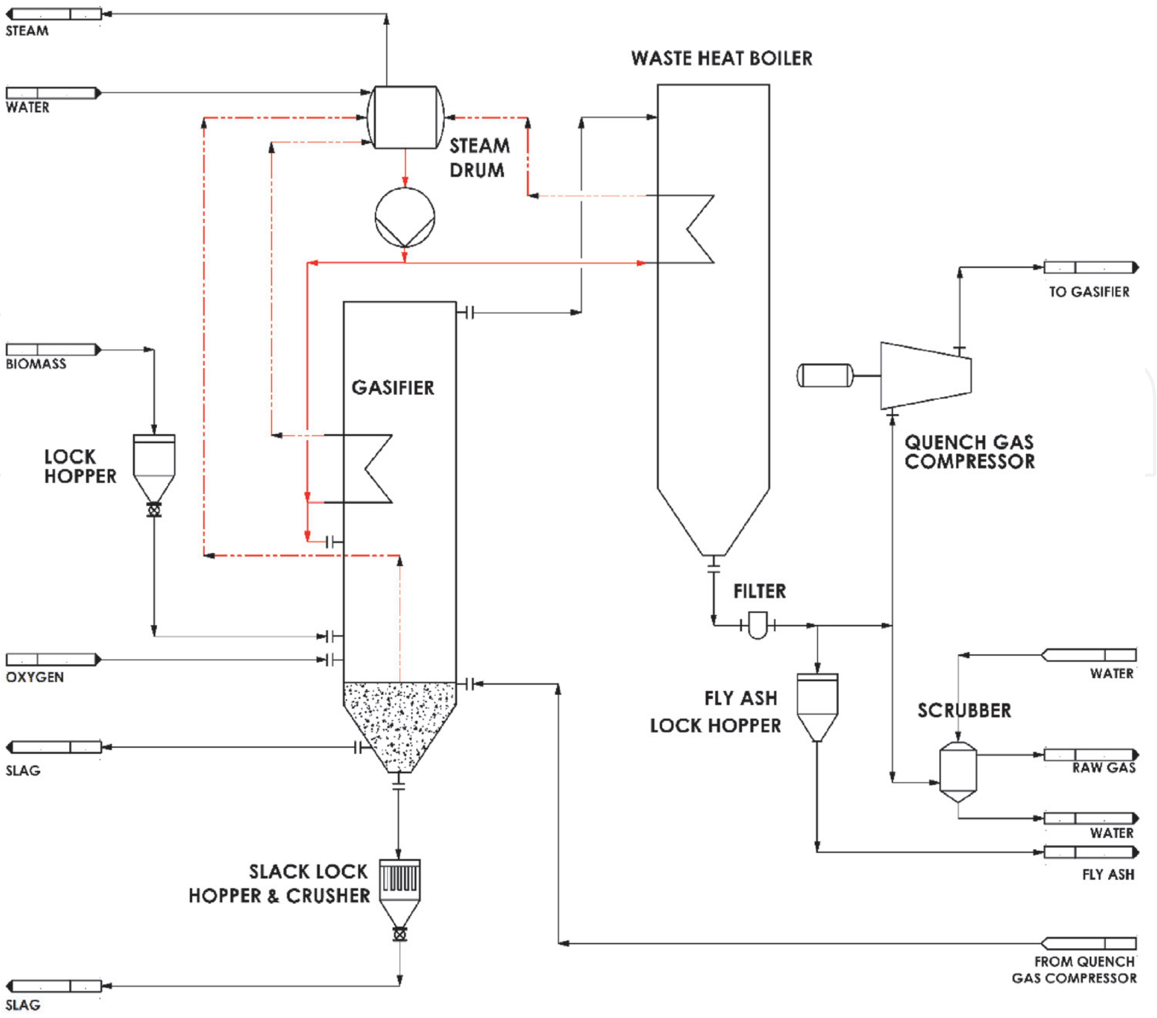

Figure 3.
Large Scale Gasification Process (Thyssenkrup PRENFLO), adapted from [32].

the low-pressure turbine (LPT), where steam rotates the turbine's rotor, and a generator produces electricity for the electrical network. Finally, the gas resulting from the combustion goes to the flue-gas desulphurization, the cleaning process creates gypsum.

The gasification process is a potential solution to deal with problems linked to MSW, plastics, and other residues, producing energy vectors at the same time. This could be a massive opportunity for LATAM countries that are dealing with exorbitant amounts of waste. Similar to pyrolysis, the gasification performance can be evaluated for a continuous improvement process.

2.2.1 Gasification performance

Gasification is a partial oxidation process in which organic material is transformed mainly into gases through heterogeneous (Eqs. (12)-(16)) and homogeneous r**eactions** (Eqs. (17)-(21)), as the following reactions describe.

$$C + O_2 \rightarrow CO_2 \tag{12}$$

$$C + CO_2 \rightarrow 2CO \tag{13}$$

$$C + CO_2 \rightarrow 2CO \tag{14}$$

$$C + H_2O \rightarrow CO + H_2 \tag{15}$$

$$C + 2H_2 \rightarrow CH_4 \tag{16}$$

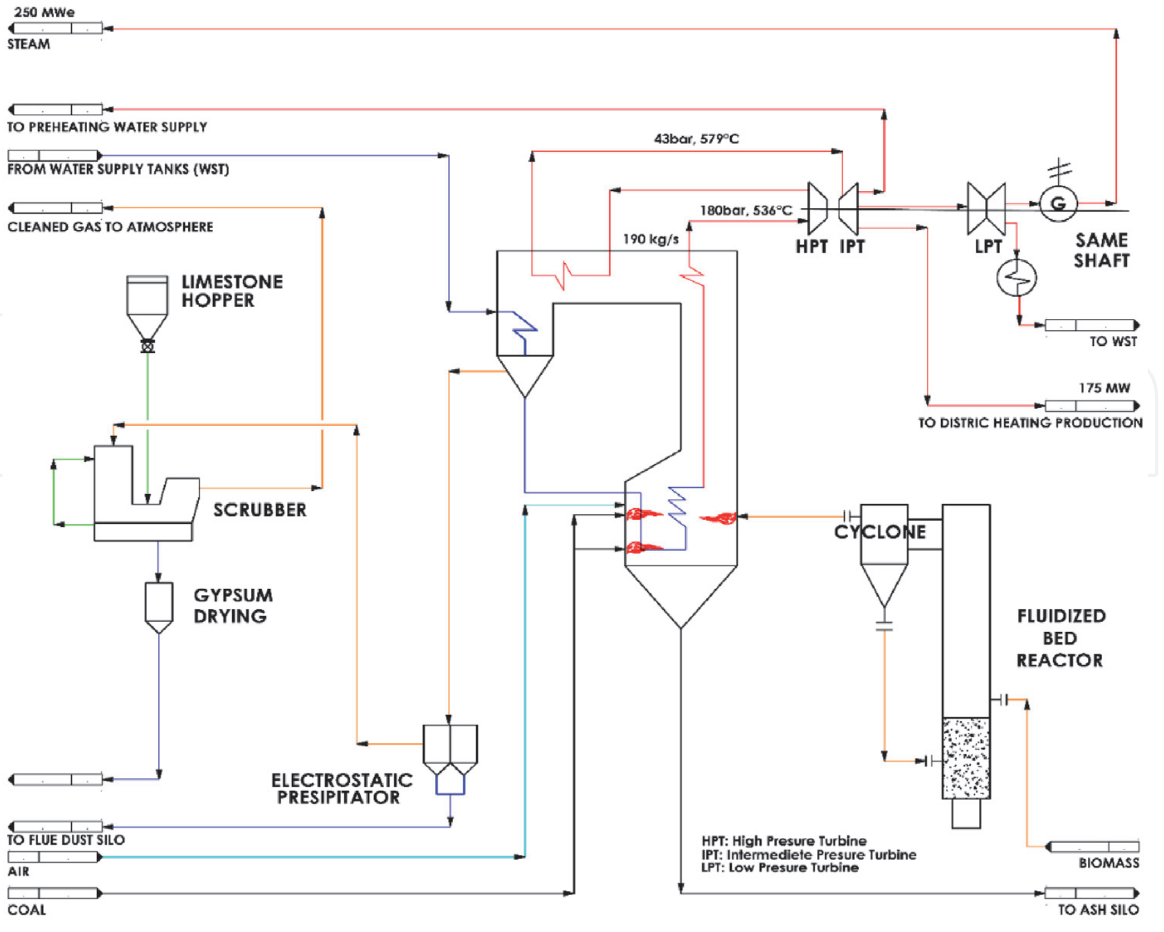

Figure 4.
Pioneer of Biofuel Plants, Producer of Combined Heat and Power adapted from [49].

$$CO + 0.5O_2 \rightarrow CO_2 \quad (17)$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad (18)$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (19)$$

$$C_2H_4 + O_2 \rightarrow 2CO + 2H_2 \quad (20)$$

$$CH_4 + 2H_2O \rightarrow CO + 3H_2 \quad (21)$$

The temperature in the gasification ranges between 600 and 700°C and plays an important role in the product yields and gas composition [51]. Besides, the product yields and LHV of the products exist another parameter to evaluate the performance of the gasification process like Cold Gas Efficiency (CGE) and Gas Efficiency (Ygas).

