

Waste to energy and materials through pyrolysis: a review

ABSTRACT

Waste biomass, such as agricultural waste, is emerging as a promising renewable energy resource because of its abundance and carbon-neutral nature. It has a high potential to be used as an alternative source of energy by employing thermochemical conversion techniques. Pyrolysis is the most efficient technique for the conversion of biomass-based waste in manufacturing renewable fuels and chemicals. However, despite pyrolysis being a well-known method to provide solid fuel (charcoal) and chemicals, the technological pathways for producing chemicals and liquid fuels at an industrial scale are not fully developed. This review addresses the relevance of pyrolysis for waste-to-energy and materials, the fundamentals of pyrolysis, different reactors, process conditions, and its products from the perspective of energy and materials recovery. Accordingly, the purpose of this review is to analyse the current application level of pyrolysis for waste management, identify gaps in our current understanding, and recommend future research directions.

Keywords: Agricultural waste. Pyrolysis. Bioproducts.

Genyr Kappler
genyr.kappler@gmail.com
Universidade UNISINOS

Tailane Hauschild
tailaneh86@gmail.com
Universidade Federal do Rio
Grande do Sul

Luís António da Cruz Tarelho
ltarelho@ua.pt
Universidade de Aveiro

Carlos Alberto Mendes Moraes
CMORAES@unisinios.br
Universidade UNISINOS

1. INTRODUCTION

Production and consumption activities generate a large volume of waste. The collecting, transporting, treatment, and disposal of waste are common concerns in every country. In developing countries, landfilling prevails as the most common choice, contributing to greenhouse gas emissions, soil, water, and air pollution, amongst other negative impacts. As an alternative to landfilling, a wide range of products, such as energy, fuels, chemicals, and other by-products, can be recovered from waste using multiple technologies, where pyrolysis is considered as an innovative alternative for waste treatment (LEHMANN; JOSEPH, 2015).

Biomass waste is emerging as a promising renewable resource for energy and chemicals because of its abundance and carbon-neutral nature. Additionally, it presents a singular characteristic over all other renewable sources, that is, the ability to produce, through the thermochemical process, carbon-based energy products (heat and transport fuel), and chemicals (UDDIN et al., 2018). Pyrolysis is a thermochemical process that presents many advantages over combustion and biochemical conversions (NSAFUL; GÖRGENS; KNOETZE, 2013). Nonetheless, the technological pathway in obtaining transport fuels on a commercial scale is still not fully developed and is still under construction (SIMS, 2004).

Pyrolysis is a well-known method for converting woody biomass into charcoal. At the beginning of the twentieth century, this process was utilized for the commercial production of a wide range of fuels, solvents, chemicals, and other products from biomass feedstock (DE WILD, 2015). Recently, due to the global problems associated with the intense use of fossil fuels and waste generation, the interest in pyrolysis-based biorefineries (in modern varieties) is renewed (PRINS; PTASINSKI; JANSSEN, 2006). This recent increase of interest from the academic field in the method of biomass conversion through pyrolysis can be observed in the number of publications in the Scopus database. The number of annual scientific journal papers in the subject "pyrolysis/biomass/energy" increased from 203 publications in 2009 to 754 publications in 2019. According to Cherubini (2009), the production of transportation biofuels is seen as the driving force for future biorefinery developments reflecting the main advantage of using the already existing infrastructure for easier market introduction (CHERUBINI et al., 2009). Fast pyrolysis is the primary technology to convert lignocellulosic biomass into bio-oil, biochar, and gas. The bio-oil is feedstock for a subsequent biorefinery approach that aims to further process the bio-oil into a spectrum of value-added products. Nonetheless, the interest in slow pyrolysis technology (both carbonization and torrefaction) is growing rapidly again because of the need for renewable fuels from biomass (DE WILD, 2015).

Many researchers are currently focused on fast pyrolysis including the mechanism of pyrolysis (SHEN et al., 2015), reaction processes (ZAMAN et al., 2017) and design of reactors (BOK et al., 2014), the development of catalysts for catalytic pyrolysis to produce transportation fuels (HEIDARI et al., 2019; WANG et al., 2017), and upgrading liquid fuels (BRIDGWATER, 2012b). Although slow pyrolysis has been used for many centuries (BHASKAR; PANDEY, 2015) in the traditional charcoal production method, the same old practices are still employed today, without the recovery of volatile products (GARCIA-PEREZ; LEWIS; KRUGER, 2011). The interest in slow pyrolysis increased considerably in the last decades due to the bespoke advantages of its products, such as the bio-oil to produce liquid

fuels (SETTER et al., 2020), and particularly biochar (SCHMIDT, 2011; WOODS et al., 2009). Biochar is believed to improve soil physicochemical characteristics and biota (RALEBITSO-SENIOR; ORR, 2016), enhance agricultural benefits (BIEDERMAN; HARPOLE, 2013; J. W. GASKIN et al., 2008), produce energy (SALGADO; TARELHO; MATOS, 2018), and store carbon (BRUCKMAN, VIKTOR J., ESIN APAYDIN VAROL, BAŞAK B. UZUN, 2016).

This review aims to present the current state-of-the-art technology in pyrolysis processes applied to lignocellulose biomass waste. This review addresses the relevance and fundamentals of pyrolysis, the different reactors, process conditions, and its products from the perspective of energy and materials recovery. The final aim is to provide essential information to understand the role of pyrolysis as a sustainable waste-management solution, identify gaps in our current understanding, and recommend future research directions.

2. PYROLYSIS TECHNOLOGY FOR WASTE TO ENERGY AND CHEMICALS PRODUCTION

2.1. Waste biomass

Biomass is the term for all organic matter produced biologically, including land and water-based vegetation as well as waste biomass. Waste biomass is generated at constant rates and huge volumes worldwide and includes all the non-edible organic materials remaining from, e.g., crop harvesting, forest debris, food processing industry, and pulp industry consisting mainly of lignocellulosic biomass. This abundant supply of renewable feedstock is globally available for being converted into biofuels and materials.

Because biomass is a renewable source of energy and materials, it has attracted considerable in conversion technologies. Among all renewable sources of energy, biomass is the only renewable carbonaceous resource; thus, it is seen as an essential feedstock to replace fossil fuels to produce heat, electricity, transport fuels, chemicals, and other products in both industries of the heat and power sectors in all parts of the world (UDDIN et al., 2018). In terms of energy feedstock, the International Agency of Energy (IEA) defines biomass as:

"Any organic, i.e., decomposing, matter derived from plants or animals available on a renewable basis. Biomass includes wood and agricultural crops, herbaceous and woody energy crops, municipal organic wastes as well as manure." (IEA, 2012).

The IEA suggests that bioenergy has the potential to provide 10% of the world's primary energy supply by 2035, and biofuels can replace up to 27% of world transportation fuel by 2050 ((WANG et al., 2017) apud (IEA, 2019)).

Biomass feedstocks vary in composition, with different shares of basic components, viz., cellulose, hemicellulose, lignin, and other such as starch, triglycerides, and proteins (average values for cellulose, hemicellulose, and lignin are, respectively, 20-50%, 10-40%, and 5-20%) (AL ARNI; BOSIO; ARATO, 2010; GODIN et al., 2010; RAVEENDRAN; GANESH; KHILAR, 1995; SONG et al., 2004) and five chemical elements: carbon, hydrogen, oxygen, and smaller percentages of nitrogen and sulphur (Table 1). Other important characteristics are water content

– M, volatile mater – VM, fixed carbon – FC, ashes – A, and higher heating value – HHV, all shown in Table 2 (CHERUBINI et al., 2009, p. 6), plus specific volume.