2.2.1.1 Cold gas efficiency (CGE)

Cold gas efficiency is the output energy by input energy [52], and it can be described mathematically with the following equation:

$$CGE = \frac{LHV_{gas} * m_{gas}}{LHV_F * m_F} * 100\% \quad (22)$$

where CGE is the cold gas efficiency, LHV_F is the lower heating value of the feed stream, LHV_{gas} is the lower heating value of the gas mixture, m_{gas} is the mass of the gas mixture, and m_F is the mass of the feed stream.

2.2.1.2 Gas efficiency (ygas)

Y gas can be also described as the ratio of the produced gas volume by the feedstock mass as the following equation expresses:

$$y_{gas} = \frac{V_{gas}}{m_F} \tag{23}$$

where m_F is the mass of the feed stream and V_{gas} the volume of the gas mixture.

3. Biomass availability in Brazil and Mexico and potential analysis

Biomass is a renewable organic material that serves as a sustainable source of energy to produce electricity or other forms of power. Some of the drivers to utilize it are lowering fossil-fuel utilization, decreasing greenhouse gas (GHG) emissions, and promote economic development and agricultural development. The following sections briefly describe the potential of Brazil and Mexico for bioenergy production using agroforestry residues and MSW.

3.1 Brazil

Brazil has an electrical matrix of predominantly renewable origin with an emphasis on the water source. Renewable sources account for 82.9% of the domestic supply of electricity in Brazil, which is the result of the sum of the amounts referring to domestic production plus imports distributed as 64.9% hydro, 8.6% wind, 8.4% biomass, and 1% solar [49]. The energy production from fossil fuels accounted for 17.1% of the national total, which 2.0% oil products, 2.5% nuclear, 9.3% natural gas, and 3.3% charcoal. This distribution represents the structure of the domestic supply of electricity in Brazil in 2019 [53].

The energy needed to move the economy of a region in a period, Internal Energy Supply in 2019, was 294 million toe (tons of oil equivalent) or Mtoe. Looking specifically the renewable sources, they increased by 2.8% in 2019 compared to 2018, that was supported by a strong increase in the production of sugarcane products with 5.5% in ethanol, adding the increase of wind, solar, and biodiesel with 4.4% [54], as shown in **Table 6**.

The choice for the energy matrix also relates to the system costs and regional conditions. For agro-industrial regions, biomass can be a viable raw material to produce clean and renewable energy, at the same time is a form to minimize the environmental impacts of agro-industrial production. In the Brazilian energy matrix, the types of biomass most used are from sugar cane and its products, firewood, black liquor, and rice husks. Considering the energy matrix in Brazil, a general view of the installed potency is shown in **Table 7**, the installed capacity of electricity generation by source in MW, and the evolution from 2015 to 2019 [53].

3.1.1 Forestry residues

Brazil is a forest country with hectares (59% of its territory) of natural and planted nearly 500 million forests [55], representing the second largest forest area in the world with 502,082.1 (1000 ha) [55], only surpassed by Russia [56]. The distribution area is 57.31% in natural forests and 1.16% in planted ones [56].

Brazil has around 10 million hectares of forest plantations, mainly with species of Eucalyptus and Pinus genera, which represent 96% of the total area. Forest

Description	Production (ktoe)		Increase or retraction %	Production (%)	
	2018	2019		2018	2019
Non-renewable	**157,972**	**158,395**	**0.3**	**54.5**	**53.9**
Petroleum and derivatives	99,627	101,051	1.4	34.4	34.4
Natural gas	35,905	35,909	0	12.4	12.2
Mineral coal and derivatives	16,418	15,480	−5.7	5.7	5.3
Uranium (u3o8) and derivatives	4174	4174	0	1.4	1.4
Other non-renewable[a]	1848	1780	−3.7	0.6	0.6
Renewable	**131,898**	**135,642**	**2.8**	**45.5**	**46.1**
Hydraulics and electricity	36,460	36,364	−0.3	12.6	12.4
Firewood and charcoal	25,511	25,725	0.8	8.8	8.7
Sugar cane derivatives	50,090	52,841	5.5	17.3	18
Other renewables[b]	19,837	20,712	4.4	6.8	7
TOTAL	**289,870**	**294,036**	**1.4**	**100**	**100**
of which fossils	153,798	154,221	0.3	53.1	

[a]*Blast furnace, melt shop, and sulfur gas.*
[b]*Black liquor, biodiesel, wind, solar, rice husk, biogas, wood waste, charcoal gas, and elephant grass.*

Table 6.
Internal Energy Supply (OIE) [54].

plantations amount to 1.2% of Brazil's area, and 2.0% of the total forest areas. The composition of forest plantations in 2018 was 7,401,334 ha of Eucalyptus, 2,030,419 ha of Pinus, and 407,933 ha of other species [56] including rubber, acacia, teak, and parica.

The industrial sector of forest plantations is based on the cultivation of trees for industrial purposes, generating a variety of products numbering nearly five thousand, including lumber, pulp, paper, flooring, wood panels, and charcoal [57]. **Figure 5** presents the area of planted trees in 2019, by state and by genus (in millions) [57].

According to the Food and Agriculture Organization of the United Nations, FAO, in 2019 the generated wood residues in Brazil were 19,140,000 m^3 [58]. Concerning the management of industrial and forest waste, the Brazilian planted tree sector has adopted sustainable practices to dispose of various types of domestic and urban waste generated during its production processes.

As shown in **Table 8**, in 2019 most of the waste from factories and forest companies was directed toward energy generation, approximately 67%. In the second place, 12% of waste was directed to other industrial sectors for reuse as a raw material. Of the total waste generated before consumption, 7.4% was kept in the field to protect and enrich the soil, 4.2% was sent to landfills, and 3.4% was recycled [57].

3.1.2 Agricultural residues

Agricultural occupation in Brazil is estimated at 65.91 million hectares, equivalent to 7.8% of the national territory [59], the numbers show that Brazil uses 7.57% of its territory for crops. This area also corresponds to only 3.41% of the cultivated area worldwide.

Agroindustry waste generation in Brazil is spread off in all the country states from North to South regions, is from various crops, varies with seasonality, and

Plants in operation		**2015**	**2016**	**2017**	**2018**	**2019**
UHE / Hydro		86.366	91.499	94.662	98.287	102.999
PCH / Hydro		4.886	4.941	5.020	5.157	5.291
CGH / Hydro		398	484	594	695	768
EOL / Wind		7.633	10.124	12.283	14.390	15.378
SOL / Solar		21	24	935	1.798	2.473
Termo	Total	39.564	41.275	41.537	40.523	41.219
	Biomass	13.257	14.147	14.505	14.790	14.978
	Bagasse	10.573	10.979	11.158	11.368	11.438
	Others	2.684	3.168	3.347	3.422	3.540
	Biogas	84	119	135	140	186
	Elephant Grass	32	66	32	32	32
	Charcoal	51	54	43	43	48
	Rice Peels	45	45	45	45	53
	Charcoal Gas	112	115	114	128	128
	Black-Liquor	1.923	2.333	2.543	2.556	2.544
	Vegetal Oil	27	4	4	4	4
	Wood Residue	409	432	431	474	544
	Fossil	24.961	25.550	25.453	24.127	24.642
	Steam Coal	3.389	3.389	3.324	2.858	3.228
	Refinery Gas	316	316	316	320	320
	Natural Gas	12.428	12.965	12.980	13.359	13.385
	Fuel Oil	3.197	4.020	4.056	3.363	3.316
	Diesel Oil	5.632	4.825	4.737	4.186	4.353
	Viscous Oil		—	—	—	—
	Others[1]		35	41	41	40
	Industrial Effluent	1.346	1.578	1.579	1.606	1.599
	Gaseous Effluent[2]	160	176	172	172	66
	Sulfur	71	71	71	71	79
	Blast Furnace Gas	216	422	422	417	512
	Process Gas	674	654	658	721	715
	Steel Gas	225	255	255	225	226
	Unknown sources			92	—	—
Nuclear		1.990	1.990	1.990	1.990	1.990
Total		140.858	150.338	157.112	162.840	170.118

[1]*Includes TAR.*
[2]*Includes heat of the process (Table in MW).*

Table 7.
Installed Capacity of Electricity Generation by Source [53].

represents a huge amount. The availability of the main selected products from agricultural residues, animal waste, and its respective analyses as to generation potential was determined [60]. The main selected products are analyzed from the

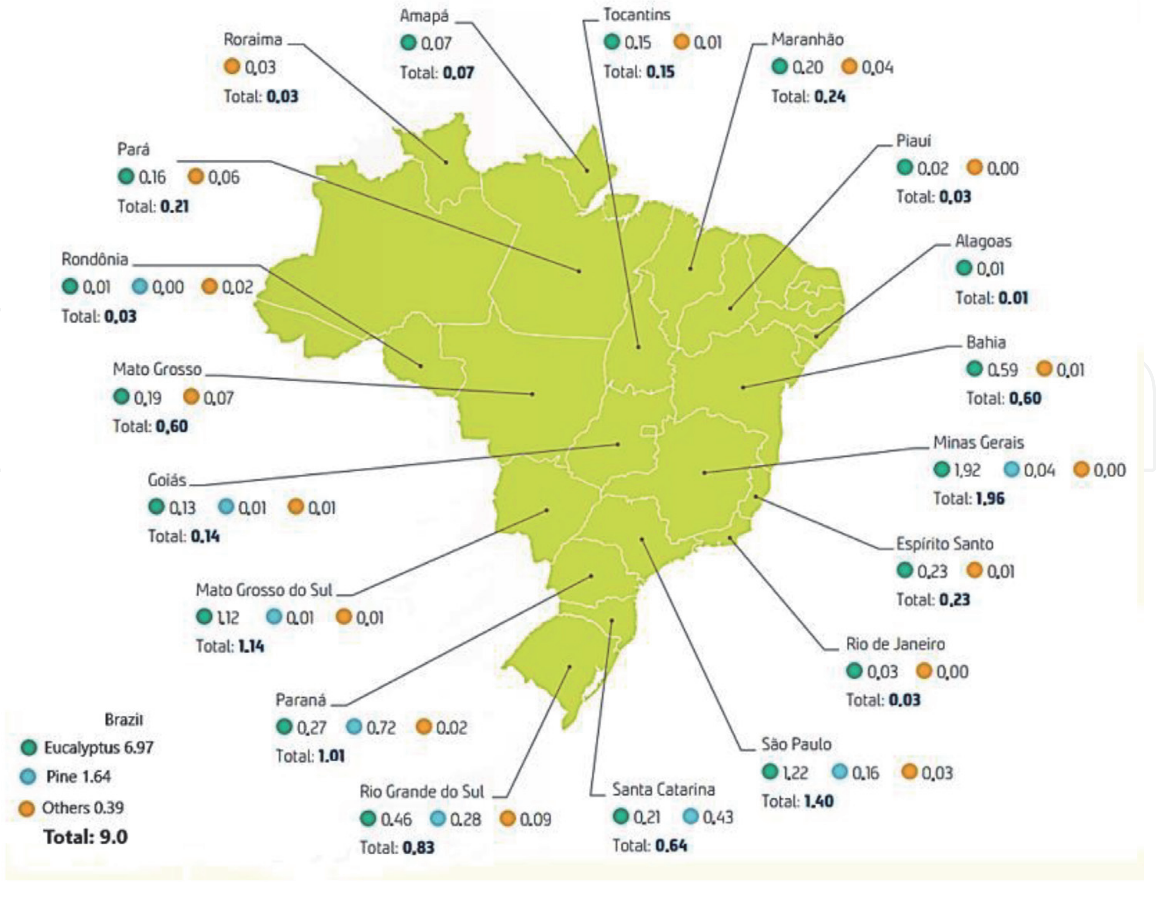

Figure 5.
Area of Planted Trees in Brazil in 2019, by state and by genus (in millions) [56].

Waste generated during the production process	% of tons by type of waste, by destination	Final destination
Bark, branches, leaves, lime sludge, boiler ash, others	7.4%	kept in the fields to protect and fertilize the soil, composted
Drags and grits, sludge, ash, metal scrap, plastic, cardboard, etc.	3.4%	recycling
Bark, branches, leaves, woodchips, sawdust, black liquor	66.6%	energy generation
Sawdust, paper scraps, lime sludge, and boiler ash	0.7%	reused as raw materials by companies in the planted tree sector
Sawdust, paper scraps, lime sludge, and boiler ash	11.7%	reused as raw materials by other industrial sectors
Paper scraps, lime sludge, non-hazardous wastes, others	4.2%	sent to landfills
Bark, sawdust, sludge/filtrate from water treatment plants, knots, and rejects from fiber lines	0.7%	sold or shipped to various companies
Various types of waste already described above and other non-specified	5.3%	other destinations, including co-processing

Table 8.
Solid Waste Generated by Type, According to Final Destination, in % of Total Waste [57].

point of view of Brazil's economy and about the necessary conditions for the rural producer to keep up with sustainable growth. **Table 9** presents the most common and produced agricultural residues [60].

Brazil stands out as a major biomass generator, the mass supply of biomass in 2005 was 558 million tons, with a projected growth to 1402 million tons in 2030 [53]. **Table 10** shows the evolution of mass supply per agricultural residue, agro-industrial, and forestry residues.

Biomass availability is a key aspect of bioenergy. The total bioenergy supply in 2019 was 93.9 Mtoe (1824 thousand bop/day), corresponding to 31.9% of the Brazilian energy matrix. Sugarcane products as bagasse and ethanol with 52.8 Mtoe,

Feedstock	Abbreviation	Generating potential index -GP[a] (tons/total residues - tons/total waste[b])
Sugar cane	SC	0.22 t TR/SC
Soybean	SO	2.05 t TR/SO
Maize (corn)	MI	1.42 t TR/MI
Rice (straw)	RI	1.49 t TR/RI
Cotton (Perennial)	CO	2.95 t TR/CO
Orange - 100	OG	0.50 t TR/OG
Wheat −70	WH	1.42 t TR/WH
Cassava - 100	CA	0.20 t TR/CA
Tobacco	TO	0.75 t TR/TO

[a]*Generating potential index GP (Tons/culture).*
[b]*GP Index abbreviation: TR= Total Residue: TW= Total waste.*

Table 9.
Estimates of generating potential index (GP) for agricultural residues and animal waste in Brazil [60].

Residue	2005	2010	2015	2020	2030
Total	558	731	898	1058	1402
Agricultural Residues	478	633	768	904	1196
Soybean	185	251	302	359	482
Maize (corn)	176	251	304	361	485
Rice (straw)	57	59	62	66	69
sugar cane	60	73	100	119	160
Agro industrial waste	80	98	130	154	207
Bagasse sugar cane	58	70	97	115	154
Rice (Husk)	2	2	3	3	3
Black Liquor	13	17	21	25	34
Wood	6	8	10	12	16
Energy Forests	13	30	31	43	46
Super plus Wood	13	30	31	43	46

Table 10.
Mass supply of biomass by agro-industrial agricultural waste and forestry (millions of tons) [61].

accounted for 56.3% of bioenergy and 18% of the matrix. Firewood, with 25.7 Mtoe, accounted for 27.4% of bioenergy and 8.7% of the matrix.