Table 1: Composition obtained in Ultimate analysis for different biomass feedstock materials

	Ultimate analysis (%w)db*					References
	C	H	N	S	O	
Rice husk	36.98	5.0	0.4		37.9	(RAVEENDRAN; GANESH; KHILAR, 1995)
Coconut shell	50.2	5.7	0.0	-	43.4	(RAVEENDRAN; GANESH; KHILAR, 1995)
Elephant grass	44.5	5.4	1.4	-	31.8	(ABBASI; ABBASI, 2010; BRAGA <i>et al.</i> , 2014)
Sugarcane bagasse	45.13	6.05	0.3	-	42.77	(AL ARNI; BOSIO; ARATO, 2010),
Miscanthus	48.1	5.4	0.5	0.1	42.2	(MCKENDRY, 2002; NACHENIUS <i>et al.</i> , 2013)
Sorghum	44	5.6	2	0.05	38	(NASIR EL BASSAM, 2010)
Switchgrass	44.7	5.79	0.31		49.13	(MCKENDRY, 2002; NASIR EL BASSAM, 2010; UDDIN <i>et al.</i> , 2018)

Table 2: Proximate analysis and energetic value for different feedstock materials

	Proximate analysis					Reference
	M (%H ₂ O)	VM (%w) db	FC (%w) db	Ash (%w) db	HHV MJ kg ⁻¹	
Rice husk	9.6	81.6	22	15	15.29	(RAVEENDRAN; GANESH; KHILAR, 1995)
Coconut shell	5.6	74.5	22.1	0.47	20.5	(RAVEENDRAN; GANESH; KHILAR, 1995)
Elephant grass	10	65	14.6	6	15.61	(ABBASI; ABBASI, 2010; BRAGA <i>et al.</i> , 2014)
Sugarcane bagasse	8.5	84	1.64	6	18.17	(AL ARNI; BOSIO; ARATO, 2010; UDDIN <i>et al.</i> , 2018)
Miscanthus	11.5	66.8	15.9	2.8	18.5	(MCKENDRY, 2002; NACHENIUS <i>et al.</i> , 2013)
Sorghum	6.2	69.1	18.5	6.3	16.9	(NASIR EL BASSAM, 2010; PANDEY <i>et al.</i> , 2015)
Switchgrass	7.9	72.6	16.4	3.1	17.4	(PANDEY <i>et al.</i> , 2015)

Note: differences in the summation on the analysis is due to ash and other minor elements not reported.

Biomass can be categorised as follows: dedicated feedstocks (sugarcane, soy, wheat, sweet sorghum, short-rotation poplar, switchgrass, miscanthus, algae, and seaweed, for example); and residues (used cooking oil, agricultural residues, sawmill residues, urban organic waste, manure, wild fruits, and crops) (CHERUBINI et al., 2009). Agricultural waste includes rice and wheat straw, corn stover, corn stalks, coconut shell, and sugarcane bagasse (WANG et al., 2017). Dedicated energy crops, water-based plants, and the organic fraction of municipal solid

waste (MSW) are also attracting attention (DHYANI; BHASKAR, 2018). Perennial grasses such as miscanthus and switchgrass are also important feedstocks (WANG et al., 2017). Tables 3 - 5 show the amount of crop production and waste generation at specific bases.

Table 3: Specific generation for agro waste and energy crop

Agro waste	Specific growth rate (ton/ha/year)	Type of waste	Waste (%)	Specific waste generation (ton/ha/year)	Reference
Rice	11.7x10 ⁶	Rice husk	21	2.5x10 ⁶	(EMBRAPA – 2017)
Sugarcane	665x10 ⁶	bagasse	27	179.3x10 ⁶	(NOVA CANA, 2016)
coconut	2.8x10 ⁶	shell	57	1.6x10 ⁶	(ROCHA <i>et al.</i> , 2015)

Table 4: Specific generation for energy crop

Energy crop	Generation rate (ton/ha/year)	Reference
Miscanthus	13 - 30	(MCKENDRY, 2002, p. 45)
Sorghum	0.2 - 19	(DONALD L. KLASS, 1998, p. 113)
Switchgrass	2.9 - 14	(DONALD L. KLASS, 1998, p. 113)
Canary-grass	2.7 – 10.8	(DONALD L. KLASS, 1998, p. 113)

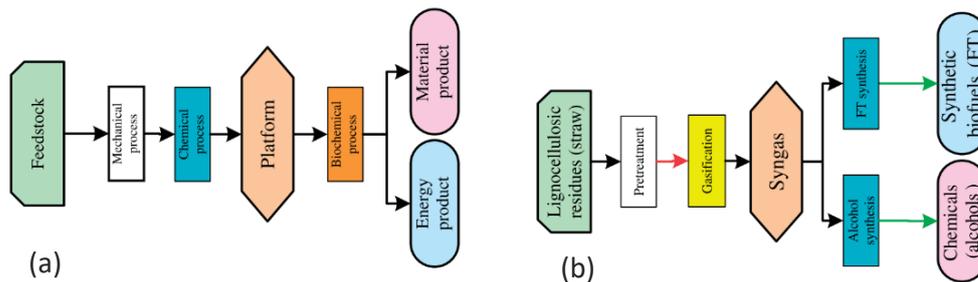
Table 5 Total generation for organic MSW

MSW	Generation rate Total (ton/year)	Organic Waste (%)	Organic waste generation (ton/year)	Reference
Organic	62.78 x10 ⁶	51.4	32.3 x10 ⁶	(CEMPRE, 2019)(SNIS, 2019)

2.2. The share of pyrolysis in the bioenergy sector

At the beginning of the twentieth century, pyrolysis processes were utilized for the commercial production of a wide range of fuels, solvents, chemicals, and other products from biomass feedstock (DE WILD, 2015; DONALD L. KLASS, 1998, cap. 8). After many decades, due to the global problems related to the intensive use of fossil fuels and waste generation, the interest is renewed by using a modern variety of pyrolysis-based biorefineries (ANTAL; GRØNLI, 2003; PRINS; PTASINSKI; JANSSEN, 2006), and recently the concept of "biorefinery" was perceived and accepted (BRIDGWATER, 2007). The IEA Bioenergy Task 42 (IEA, 2020) provides the scope, definition, aim, and objectives for biorefineries. Nonetheless, the classification for specific applications is still under development, and a general approach to classify biorefinery systems is given by Cherubini (2009). Fig. 1 shows how a biorefinery might be structured based on the classification proposed by IEA.

Figure 1: Example of the combination of features for the classification of a biorefinery system: generic system (a) and example (b). Source: (CHERUBINI et al., 2009)



According to Cherubini (2009), the production of transportation biofuels is seen as the driving force for future biorefinery developments reflecting the main advantage of using the already existing infrastructure for easier market introduction. Fast pyrolysis is the primary technology to convert lignocellulosic biomass into bio-oil, biochar, and gas.