Other bioenergy (black liquor, biogas, wood residues, residues from agribusiness, and biodiesel), with 15.3 Mtoe, accounted for 16.3% of bioenergy and 5.2% of the matrix [49]. **Tables 11** and **12** show the energy supply and consumption by sugarcane products: sugarcane bagasse as input for electricity generation and sugarcane juice for alcohol production [50].

3.1.3 Municipal solid waste residues

Between 2010 and 2019, the generation of MSW in Brazil registered a considerable increase, going from 67 million to 79 million tons per year (in 2020). In Brazil, most of the collected MSW goes to disposal in landfills, having registered an increase of 10 million tons in a decade, going from 33 million tons per year to 43 million tons. On the other hand, the amount of waste that goes to inadequate units (dumps and controlled landfills) has also grown, from 25 million tons per year to just over 29 million tons per year [62].

It should be noted, in **Figure 6**, that the organic fraction remains the main component of MSW, with 45.3%. Dry recyclable waste, on the other hand, adds up to 35% being mainly composed of plastics (16.8%), paper and cardboard (10.4%), in addition to glass (2.7%), metals (2.3%), and multilayer packaging (1.4%) [58].

Flow	2015	2016	2017	2018	2019
Production	162.6	168.6	165.6	157.8	162.2
Total consumption	162.6	168.6	165.6	157.8	162.2
Transformation*	28.0	28.7	28.9	28.5	29.3
Final consumption	134.6	139.9	136.8	129.3	132.9
Final energy Consumption	134.6	139.9	136.8	129.3	132.9
Energy sector	61.8	57.5	56.0	67.1	71.1
Industrial	72.8	82.4	80.8	62.1	61.9
Chemical	0.0	0.0	0.0	0.0	0.0
Foods and beverages	72.7	82.3	80.6	62.0	61.7
Paper and pulp	128.0	141.0	146.0	157.0	147.0
Others	0.0	0.0	0.0	0.0	0.0

Input for alcohol production (Table in 10^3 ton).

Table 11.
Sugar Cane Bagasse [53].

Flow	2015	2016	2017	2018	2019
Production	209.3	183.7	179.9	243.1	260.5
Total Consumption	209.3	183.7	179.9	243.1	260.5
Transformation*	209.3	183.7	179.9	243.1	260.5

Input for alcohol production (Table in 10^3 ton).

Table 12.
Sugar Cane Juice [53].

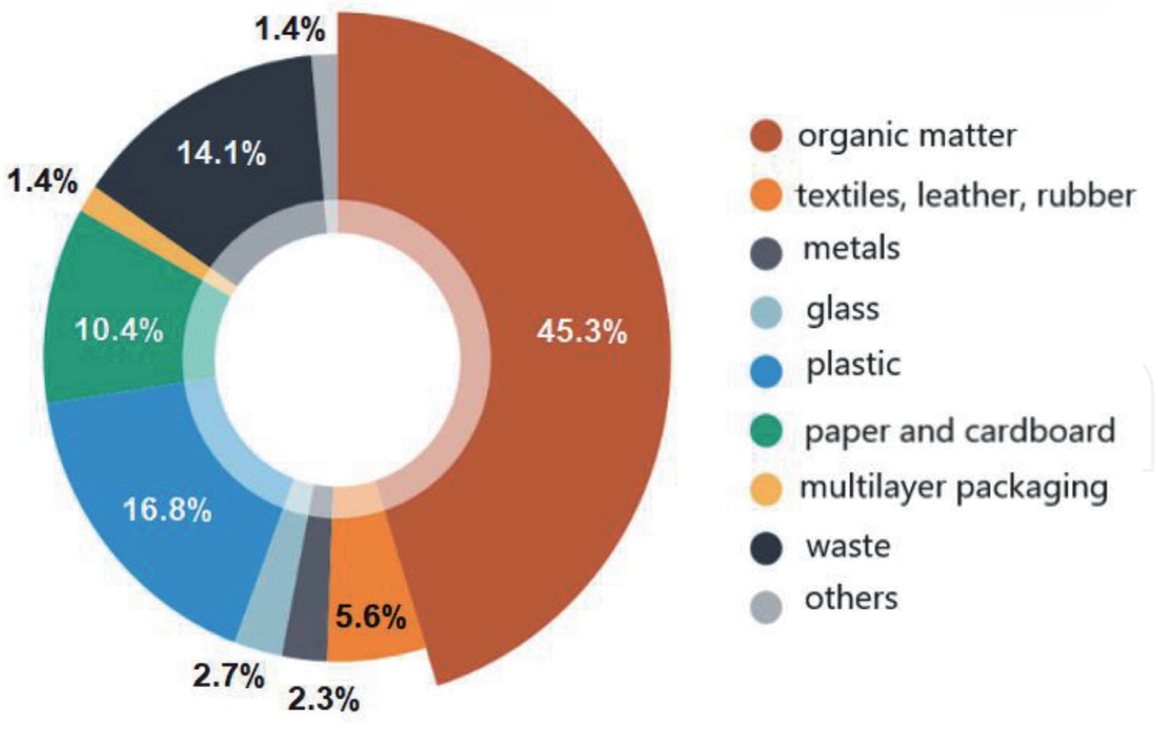

Figure 6.
Gravimetry of MSW in Brazil [62].

The tailings, in turn, correspond to 14.1% of the total and mainly contemplate the sanitary materials. As for the other fractions, we have textile waste, leather, and rubber, with 5.6%, and other waste, also with 1.4%, which contemplate various materials theoretically reverse logistics objects [62].

The national gravimetry, in **Figure 6**, was estimated based on the weighted average of the total generation of MSW by income bracket of the municipalities and their respective gravimetry, considering the population and generation per capita.

It is possible to estimate the economic development of a country by analyzing the physical composition of its MSW. In general, the greater the income of a country the higher the consumption and, therefore, the amount of waste generated [63]. The physical compositions of MSW from towns in different regions of Brazil are shown in **Table 13** [63].

The National Solid Waste Policy (NSWP) was established by Federal Law n. 12,305 in August 2010, and it can be a milestone for waste management in Brazil [64]. The goals of this law are the reduction, reuse, recycling, treatment, and appropriate disposal of MSW, including energy recovery systems, to avoid damage to the environment and public health. This law prohibits the open dump disposal of MSW, and it is stipulated that all states and cities must have closed their open dumps by 2014. Nevertheless, the situation about MSW in Brazil has changed very little since the introduction of the NSWP [63].

3.1.4 Brazilian politics related to the bioenergy sector

In Brazil, the bioenergy sector is promoted by programs instituted by the federal government. In 2002 the Brazilian government launched the Incentive Program for Alternative Sources of Electric Energy (PROINFA), of the Ministry of Mines and Energy in response to the scarcity of energy in the country, in search of renewable sources [63].

As part of the incentive to biodiesel, the National Biodiesel Production and Use Program (PNPB) was launched in 2004 [65]. The PNPB's strategy is to make

Regions	North[a] (%)	North-east[b] (%)	Mid-west[c] (%)	South-east[d] (%)	South[e] (%)	Brazil[f] (%)
MSW						
Organic matter	54.68	57.00	54.02	52.00	57.27	51.4
Recyclables	27.46	10.31	29.72	41.70	26.87	31.9
Metal	1.09	1.74	3.64	1.66	1.46	2.9
Paper and cardboard	10.87	3.7	7.48	15.39	11.62	13.1
Plastic	14.67	3.86	16.73	21.15	11.23	13.5
Glass	0.83	1.01	1.87	3.50	2.56	2.4
Others	17.86	32.69	16.26	6.30	15.86	16.7
Total	100	100	100	100	100	100

[a]*Prefeitura Municipal de Araguaína (2013).*
[b]*Contrato Prefeitura Municipal de Cubatí (2013).*
[c]*Prefeitura de Paranaíba (2014).*
[d]*Prefeitura da Cidade do Rio de Janeiro (2015).*
[e]*Prefeitura de Porto Alegre (2013).*
[f]*Ministério do Meio Ambiente (2012).*

Table 13.
Physical composition of MSW from towns in different regions of Brazil [63].

feasible the production and use of biodiesel in the country, with a focus on competitiveness, the quality of the biofuel produced, the guarantee of security of its supply, the diversification of raw materials, the social inclusion of family farmers and in strengthening the regional potential for the production of raw materials [66].