Since pyrolysis is a flexible process, in terms of size and process mode, small units can be installed in the vicinity where biomass waste is generated. Process modes or platforms can vary from torrefaction, slow pyrolysis, medium or intermediate pyrolysis, fast pyrolysis, flash pyrolysis, and gasification, for example. The choice for the platform depends on the feedstock type and designed products. The energy products can be used/processed directly at the product stream or be stored and transported to other units. For instance, gases can be co-combusted with original biomass waste to provide part of the heat to the process, and biochar can be applied to soils in the vicinity to carbon sequestration and enhance soil fertility. According to Woolf (2010), the production of biochar and its storage in soils can contribute to a reduction of up to 12 % of current anthropogenic emissions.

2.3. The relevance of biomass pyrolysis in the world

The growing interest in pyrolysis in producing renewable fuels and biomaterials is highlighted here through quantitative and qualitative data collected in the Science Direct directory (ELSEVIER, 2020). The figures are based on a non-exhaustive search restricted to the period from 1980 to 2020, and with the following keywords: "Pyrolysis/Lignocellulosic biomass", "Pyrolysis/Biomass/Energy", and "Pyrolysis/Biomass/Biochar". The outcomes show the trend of research growth in the subject area evaluated. Additionally, to understand the role of Brazil in the context of pyrolysis, the number of publications in this country are analysed comparatively. Figure 2 shows the line charts (A, C, and E) and the pie charts (B, D, and F). The line charts show the rate of increase throughout the years, and the pie charts inform the contribution in percent in publications of ten countries plus Brazil in the whole period. Figure 3 shows the number of publications about pyrolysis per subject areas of science for the period assessed: Figure 3A shows the share of publications during the year 1980, and Figure 3B during the year 2019.

Figure 2: Overview of publications in pyrolysis in the world. Source: Elsevier (2020)

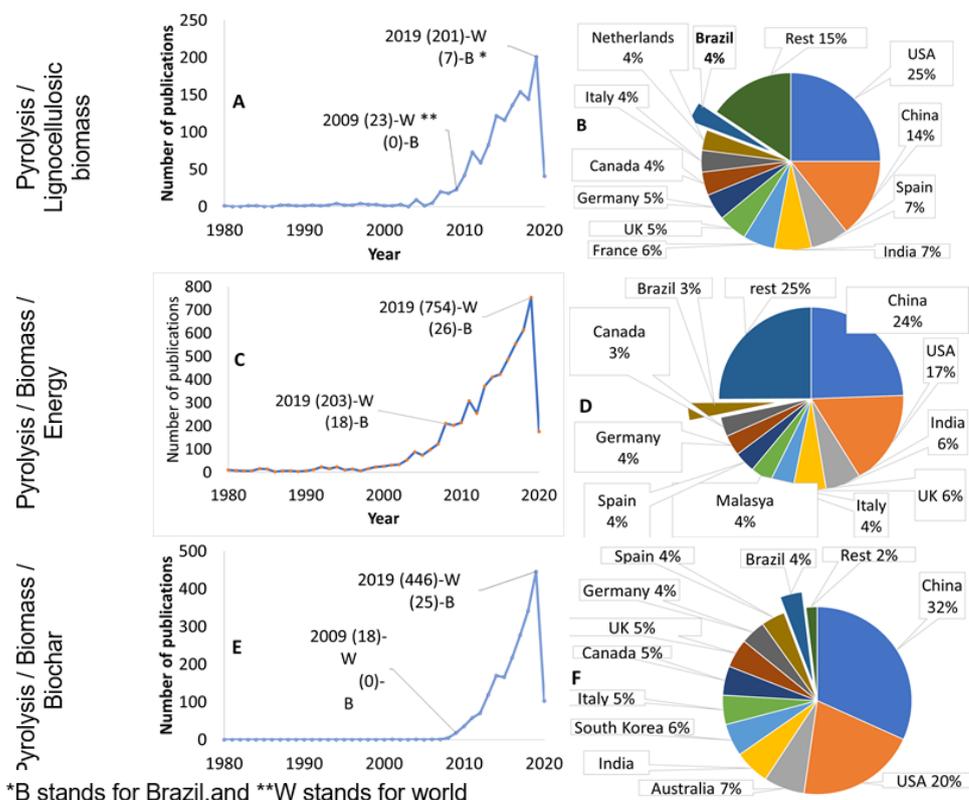
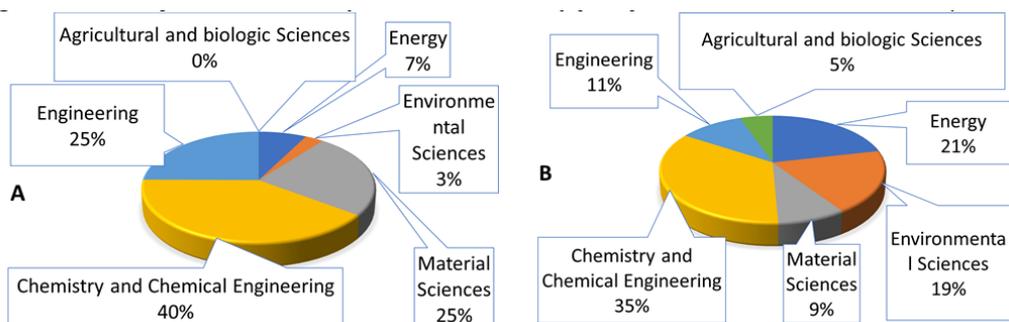


Figure 1: Subject areas of publications in pyrolysis. Source: Elsevier (2020)



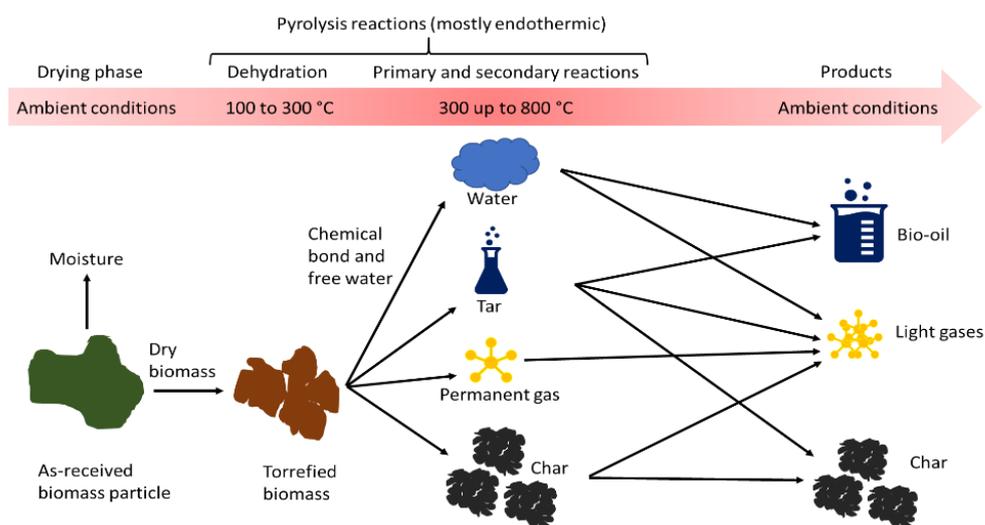
2.4. Pyrolysis reactions and influencing factors

Pyrolysis is a collective term given to all thermochemical processes, including slow pyrolysis (torrefaction and carbonization), fast pyrolysis and gasification, in which heat is applied under oxygen-free or oxygen limiting conditions to decompose or convert biomass into more useful product streams (RONSSE; NACHENIUS; PRINS, 2015). It is a temperature-dependent process nonetheless, besides temperature, many other variables may affect pyrolysis products yields and compositions, including the type of biomass and the conditions of the pre-

treatment (physical, chemical, and biological treatments), heating rate, the use of different catalysts, type of fluidizing/carrier gas and its flow rate, and type of reactor, for example. Moreover, how the pyrolysis conditions affect the formation of the organics in bio-oil, the properties of biochar, and the composition of pyrolytic gas still need to be further investigated (HU; GHOLIZADEH, 2019).

When a biomass particle enters the reactor, it undergoes thermal degradation induced by the heat absorbed from the surrounding gas, causing it to decompose into many products. Fig. 4 shows the thermal degradation of a biomass particle inside the pyrolysis reactor. The particle undergoes a series of physical and chemical changes, i.e., drying, dehydration, primary and secondary reactions until it leaves the reacting zone.

Figure 4: Thermal degradation of a solid biomass particle under pyrolysis. The arrows indicate the main routes for the formation of products. Source: Adapted from (NEVES et al., 2011)

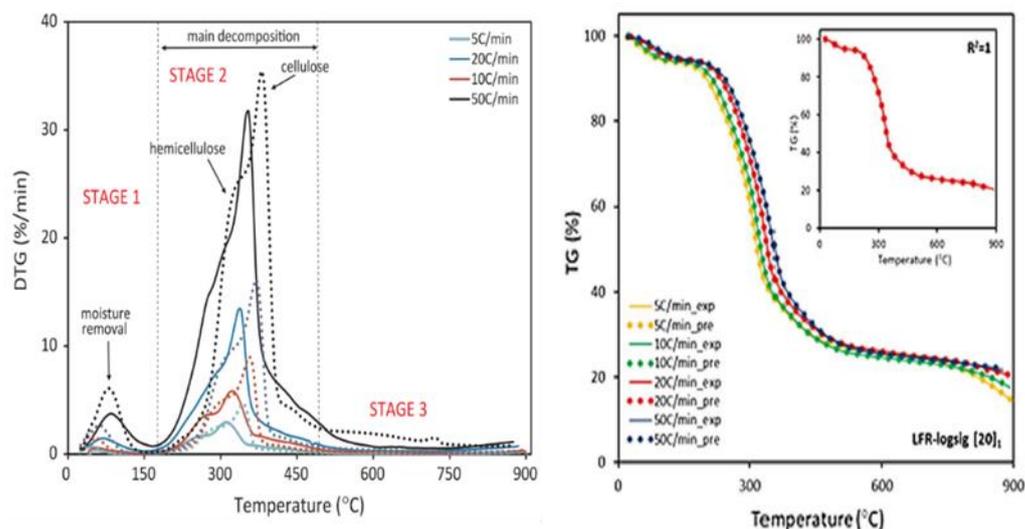


The temperature dependent behaviour of biomass particles is demonstrated by the thermal analysis, i.e., the TG/DTG curves shown in Fig. 5. Below 150 °C the mass loss is respective to water evaporation. At around 180 to 200°C (CHATTOPADHYAY et al., 2008) the thermal decomposition starts, and the primary volatiles are produced from the thermal scission of the polymers chemical bonds comprising permanent gas species (e.g., CO₂, CO, CH₄) and condensable species at ambient conditions (several organic compounds and water) (NEVES et al., 2011). Volatilization during pyrolysis causes mass loss and, therefore, volume reduction and shrinking without causing much change to the original structure of the particle for woody biomass (LAINE; SIMONI; CALLES, 1991), forming a solid material, denominated biochar. A significant part of the mineral matter formerly present in the parental material remains in the char.

Although the reaction rates for individual components occur at different velocities at different temperatures, the primary reaction is complete at relatively low temperatures, e.g., below 500 °C as seen on DTG curves (Fig. 5). However, at higher temperatures, some of the primary volatiles released from the particle can further participate in a variety of secondary reactions to form second-order

products. Multiple reactions can take place simultaneously, both primary and secondary, e.g., cracking, reforming, dehydration, condensation, polymerization, oxidation, and gasification reactions (NEVES et al., 2011).

Figure 5: Differential thermal analysis and thermogravimetric analysis of main biomass components at different heating rates. Source: (ÇEPELIOĞULLAR et al., 2018)



The general pyrolysis reactions inside the reactor can be expressed as:



where, $C_xH_yO_z$ is the empirical formula for the molar fractions of the feedstock; Q_{in} in $(kJ.kg^{-1})$ is the heat that needs to be input to the reactor for the reactions to take place; $Y_{solid} + Y_{liquid} + Y_{gas}$ is the yield for the pyrolysis products; and, Q_{out} in $(kJ.kg^{-1})$ is the radiation heat loss to the surrounding and through the flue gas.

2.5. Energy balance

Pyrolysis, as an endothermic reaction, requires heat from an external source, typically from the combustion of feedstock or pyrolysis products (CHOPRA; JAIN, 2007), microwave (LUO et al., 2020), electric furnace (FUNKE et al., 2018), plasma (MUVHIIWA et al., 2019), or concentrated solar heat (GIWA et al., 2019), for example. The energy required in the process is the summation of the energy required for heating the feedstock, i.e., pyrolysis heat, the energy required for the reaction occur, i.e., reaction heat, and the energy losses, i.e., moisture evaporation, radiation loss, fuel heat, and the heat carried in flue gas and with the products. A general equation for the net energy in a pyrolysis reactor can be expressed as:

$$Q_{net} = m_{fs} \sum H_{LHV_{char,biooil,gas}} - \sum Q_{in_{m,out_n}} \quad (2)$$

where, Q_{net} is the net energy in $kJ.kg^{-1}$ for a general pyrolysis process; m_{fs} in kg is the mass of original feedstock; $\sum H_{LHV_{char,biooil,gas}}$ is the summation of the energy of the three products, and $\sum Q_{in_{m,out_n}}$ is the amount of energy in $kJ.kg^{-1}$ required for the pyrolysis process to occur.

2.6. Pyrolysis processes

Pyrolysis is used to convert primary energy carriers into intermediate products (pyrolysis oil and syngas) and energy carriers (biochar, bio-oil, and pyrolytic gas), which ultimately are utilized in various forms of energy (e.g., heat, electricity, and mobility) or as chemicals (KIC INNOENERGY, 2015). The process can be designed as small distributed pyrolysis units that can deliver intermediate products to modern processing units, or pyrolysis reactors can be integrated into novel biorefineries to produce transportation biofuels, power, and chemicals from biomass (BALAGURUMURTHY et al., 2015).

Overall, the pyrolysis processes can be classified from slow to fast, depending on the heating rate. Tab. 6 summarizes some basic characteristics of different types of the pyrolysis process.