RenovaBio is the new National Biofuel Policy, instituted by Law 13,576/ 2017 [67], whose objective is to expand the production of biofuels in Brazil, based on predictability, environmental, economic, and social sustainability, and compatible with the growth of the market. Based on this expansion, the aim is to make an important contribution by biofuels in reducing greenhouse gas emissions in the country. The program will seek its performance based on four strategic axes: discussing the role of biofuels in the energy matrix; development based on environmental, economic, and financial sustainability; marketing rules and attention to new biofuels [68].

Regarding MSW and its destination to the bioenergy sector, in 2020, an association of four important sectorial entities - ABCP (portland cement), Abetre (waste and effluent treatment), Abiogás (production and use of biogas), and Abrelpe (public cleaning) - launched the FBRER (Brazil Front for Energy Recovery of Waste), which aims to boost energy capture from waste deposited in landfills. The signing of the Cooperation Agreement for Energy Recovery of Waste was signed by the entities and the Ministry of the Environment of the federal government [69].

The cooperation agreement will seek to coordinate efforts to remove regulatory barriers that hinder the more intense use of waste. Besides, it intends to make feasible projects for the energy recovery of solid waste and promote its integration into the clean and renewable energy market [69].

3.1.5 Limitations for implementing pyrolysis and gasification of biomass in Brazil

In Brazil, one of the challenges faced by biomass gasification projects is that the facilities are constructed and operated in the laboratory, and on a small scale, it was not possible managed to show viability on a large scale. The lack of gasification plants in operation leads to the unreliability of the business, which alienates investors.

Another factor observed is the comparison between the technologies used to reduce MSW. Considering gasification, pyrolysis, and incineration, it is observed that for the gasification process, solid waste generally needs to have humidity lower than 30%, an average granulometry of 50 mm, and an average calorific value of 3500 kcal/kg [70], the solid waste must be prepared as fuels derived from municipal waste. Such treatment of waste to transform it into a good fuel requires an increase in the costs of production.

Likewise, in the pyrolysis process, waste also needs to be pre-treated. This pre-treatment raises the costs of the MSW energy plant. The pyrolysis process produces gases, oils, and solid waste (metals, oxides, and inert material), which need to be of high quality to identify markets for their absorption. Given these characteristics of gasification and pyrolysis process, energy reuse projects for solid waste end up using incineration technology.

There are several challenges for Brazil to achieve high levels of sustainability in the management of MSW as waste to energy through gasification or pyrolysis technologies. The biggest of these is related to the sale of energy that will be generated by plants using MSW, as it is the largest revenue of this enterprise since this market is not yet regulated.

3.2 México

In contrast with Brazil, around 88.70% of the energy production in Mexico comes from fossil fuels, 3.17% charcoal, 1.16% Nuclear, and 6.97% renewable (3.79% biomass, 1.62% geothermal, hydropower 1.42%, solar and wind 0.14%). Regarding energy contribution to power generation, 78% comes from fossil fuels, 2.8% nuclear, biomass 9.30%, hydropower 3.70%, and 6% from others. As one may infer, energy production in Mexico relies mostly on fossil fuels [71]. Therefore, the potential of other resources such as biomass is not being exploited, preventing the strengthening of the agricultural sector and the reduction of GHG.

Mexico occupies 3rd place in LATAM and the Caribbean in terms of cropland area, after Brazil and Argentina. The cultivated area in 2007 was 21.7 million ha, producing 270 million tons. The residuals from these crops are currently used for animal feed and bedding, mulch, and burning to produce energy and compost. In fact, in 2012 bioenergy has an operational capacity of 645 MW installed, of which 598 MW are from bagasse and the rest from biogas. However, in 2019, it is registered that Mexico increased its capacity of bagasse to 791 MW, which means 32% more, or a 4.28% increase per year [71]. Although the production of energy from biomass has increased, the full potential is not being exploited. The following section presents the biomass availability in Mexico.

3.2.1 Forestry residues

Mexico has 138 million hectares of forest, equivalent to 70% of the national territory. The forests and jungles are an important part of these lands and cover 64.9 million hectares, of which it is estimated that 15 million hectares have the potential for commercial use. The available forest biomass is distributed in different areas of the country. However, the greatest potential is in the mountain ranges of and the Yucatan peninsula [72].

Forest biomass contributes 8% of primary energy demand, being used in residential firewood and small industries. However, it can be considered as an alternative source for renewable energy generation and provide multiple benefits [72].

Forest management, extraction, and industrialization activities generate a significant amount of residual forest biomass annually. Some studies have been carried out on the use of forest residues in the production of bioenergy, and the results indicate that Mexico generates around 703,323.6 (1,774,994.0 m^3r, cubic meters of unbarked round timber) tons of dry base biomass, which come from forest residues of mainly pine, and oak. [72].

According to the production of forest biomass, 598,858.1 tons correspond to pine and 104,465.5 tons to oak. In terms of energy, this forest biomass represents a renewable energy resource of 12,827.8 TJ of which 11,425.4 TJ corresponds to pine and 1402.4 TJ to oak. [72]. In Mexico, the main industry supply forest basins have been identified (**Figure 7**), where a remarkable amount of sawmill waste is concentrated, which can be used as feedstock for integrated energy generation systems (thermal and electrical) [72]. The fact of integrating forest residues into energy generation is an opportunity for community forest companies, ejidos, and communities, to generate income that comes from forest biomass that is now used for waste or that has a minimal economic recovery.

3.2.2 Agricultural residues

Several studies have pointed out and assessed the potential of biomass energy production in Mexico, considering three main categories: wood & forestry residues, crop, and agro residues, and MSW [72]. Some estimates range from 3035 to 4550 PJ/y, where wood forestry residues share is 27–54%, crop and agro residues 26, and 0.6% from MSW. Other estimates more conservative said 626 PJ/y and 2228 PJ/y.

Table 14 shows the main agricultural residues produced in Mexico, which considers the residue index (RI) of each crop. Maize primary residue has a 44% share of the main crop residues producing in Mexico. While sorghum primary

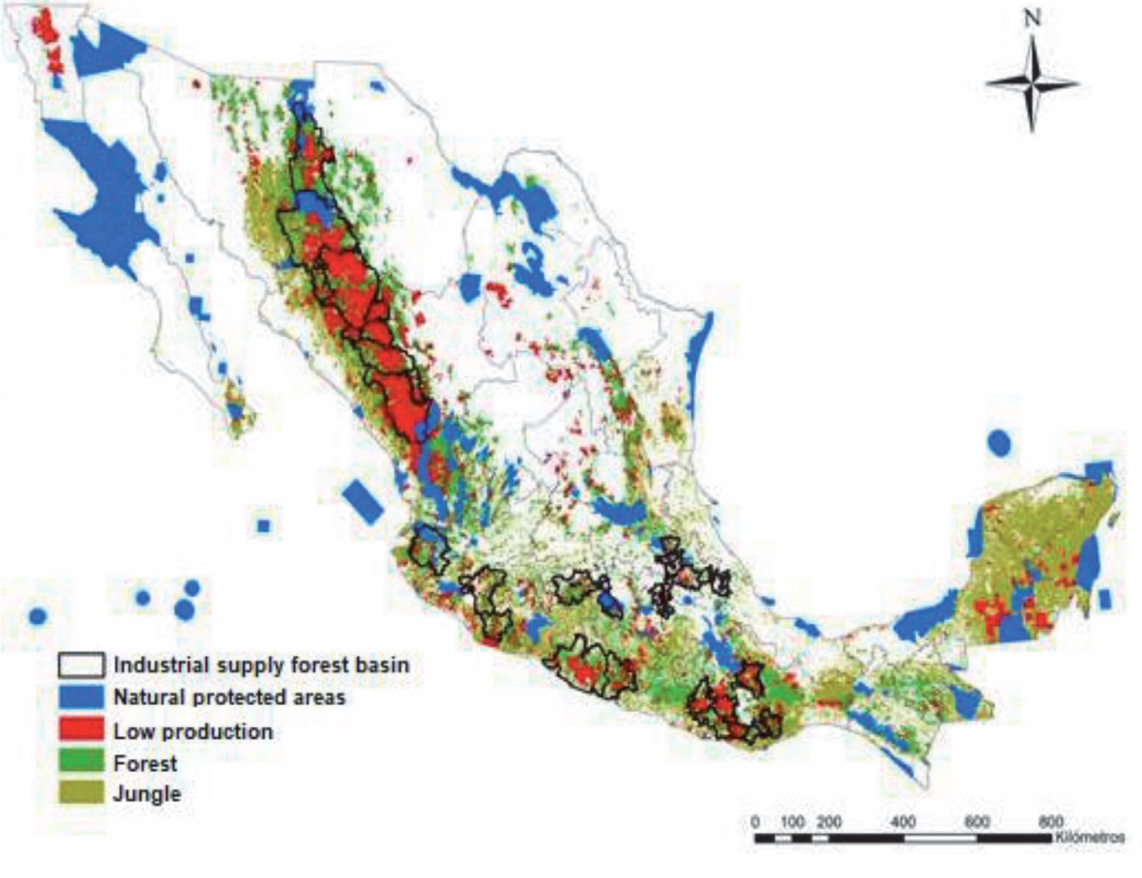

Figure 7.
Main Industrial supply forest basin in Mexico adapted from [72].

Crop Information				Primary Residue						Secondary Residue						
Crop	Crop Production (kt/yr)	C.V. (%)	Residues Energy Potential (PJ/yr)	Residue	Residue Index	Production (kt/y)	Available Material * (kt/y)	HHV (MJ/kg)	Energy Potential (PJ/y)	Residue	Residue Index	Recovery Factor	Production (kt/yr)	Available Material * (kt/yr)	HHV (MJ/kg)	Energy Potential (PJ/yr)
Sugarcane	53,834.44	7.10	124.19	Tops & leaves	0.14	7536.82	3014.73	17.31	52.18	Bagasse	0.14	0.50	7536.82	3768.41	19.11	72.01
Maize	23,740.53	12.97	278.92	Stover	1.41	33,474.15	13,389.66	17.18	230.03	Cob	0.15	0.80	3561.08	2848.86	17.16	48.89
Sorghum	6127.56	17.85	174.93	Straw/ stalk	3.90	23,897.48	9558.99	18.30	174.93	—	—	—	—	—	—	
Wheat	3622.61	9.64	45.45	—	1.62	5868.63	2347.45	19.36	45.45	—	—	—	—	—	—	
Coffee	1186.38	—	2.04	—	—	—	—	—	—	Pulp	0.10	0.90	118.64	106.77	19.10	2.04
Coffee	1186.38	—	0.84	—	—	—	—	—	—	Hull	0.04	0.90	47.46	42.71	19.59	0.84
Beans	1079.82	17.62	7.12	—	0.88	950.24	380.10	18.74	7.12	—	—	—	—	—	—	
Barley	776.21	25.44	10.70	—	1.75	1358.37	543.35	18.45	10.02	Husk	0.10	0.50	77.62	38.81	17.50	0.68
Cotton	631.66	23.37	5.66	—	1.28	808.52	323.41	17.50	5.66	—	—	—	—	—	—	
Soybean	268.04	49.09	3.01	—	1.60	428.86	171.55	17.52	3.01	—	—	—	—	—	—	
Rice	233.53	14.43	2.67	—	1.61	375.98	150.39	15.37	2.31	Husk	0.20	0.50	46.71	23.35	15.36	0.36
Chickpea	159.22	32.86	1.96	—	1.70	270.67	108.27	18.10	1.96	—	—	—	—	—	—	
Safflower	120.56	42.24	2.11	—	2.28	274.88	109.95	19.23	2.11	—	—	—	—	—	—	
Oat	96.73	29.36	1.70	—	2.52	243.76	97.50	17.48	1.70	—	—	—	—	—	—	
Groundnut	92.91	12.39	1.92	—	2.12	196.97	78.79	19.01	1.50	Shells	0.30	0.80	27.87	22.30	18.73	0.42
Sesame	45.10	21.29	1.20	—	3.80	171.38	68.55	17.47	1.20	—	—	—	—	—	—	
Fava bean	27.72	30.69	0.26	—	1.43	39.64	15.86	16.31	0.26	—	—	—	—	—	—	
Tobacco	12.97	25.64	0.48	—	5.00	64.85	25.94	18.52	0.48	—	—	—	—	—	—	
Lentil	6.18	46.71	0.09	—	2.10	12.98	5.19	17.08	0.09	—	—	—	—	—	—	

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Crop Information				Primary Residue						Secondary Residue						
Crop	**Crop Production (kt/yr)**	**C.V. (%)**	**Residues Energy Potential (PJ/yr)**	**Residue**	**Residue Index**	**Production (kt/y)**	**Available Material * (kt/y)**	**HHV (MJ/kg)**	**Energy Potential (PJ/y)**	**Residue**	**Residue Index**	**Recovery Factor**	**Production (kt/yr)**	**Available Material * (kt/yr)**	**HHV (MJ/kg)**	**Energy Potential (PJ/yr)**
Sunflower	7.83	6.68	0.16	—	3.00	23.49	9.40	17.50	0.16	—	—	—	—	—	—	
Agave (tequila)	1369.95	23.52	3.98	Leaves	0.20	273.99	109.60	17.50	1.92	Bagasse	0.12	0.80	164.39	131.52	16.35	2.15
Agave (mescal)	279.59	26.71	0.88	Leaves	0.20	55.92	22.37	18.84	0.42	Bagasse	0.12	0.80	33.55	26.84	16.09	0.43
Total	94,905.9		670.34						542.53							127.81

** Recovery factor 0.4.*

Table 14.
Agricultural Residues in Mexico [73].

residue is 31%. As forestry residues, the use of agro residues is an opportunity for agro communities and industries to generate income by a better valorization of residues.

3.2.3 Municipal solid waste residues

In Mexico, 102,895.00 tons of waste are generated daily, from which 83.93% are collected and 78.54% are disposed of in landfills or open-air dumps, recycling only 9.63% of the waste generated. That translates into an economic loss by diverting materials that are susceptible to rejoining the production system, reducing the demand and exploitation of new resources, unlike countries like Switzerland, the Netherlands, Germany, Belgium, Sweden, Austria, and Denmark, where the final disposal of waste is less than 5% in sanitary landfills [74].

Article 10 from the Mexican General Law for the Prevention and Comprehensive Management of Waste (LGPGIR) establishes municipalities oversee the integral management of MSW, which consists of the collection, transfer, treatment, and final disposal [75].

Municipalities encounter challenges that fall outside their technical and financial capacities due to the lack of trained personnel in acquiring or committing financial resources that give certainty to private sector investments. This situation is maybe because of the short time of the municipal administrations, which leads to the breaking of the learning curve, and therefore to a lack of continuity in actions and projects that guarantee integral management of urban solid waste [74]. Whatever the case, the reality is that MSW has become a big problem in Mexico, especially in big cities like Mexico City.

Mexico has 2203 areas (landfills or open-air dumps) for final MSW disposal. **Figure 8** shows the average composition of MSW in Mexico.

Food and garden waste and disposable diapers have a share of 48.98% of the total MSW in Mexico. While other MSW fractions like paper, paperboard, rags, and plastics represent around 25% of the total MSW in Mexico. Those fractions can be