Table 6: Principal pyrolysis methods. Source: Adapted from (ZAMAN et al., 2017)

Pyrolysis types	Retention time	Heating rate	Peak temperature	Main products
Ultra-rapid	< 0.5 s	Very high	1000 (°C)	Chemicals/Gas
Fast	< 2 s	Very high	500 (°C)	Bio-oil
Flash	< 1 s	High	< 650 (°C)	Bio-oil/Chemicals/Gas
Hydro-pyrolysis	< 10 s	High	< 500 (°C)	Bio-oil
Vacuum	2 to 30 s	Medium	400 (°C)	Bio-oil
Conventional	5 to 30 min	Low	600 (°C)	Char/ Bio-oil /Gas
Carbonization	Hour to days	Very low	400 (°C)	Charcoal/Biochar/Bio-oil

Figures 6 and 7 show, respectively, slow pyrolysis and circulating fluidized bed pyrolysis processes schemes with mainstreams of feedstock and products.

Figure 6: Integrated pyrolysis-based carbon storage and bio-renewables system. Source: (RONSSE; NACHENIUS; PRINS, 2015)

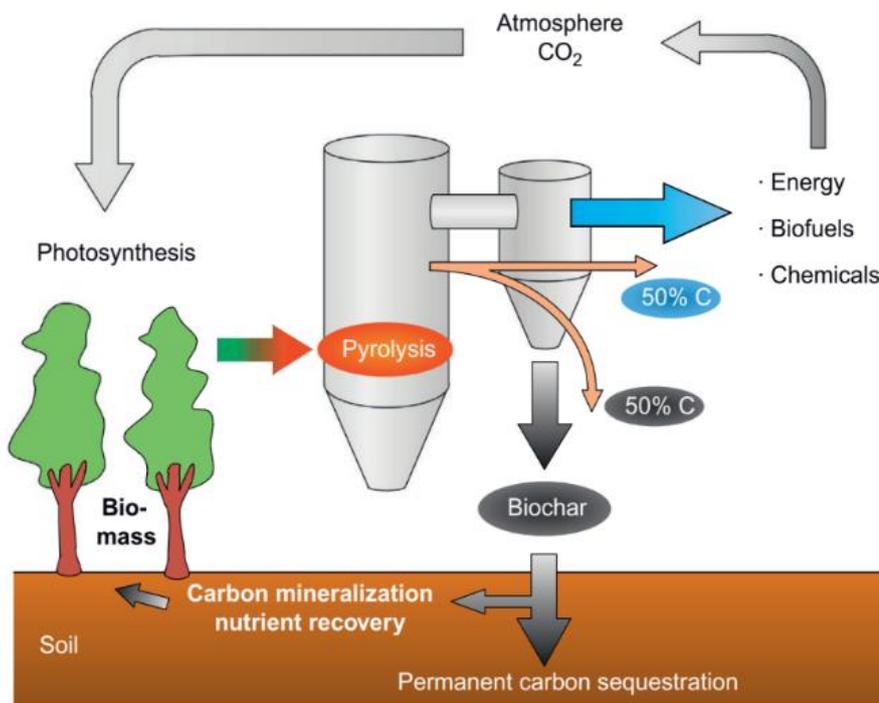
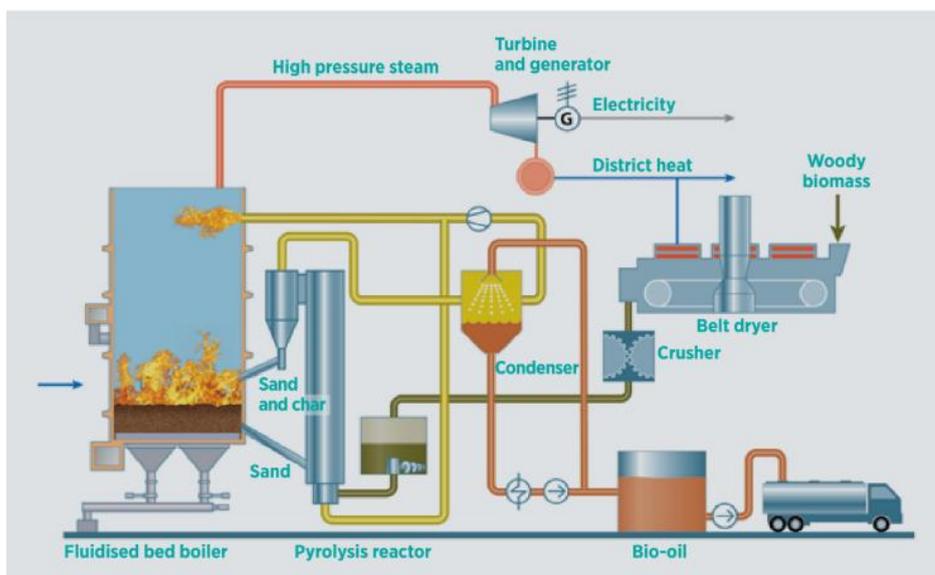


Figure 7: Integration of fast pyrolysis with circulating fluidized bed combustion boiler. Source: (IRENA, 2018)



Slow pyrolysis is usually performed in fixed bed pyrolysis systems as a batch reaction, or auger reactors. These consist of simple, reliable, and proven effective processes for fuels with biomass feed particles of uniform size. The feedstock is preferably heated by the external application of heat to the reactor (JAHIRUL et al., 2012). For auger reactors, normally, an inert gas is fed into the biomass hopper unit to ensure that no oxygen enters with the biomass (BRIDGWATER, 2012a).

Fluidized bed reactor – FBR is the most popular configuration employed from laboratory to commercial scale. FBR is more efficient because the feedstock input and bio-oil production are continuous (LV et al., 2004).

2.7. Technology readiness level for pyrolysis

Technology readiness levels (TRLs) are a method created by (NASA, 2012) for estimating the maturity of technologies during the developing phase until its deployment. As shown in Tab. 7, fast pyrolysis technology is at TRL 5 to 8, while the downstream pyrolysis oil upgrading is in the order of TRL = 3 to 5. The principal intended use for bio-oils from fast pyrolysis oil upgrading has been as a substitute for heavy and light fuel oil in boiler and heating boiler applications. However, the prevailing main driver appears to be the upgrading of the bio-oil to hydrocarbon biofuels, and in particular, to aviation fuels (KIC INNOENERGY, 2015). For slow pyrolysis, Ortwein and Lenz (2015) state that the technology is fully developed for the production of charcoal. Table 7 shows the TRLs for the main thermochemical conversion processes and products as well.

Table 7: Source: TRL form main thermochemical processes. Source: Adapted from charcoal (KIC INNOENERGY, 2015; ORTWEIN; LENZ, 2015)

Process	Main product	Process phase	Product upgrading phase
Combustion	Heat (flue gas)	TRL 9	TRL 9
Gasification	Syngas	TRL 9	TRL 5-6
Fast pyrolysis	Pyrolysis oil	TRL 5-8	TRL 3-5
Slow pyrolysis	Charcoal/Biochar	TRL 9	TRL 9
Torrefaction	Terrified biomass	TRL 7-8	TRL 9

2.8. Pyrolysis industrial-scale installations

Table 8 shows some pyrolysis technology plants, including slow and fast pyrolysis, and presents the TRL level, the status of the deployment, and other relevant operating information.