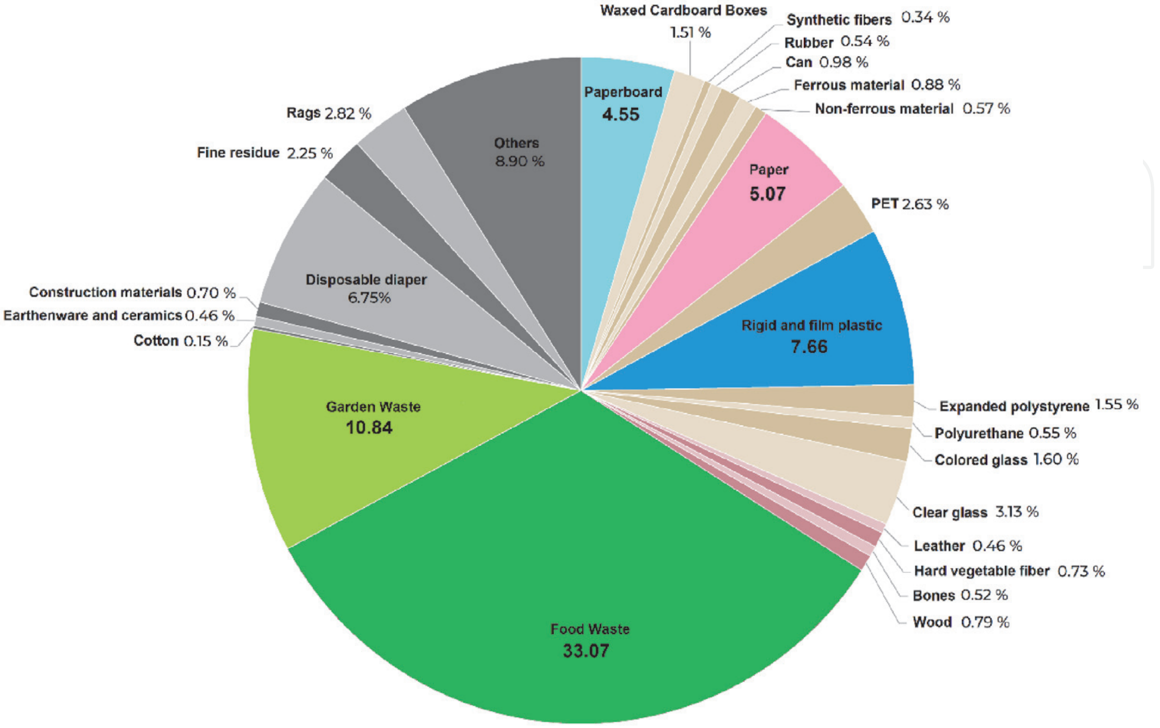

Figure 8.
Mexican MSW Composition 2017 adapted from [76].

utilized to produce a refuse-derived fuel, which can be used as feedstock for gasification or pyrolysis processes, generating energy vectors and adding value to materials that did not have any other purpose than to be disposed of.

3.2.4 Mexican politics related to the bioenergy sector

The law for the promotion and development of bioenergetics published in 2008 aims to promote and develop bioenergetics to contribute to energy diversification and sustainable development as conditions that allow guaranteeing the development of the agricultural sector [77].

Another low that is related to the bioenergy sector is the Mexican General Law on Climate Change published in 2012 and modified in 2018, which sets the rights and responsibilities of state governments to climate change mitigation and adaptation. Since then, state governments have made progress in developing specific policy instruments, provided in both the Law and the National Climate Change Strategy. However, little clarity regarding the current level of progress of these state efforts exists at the national level. In this sense, seventeen policy instruments (laws, regulations, plans, programs, among others) of the 32 states of Mexico were set [78]. Four of them are related to MSW management, which is potential biomass to produce bioenergy.

3.2.5 Limitations for implementing pyrolysis and gasification of biomass in Mexico

Even though Mexico has a high potential for Renewable Energy Sources (RES) development, only a small amount of this energy has been utilized. This may be due to the following reasons:

- The lack of an energy plan that evaluates the RES feasibility in short term.
- Consume the cheapest energy source, usually fossil fuels, rather than sustainable and eco-friendly resources. This situation is preventing RES development.
- Complex supply-chains and vulnerable to fossil carbon inputs mainly associated with feedstock transport.
- Higher abatement CO2 costs compared to actions in other sectors. For liquid biofuels, the estimated cost ranges from 7 to 12 US$/tCO2e, while for biogas and upgraded wastewater treatment plants the cost is around 60 US$/tCO2e.

Whether forestry agricultural residues or municipal solid waste, it exists a great potential to produce energy vectors in Mexico. However, socio-political factors have delayed their use. To overcome such limitations is vital to have a national plan for renewable energy in Mexico by the explicit establishment of RES participation, considering financial schemes that help small renewable energy producers as it was established in the law for the promotion and development of bioenergetics published in 2008. Another noteworthy point is the palletization of agroforestry residues or MSW to produce fuel pellets, also known as RDF, which is a more uniform fuel than MSW regarding particle size and heating value, and it is easy to transport.

Another important factor is to know beforehand the composition and yields of each technology's products, considering the available feedstocks in each country. Unfortunately, this would require major investments to produce experiential data.

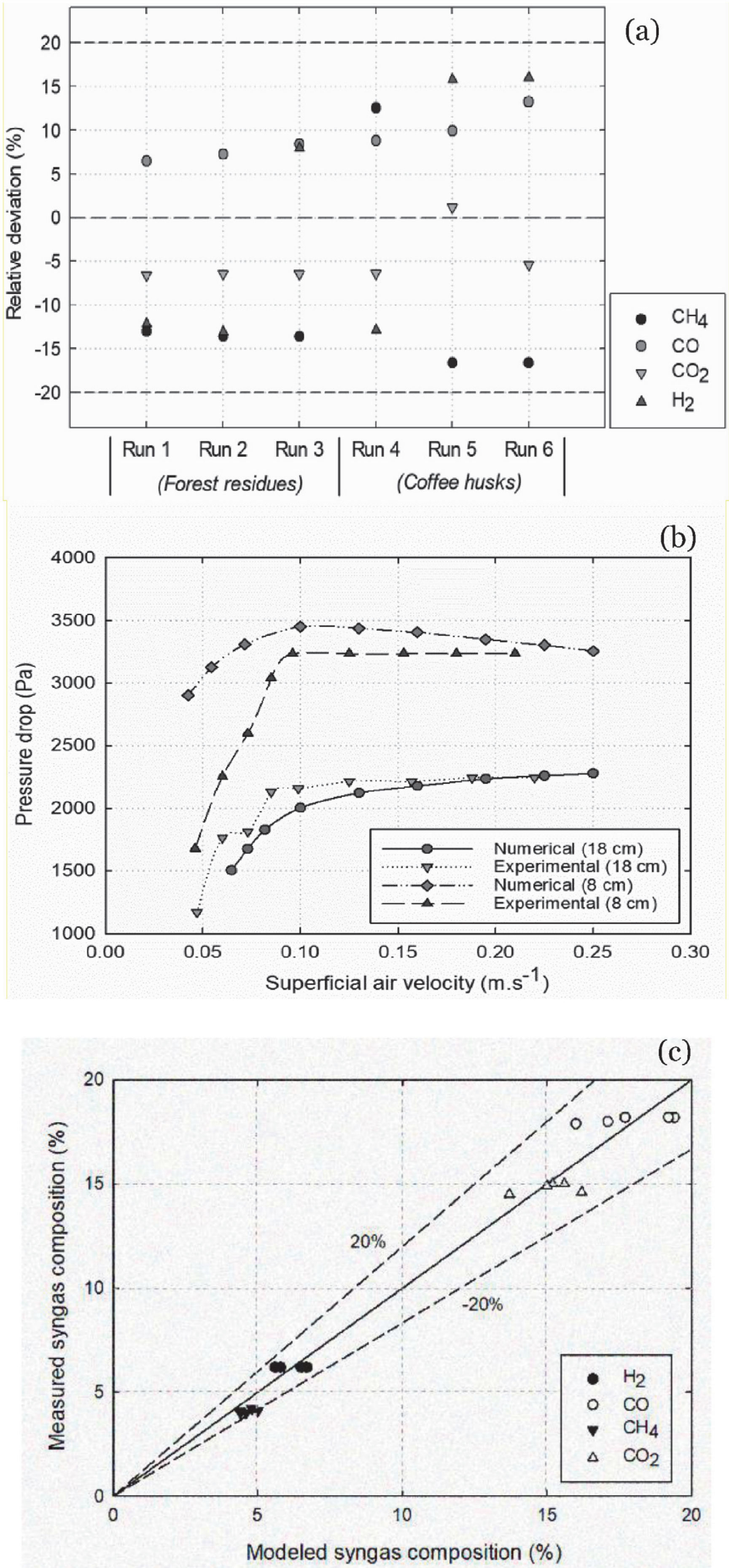

Figure 9.
(a) Relative deviation between the experimental and numerical syngas composition produced in the 250 kWth gasifier using forest residues and coffee husks (b) Experimental and numerical fluidization curves gathered at 8 and 18 cm height from the 75 kWth reactors (c) Model gas composition of wood (adapted from [83, 84]).

Knowing this information can help decision-makers to decide which agroforestry residue is a priority, the type of technology to employ, and the use of the products. Fortunately, mathematical models of these technologies can help predict with certainty this information. The following chapter describes a mathematical model used for the gasification of wood residues, an important residue in Brazil and Mexico.