Table 8: Biomass conversion facilities. Source: (IEA BIOENERGY, 2019)

Project Owner	Location	Technology Brief	Status	TRL	Technology	Input	Output
Äänevoima Oy	Finland	3 boilers; BFB and 2 oil burners, 173 MW fuel input	operational Since 2000	TRL 9 Commercial	Bubbling Fluidized Bed	Peat, sludge, HFO	Power (electricity) (38 MWel) Heat (230 MWth) Pyrolysis oil (1,300 kg/h)
ABRITech	Canada	50 dry tonne per day - Heavy fuel oil	Under construction	TRL 6-7 Demonstration	Auger	Forest residues soft wood bark (2,000 kg/h)	Solids (280 kg/h) Clean syngas (320 kg/h)
Advanced Biofuels Solutions	United Kingdom	Plasma stage removes tars leaving a syngas which is predominantly CO and H2 and is also used to vitrify the ash.	Under construction	TRL 8 First-of-a-kind commercial	Advanced Plasma Power - fluidized bed gasifier	Organic residues and waste streams	SNG (1,500 t/y)
Agnion Technologies GmbH	Germany	A technology that offers the solution to the all thermal reformer heat transport issue by using heat pipes.	operational since 2001	TRL 4-5 Pilot	Power / CHP	Waste Wood (80,000 t/y)	Heat (28 MWth) Power (electricity) (6.1 MWel)
Ensyn	Brazil	Partner-Fibria	Planned	TRL 8 First-of-a-kind commercial	Circulating Fluid Bed	eucalyptus (16,667 kg/h)	pyrolysis oil (11,470 kg/h)
Iberomassa Florestal	Portugal	Slow pyrolysis	Operational Since 2014	TRL 9	Fixed bed	Forestry-Acacia	Main Charcoal / secondary biochar Biochar-700 tons/Y.
Carbofex Oy	Finland	EBC* Carbonizes 400-500 kg of wood chip per hour	Operational	TRL 9	Auger	Forest residues Wood chips	Bio-oil-600tons/y 1-2 MW heat

* EBC – European Biochar Certificate

3. COMMENTS AND CONCLUSION

Pyrolysis is an efficient technology for converting a wide range of lignocellulosic waste biomass and dedicated crop biomass into renewable energy. The development of fast pyrolysis to produce renewable transport fuels and fuel components from waste biomass is maturing quickly. Processes for fast pyrolysis catalytic upgrading of bio-oil is an area currently receiving significant research and development interest. The interest in slow pyrolysis products, such as biochar, is growing rapidly, and despite Brazil is the largest charcoal producer in the world, most producing sites use rudimentary process technology without recovery of the energy in the exhaust gases.

The conversion of waste biomass into energy and chemical products is unquestionably sustainable because the waste generation is increasing in every country. The recovery of energy and materials from waste via pyrolysis is an efficient waste management method, requiring less capacity of landfills, lowers pollution, brings revenue and local jobs. Additionally, according to Gvero (2013) Gvero (2013), biomass plays an essential role as a sustainable development driver and is a fundamental ingredient for the deployment of the bioeconomy (IEA TASK 42, [s. d.]), requiring even more investment in research and support from decision-makers in developing countries.

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RESUMO

Resíduos de biomassa, como os agro-resíduos, vêm se destacando como um recurso promissor de energia renovável devido à sua abundância e natureza neutra em carbono. Têm alto potencial para serem usados como fonte alternativa de energia, empregando técnicas de conversão termoquímica. A pirólise é a técnica mais eficiente para a conversão de resíduos de biomassa na fabricação de combustíveis e produtos químicos renováveis. No entanto, apesar da pirólise ser um método bem conhecido para fornecer combustível sólido (carvão vegetal) e produtos químicos, as vias tecnológicas para a produção de produtos químicos e combustíveis líquidos em escala industrial não estão totalmente desenvolvidas. Esta revisão aborda a relevância da pirólise para conversão de resíduos em energia e materiais, os fundamentos da pirólise, diferentes reatores, condições do processo e seus produtos na perspectiva da recuperação de energia e materiais. Consequentemente, o objetivo desta revisão é analisar o corrente nível de aplicação da pirólise no gerenciamento de resíduos, identificar lacunas em nosso entendimento atual e recomendar orientações futuras para pesquisas.

Palavras-chave: Agro resíduos. Pirólise. Bioprodutos.

REFERENCES

ABBASI, T.; ABBASI, S. A. Biomass energy and the environmental impacts associated with its production and utilization. *Renewable and Sustainable Energy Reviews*, [S. l.], v. 14, n. 3, p. 919–937, 2010. Available at: <https://doi.org/10.1016/j.rser.2009.11.006>

AL ARNI, S.; BOSIO, B.; ARATO, E. Syngas from sugarcane pyrolysis: An experimental study for fuel cell applications. *Renewable Energy*, [S. l.], v. 35, n. 1, p. 29–35, 2010. Available at: <https://doi.org/10.1016/j.renene.2009.07.005>

ANTAL, M. J.; GRØNLI, M. The Art, Science, and Technology of Charcoal Production †. *Industrial & Engineering Chemistry Research*, [S. l.], v. 42, n. 8, p. 1619–1640, 2003. Available at: <https://doi.org/10.1021/ie0207919>

BALAGURUMURTHY, B. et al. Thermochemical Biorefinery. In: *Recent Advances in Thermo-Chemical Conversion of Biomass*. [S. l.]: Elsevier, 2015. p. 157–174. E-book. Available at: <https://doi.org/10.1016/B978-0-444-63289-0.00006-5>

BHASKAR, T.; PANDEY, A. Advances in Thermochemical Conversion of Biomass—Introduction. In: *Recent Advances in Thermo-Chemical Conversion of Biomass*. Elsevier, 2015. p. 3–30. Available at: <https://doi.org/10.1016/B978-0-444-63289-0.00001-6>

BIEDERMAN, L. A.; HARPOLE, W. S. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy*, [S. l.], v. 5, n. 2, p. 202–214, 2013. Available at: <https://doi.org/10.1111/gcbb.12037>. Accessed in: 10 maio. 2019.

BOK, J. P. et al. Fast pyrolysis of Douglas fir by using tilted-slide reactor and characteristics of biocrude-oil fractions. *Renewable Energy*, [S. l.], v. 65, p. 7–13, 2014. Available at: <https://doi.org/10.1016/j.renene.2013.06.035>

BRAGA, R. M. et al. Characterization and comparative study of pyrolysis kinetics of the rice husk and the elephant grass. *Journal of Thermal Analysis and Calorimetry*, v. 115, n. 2, p. 1915–1920, 2014. Available at: <https://doi.org/10.1007/s10973-013-3503-7>

BRIDGWATER, A. V. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, [S. l.], v. 38, p. 68–94, 2012 a. Available at: <https://doi.org/10.1016/j.biombioe.2011.01.048>

BRIDGWATER, T. Biomass Pyrolysis: IEA Bioenergy Task 34. [S. l.: s. n.].

BRIDGWATER, A. V. Upgrading biomass fast pyrolysis liquids. *Environmental Progress & Sustainable Energy*, [S. l.], v. 31, n. 2, p. 261–268, 2012 b. Available at: <https://doi.org/10.1002/ep.11635>

BRUCKMAN, VIKTOR J., ESIN APAYDIN VAROL, BAŞAK B. UZUN, J. L. Biochar: a regional supply chain approach in view of climate change mitigation. [S. l.: s. n.]. E-book.