4. Experimental and numerical analysis

Mathematical models reduce efforts, investments, and time, promoting a better perception of the physical and chemical mechanisms immerse in complex technologies like pyrolysis and gasification [79]. Modeling approaches can be as complex as the available software allows. However, the approach can also be simple, effective, and with an excellent degree of certainty. For example, equilibrium models are reliable and uncomplex [79]. Nevertheless, they do not deal with essential parameters such as hydrodynamics, transport process, or reaction kinetics. In contrast with kinetic models that consider reactions' kinetic, being much more accurate but computationally expensive [80].

Fortunately, the growth of computational power is leading to better software that is gradually replacing empirical or semi-empirical models for computational fluid dynamics. These models can provide relevant information on what is happening inside the reactor, which can lead to a better understanding of the technology as well as improvements in it. However, their extreme complexity means that these models are still in the development stage [81, 82].

Gasification and pyrolysis processes involve multiple phases, which makes them very complex. **Figure 9** summarize the validation of a model applied to two fluidized bed reactors with 250 kWth and the other 75 kWth, both operated by our research team. The relative deviation between the experimental and numerical syngas composition produced in the 250 kWth gasifier using forest residues and coffee husks is depicted in **Figure 9a**.

Figure 9b displays the deviation between the experimental and the numerical fluidization curves performed at two different bed heights (8 and 18 cm) in the 75 kWth reactors. Overall, the numerical curves successfully forecasted the slope of the experimental curve with acceptable precision. The broader deviations arose at the lowest velocities. This is due to the movement of the solid before fluidization occurred. It can be also due to the inefficiency of the mathematical model since it considers a low entropy.

The mathematical model effectively predicted the acquired experimental data trends with acceptable accuracy for both equipment at different validation points and experimental conditions. It is worth acknowledging that this model has already been extensively validated and submitted to constant improvements in dealing with different biomass substrates and the heterogeneity of MSW at distinct operating conditions, gasifying agents, and reactor scales. In this example, the gas composition of wood gasification could contain an excellent number of combustible gases, namely H2, CO, CH4, and CO2 (see **Figure 9c**), which can be used to produce energy or heat in Brazil and Mexico.

5. Feasibility

As it was discussed in Section 2, gasification and pyrolysis are already at full-scale, mostly in developed countries [85]. However, small-scale energy systems demonstrated to be more advantageous and cost-effective to install in certain regions since this model offers mobility and simplicity [86].

These models can provide energy to decentralized areas or rural households communities, particularly in developing countries like Brazil and Mexico, delivering alternative electric power solutions to communities where connection to the central grid is economically unfeasible. Furthermore, blending biomass residues with other wastes, such as MSW (RDF included), is praised as a clever strategy to lessen exploration costs, boost plant production efficiency, and avoid biomass exploration excess and consequent disequilibrium of ecosystems [87]. In fact, small-scale biomass gasification systems became attractive for off-grid functions due to their cost-effectiveness and high plant load factor.

Biomass-based systems afford an important asset particularly in rural areas since agricultural and timber residues are easily accessible. Furthermore, biomass exploration affords a helping hand towards wildfire hazards reduction, promoting forest biomass harvesting and cleaning in overgrown areas [88]. These units have already proved their suitability for power generation in small towns, being already widely used for rural electrification solutions. In fact, small towns require low electrical load demand. Thus, biomass gasification systems are more cost-competitive than solar PV or even grid electrification for rural areas that are off-grid [89].

These factors could point to the feasibility of energy production through biomass in Brazil and Mexico because of their large amounts of biomass and regions that are not connected to the grid. Besides, the used small stations could be the step towards large-scale production using, for example, MSW, which has become a big problem in large cities such as Brasilia and Mexico City.

The feasibility of financial indicators is resolved by measuring their flexibility and assessing the project performance response to stressful scenarios, appointing either a favorable or unfavorable evolution of several variables simultaneously, where some variables may be more uncertain than others. Some of the variables that can affect the feasibility of a gasification or pyrolysis project are: (1) the initial investment, (2) the return of investment, (3) future costs and benefits, (4) electricity sales price (5) electricity production, (6) biomass cost, (7) governmental policies, etc. In short, sensitivity analysis allows assessing the project's risk by simulating several scenarios and forecasting their outcomes, assessing decision-making over uncertainty [90]. The World Bank Group has released a set of typical key financial benchmarks for success in biomass related energy projects, considering some financial indicators, namely Net Present Value (NPV) ought to be a positive value, International Rate of Return (IRR) above 10%, and a Payback Period (PBP) less than 10 years [91]. Some of these financial indicators might provide an idea of the benchmarks in the biomass to the energy sector. However, these financial indicators or models may not encompass all factors that can influence the success of a project. Some of these factors are the policy of a set country and its project-specific constraints. Yet, to the point, benchmarks allow standardizing decision-making by building trust within investors less willing to take risks.

6. Conclusions

Latin American countries have one of the highest rates of urbanization in the world. Among the various problems caused by large urbanization, those that refer to mobility, safety, health, well-being, sanitation, and adequate management of MSW stand out. It is important to highlight that a waste energy recovery plant (WTE) is not exactly an energy generation undertaking, but essentially a sanitation agent whose energy input is a valuable by-product. This context is essential to demonstrate to the authorities the nature and essentiality of WTE plants, especially in terms of cost and benefit, when compared to other sources of power generation. Biomass and MSW have the potential to become a major source in LATAM's primary energy sector, as presented in Section 3, with a survey of the availability of biomass and MSW found in Brazil and Mexico.

Implementing gasification and pyrolysis in these countries can offer benefits in terms of reducing the use of fossil fuels, reducing greenhouse gas emissions by preventing the extraction of virgin fossil fuels, and providing income diversification to farmers. However, the integration of these energy vectors on large scale should pass for a previous step, which is decentralized gasification and pyrolysis plants as was analyzed in the feasibility section. This is because many rural areas are not connected to the grid yet, in addition, the logistics of biomass is complicated in rural areas and involves an extra cost.

There is still a long way to go. However, the major urgency relies on real policy integration that enables a full converge of the different bioenergy actors. Therefore, catalyze the economic and environmental benefits that pyrolysis and gasification of biomass can provide.

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Conflict of interest

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

Nomenclature

BR	Brazil
MX	Mexico
VE	Venezuela
CO	Colombia
AR	Argentina
CL	Chile
PY	Paraguay
PE	Peru
EC	Ecuador
UY	Uruguay
BO	Bolivia
CAM*	Central America
Lat	Latin America
EU	European Union

W**	World
SE	Sweden
FI	Finland
CA	Canada
NL	Netherlands
USA	The United States
IE	Ireland
DE	Germany
CH	Switzerland
IN	India
LATAM	Latin America
CHP	Coal handling plant
EU	European Union
GHG	greenhouse gas
MSW	municipal solid waste
RDF	refuse-derived fuel
RES	Renewable Energy Sources
CGE	cold gas efficiency
LHV_F	lower heating value of the feed stream
LHV_{gas}	LHV of the gas
LHV_i	LHV of the component "i"
LHV_{liquid}	LHV of the liquid
LHV_{solid}	LHV of the solid
m_F	feedstock mass
m_{gas}	gas mass
m_i	mass of the component "i"
m_{liquid}	liquid mass
m_{solid}	solid mass
y_{igas}	mass fraction of the component "i" in the gas
$y_{iliquid}$	mass fraction of the component "i" in the liquid
y_{isolid}	mass fraction of the component "i" in the solid
Y_{gas}	gas yield
y_{gas}	gas Efficiency
Y_{liquid}	liquid yield
Y_{solid}	solid yield
V_G	Gas Volume

Author details

José Antonio Mayoral Chavando[1], Valter Silva[1,2*], Danielle Regina Da Silva Guerra[3], Daniela Eusébio[1], João Sousa Cardoso[1,4] and Luís A.C. Tarelho[5]

1 Polytechnic Institute of Portalegre, Portalegre, Portugal

2 ForestWise, Collaborative Laboratory for Integrated Forest and Fire Management, Vila Real, Portugal

3 Federal University of Pará, Belém, Pará, Brazil

4 Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

5 Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Aveiro, Portugal

*Address all correspondence to: valter.silva@ipportalegre.pt; valter.silva@forestwise.pt

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