CEMPRE. CEMPRE review 2019. São Paulo-SP: [s. n.], 2019. Available at: www.cempre.org.br. Accessed in: 12 abr. 2020.

ÇEPELIOĞULLAR, Ö. et al. Activation energy prediction of biomass wastes based on different neural network topologies. *Fuel*, [S. l.], v. 220, p. 535–545, 2018. Available at: <https://doi.org/10.1016/j.fuel.2018.02.045>. Accessed in: 13 abr. 2020.

CHATTOPADHYAY, J. et al. Thermogravimetric characteristics and kinetic study of biomass co-pyrolysis with plastics. *Korean Journal of Chemical Engineering*, [S. l.], v. 25, n. 5, p. 1047–1053, 2008. Available at: <https://doi.org/10.1007/s11814-008-0171-6>

CHERUBINI, F. et al. Toward a common classification approach for biorefinery systems. [S. l.], 2009. Available at: <https://doi.org/10.1002/bbb.172>. Accessed in: 17 abr. 2020.

CHOPRA, S.; JAIN, A. K. A Review of Fixed Bed Gasification Systems for Biomass. *Agricultural Engineering International: the CIGR Ejournal*. Invited Overview, [S. l.], v. 9, n. 5, p. 23, 2007.

DE WILD, P. J. Biomass Pyrolysis for Hybrid Biorefineries. In: *Industrial Biorefineries & White Biotechnology*. [S. l.]: Elsevier, 2015. p. 341–368. E-book. Available at: <https://doi.org/10.1016/B978-0-444-63453-5.00010-0>

DHYANI, V.; BHASKAR, T. A comprehensive review on the pyrolysis of lignocellulosic biomass. *Renewable Energy*, [S. l.], v. 129, p. 695–716, 2018. Available at: <https://doi.org/10.1016/j.renene.2017.04.035>

DONALD L. KLASS. *Biomass for Renewable Energy, Fuels, and Chemicals*. [S. l.]: ACADEMIC PRESS, 1998. E-book.

ELSEVIER. Scopus - Document search, 2020. Available at: <https://www.scopus.com/search/form.uri?display=basic>. Accessed in: 5 mar. 2020.

EMBRAPA – EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA; MINISTÉRIO DA AGRICULTURA PECUÁRIA E ABASTECIMENTO. Embrapa em Números - Portal Embrapa Secretaria de Comunicação. Brasília, DF: [s. n.], 2017. Available at: <https://www.embrapa.br/embrapa-em-numeros>. Accessed in: 16 abr. 2019.

FUNKE, A. et al. Application of fast pyrolysis char in an electric arc furnace. *Fuel Processing Technology*, [S. l.], v. 174, p. 61–68, 2018. Available at: <https://doi.org/10.1016/J.FUPROC.2018.02.013>. Accessed in: 13 abr. 2020.

GARCIA-PEREZ, M.; LEWIS, T.; KRUGER, C. E. Methods for Producing Biochar and Advanced Biofuels in Washington State Part 1: Literature Review of Pyrolysis Reactors. Pullman: 2011. Available at: www.pacificbiomass.org. Accessed in: 2 mar. 2020.

GIWA, A. et al. Pyrolysis of date palm waste to biochar using concentrated solar thermal energy: Economic and sustainability implications. *Waste Management*, [S. l.], v. 93, p. 14–22, 2019. Available at: <https://doi.org/10.1016/J.WASMAN.2019.05.022>. Accessed in: 13 abr. 2020.

GODIN, B. et al. Détermination de la cellulose, des hémicelluloses, de la lignine et des cendres dans diverses cultures lignocellulosiques dédiées à la production de bioéthanol de deuxième génération. *Biotechnol. Agron. Soc. Environ*, [S. l.], 2010. Available at: https://www.researchgate.net/publication/49587888_Cellulose_hemicelluloses_lignin_and_ash_contents_in_various_lignocellulosic_crops_for_second_generation_bioethanol_production

GVERO, P. et al. Biomass as Potential Sustainable Development Driver – Case of Bosnia and Herzegovina. In: *Biomass Now - Sustainable Growth and Use*. [S. l.]: InTech, 2013. E-book. Available at: <https://doi.org/10.5772/51551>

HEIDARI, A. et al. Evaluation of fast and slow pyrolysis methods for bio-oil and activated carbon production from eucalyptus wastes using a life cycle assessment approach. *Journal of Cleaner Production*, [S. l.], v. 241, p. 118394, 2019. Available at: <https://doi.org/10.1016/j.jclepro.2019.118394>

HU, X.; GHOLIZADEH, M. Biomass pyrolysis: A review of the process development and challenges from initial research up to the commercialisation stage. *Journal of Energy Chemistry*, [S. l.], v. 39, p. 109–143, 2019. Available at: <https://doi.org/10.1016/j.jechem.2019.01.024>

IEA. Technology roadmap: bioenergy for heat and power OECD/IEA. Paris, France: [s. n.], 2012. Available at: <https://www.iea.org/reports/technology-roadmap-bioenergy-for-heat-and-power>. Accessed in: 12 abr. 2020.

IEA. Bioenergy - Fuels & Technologies - IEA, 2019. Available at: <https://www.iea.org/fuels-and-technologies/bioenergy>. Accessed in: 12 abr. 2020.

IEA. Factsheets Biorefineries. [s. l.], 2020. Available at: <https://www.iea-bioenergy.task42-biorefineries.com/en/ieabiorefinery/Factsheets.htm>. Accessed in: 17 abr. 2020.

IEA BIOENERGY. Installations | Bioenergy, 2019. Available at: <https://www.ieabioenergy.com/installations/>. Accessed in: 24 abr. 2020.

IEA TASK 42. Biorefining in a Circular Economy. [s. l.], [s. d.]. Available at: <https://www.ieabioenergy.com/task/biorefining-sustainable-processing-of-biomass-into-a-spectrum-of-marketable-biobased-products-and-bioenergy/>. Accessed in: 17 abr. 2020.

IRENA. Bioenergy from Finnish forests: Sustainable, efficient, and modern use of wood. [S. l.: s. n.]. E-book. Available at: www.irena.org. Accessed in: 23 abr. 2020.

J. W. GASKIN et al. Effect of Low-Temperature Pyrolysis Conditions on Biochar for Agricultural Use. *Transactions of the ASABE*, [S. l.], v. 51, n. 6, p. 2061–2069, 2008. Available at: <https://doi.org/10.13031/2013.25409>

JAHIRUL, M. et al. Biofuels Production through Biomass Pyrolysis —A Technological Review. *Energies*, [S. l.], v. 5, n. 12, p. 4952–5001, 2012. Available at: <https://doi.org/10.3390/en5124952>

KIC INNOENERGY. Energy from Chemical Fuels. Strategy and Roadmap 2015-2019. [S. l.: s. n.]. Available at: www.kic-innoenergy.com. Accessed in: 2 mar. 2020.

LAINE, J.; SIMONI, S.; CALLES, R. PREPARATION OF ACTIVATED CARBON FROM COCONUT SHELL IN A SMALL SCALE COCURRENT FLOW ROTARY KILN. *Chemical Engineering Communications*, [S. l.], v. 99, n. 1, p. 15–23, 1991. Available at: <https://doi.org/10.1080/00986449108911575>

LEHMANN, J.; JOSEPH, S. Biochar for Environmental Management: An Introduction. In: *Biochar for Environmental Management: Science, Technology, and Implementation*. (Lehmann, J., Joseph, S. ed.). [S. l.: s. n.] Available at: http://www.routledge.com/books/details/9780415704151/?utm_source=shared_link&utm_medium=post&utm_campaign=SBU3_KDK_2PR_6sl_9ENV_OTH15_InternationalBiocharInitiative_X. Accessed in: 8 ago. 2019.

LUO, J. et al. Bio-fuels generation and the heat conversion mechanisms in different microwave pyrolysis modes of sludge. *Applied Energy*, [S. l.], v. 266, p. 114855, 2020. Available at: <https://doi.org/10.1016/J.APENERGY.2020.114855>. Accessed in: 13 abr. 2020.

LV, P. et al. An experimental study on biomass air–steam gasification in a fluidized bed. *Bioresource Technology*, [S. l.], v. 95, n. 1, p. 95–101, 2004. Available at: <https://doi.org/10.1016/j.biortech.2004.02.003>

MCKENDRY, P. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, [S. l.], v. 83, n. 1, p. 37–46, 2002. Available at: [https://doi.org/10.1016/S0960-8524\(01\)00118-3](https://doi.org/10.1016/S0960-8524(01)00118-3)

MUVHIIWA, R. et al. Study of biochar from pyrolysis and gasification of wood pellets in a nitrogen plasma reactor for design of biomass processes. *Journal of Environmental Chemical Engineering*, [S. l.], v. 7, n. 5, p. 103391, 2019. Available at: <https://doi.org/10.1016/J.JECE.2019.103391>. Accessed in: 13 abr. 2020.

NACHENIUS, R. W. et al. Biomass Pyrolysis. *Advances in Chemical Engineering*, [S. l.], v. 42, p. 75–139, 2013. Available at: <https://doi.org/10.1016/B978-0-12-386505-2.00002-X>. Accessed in: 7 jul. 2019.

NASA. Technology Readiness Level. [S. l.], n. 2006, p. 1–4, 2012.

NASIR EL BASSAM. *Handbook of Bioenergy Crops A Complete Reference to Species, Development and Applications*. India: Routledge, 2010. E-book.

NEVES, D. et al. Characterization and prediction of biomass pyrolysis products. [S. l.: s. n.] Available at: <https://doi.org/10.1016/j.peccs.2011.01.001>. Accessed in: 26 mar. 2019.

NOVA CANA. *A cana-de-açúcar como fonte de energia elétrica*. [s. l.], 2016. Available at: <https://www.novacana.com/estudos/a-cana-de-acucar-como-fonte-de-energia-eletrica-241013>. Accessed in: 16 abr. 2019.

NSAFUL, F.; GÖRGENS, J. F.; KNOETZE, J. H. Comparison of combustion and pyrolysis for energy generation in a sugarcane mill. *Energy Conversion and Management*, [S. l.], v. 74, p. 524–534, 2013. Available at: <https://doi.org/10.1016/j.enconman.2013.07.024>

ORTWEIN, A.; LENZ, V. Flexible Power Generation from Solid Biofuels. In: THRÄN, D. (org.). *Smart Bioenergy*. Cham: Springer International Publishing, 2015. p. 49–66. E-book. Available at: https://doi.org/10.1007/978-3-319-16193-8_4

PANDEY, A. et al. Recent advances in thermochemical conversion of biomass. Amsterdam, Netherlands: Elsevier B.V., 2015.

PRINS, M. J.; PTASINSKI, K. J.; JANSSEN, F. J. J. G. More efficient biomass gasification via torrefaction. *Energy*, [S. l.], v. 31, n. 15, p. 3458–3470, 2006. Available at: <https://doi.org/10.1016/j.energy.2006.03.008>

RALEBITSO-SENIOR, T. K.; ORR, C. H. Biochar Application: Essential Soil Microbial Ecology. Middlesbrough, United Kingdom: Candice Janco, 2016. E-book.

RAVEENDRAN, K.; GANESH, A.; KHILAR, K. C. Influence of mineral matter on biomass pyrolysis characteristics. *Fuel*, [S. l.], v. 74, n. 12, p. 1812–1822, 1995. Available at: [https://doi.org/10.1016/0016-2361\(95\)80013-8](https://doi.org/10.1016/0016-2361(95)80013-8)

ROCHA, A. M. et al. Aproveitamento de Fibra de Coco para Fins Energéticos: Revisão e Perspectivas. *Agrenergd 2015*, [S. l.], p. 10, 2015. Available at: <http://www.iee.usp.br/agrenerg2015/sites/default/files/tematica8/744.pdf>. Accessed in: 16 abr. 2019.

RONSSSE, F.; NACHENIUS, R. W.; PRINS, W. Carbonization of Biomass. In: PANDEY, A. et al. (org.). *Recent Advances in Thermo-Chemical Conversion of Biomass*. [S. l.]: Elsevier, 2015. p. 293–324. E-book. Available at: <https://doi.org/10.1016/B978-0-444-63289-0.00011-9>

SALGADO, M. A. H.; TARELHO, L. A. C.; MATOS, A. Analysis of Combined Biochar and Torrefied Biomass Fuel Production as Alternative for Residual Biomass Valorization Generated in Small-Scale Palm Oil Mills. *Waste and Biomass Valorization*, [S. l.], v. 0, n. 0, p. 0, 2018. Available at: <https://doi.org/10.1007/s12649-018-0467-7>

SCHMIDT, H.-P. Ithaka: Journal für Terroirwein, Biodiversität und Klimafarming. [s. l.], 2011. Available at: <http://www.ithaka-journal.net/wege-zu-terra-preta-aktivierung-von-biokohle?lang=en>. Accessed in: 15 mar. 2019.

SETTER, C. et al. Slow pyrolysis of coffee husk briquettes: Characterization of the solid and liquid fractions. *Fuel*, [S. l.], v. 261, p. 116420, 2020. Available at: <https://doi.org/10.1016/j.fuel.2019.116420>

SHEN, D. et al. An overview on fast pyrolysis of the main constituents in lignocellulosic biomass to valued-added chemicals: Structures, pathways and interactions. *Renewable and Sustainable Energy Reviews*, [S. l.], v. 51, p. 761–774, 2015. Available at: <https://doi.org/10.1016/j.rser.2015.06.054>

SIMS, R. E. H. Biomass, Bioenergy, and Biomaterials: Future Prospects. In: Biomass and Agriculture Sustainability, Markets and Policies: Sustainability, Markets and Policies. Mas New Zealand: OECD Publishing, 2004. p. 568. E-book.

SNIS. Diagnóstico do manejo de Resíduos Sólidos Urbanos - 2018. [s. l.], 2019. Available at: <http://www.snis.gov.br/diagnostico-anual-residuos-solidos/diagnostico-do-manejo-de-residuos-solidos-urbanos-2018>. Accessed in: 24 abr. 2020.

SONG, C. et al. Nonisothermal Catalytic Liquefaction of Corn Stalk in Subcritical and Supercritical Water. Energy & Fuels, [S. l.], v. 18, n. 1, p. 90–96, 2004. Available at: <https://doi.org/10.1021/ef0300141>

UDDIN, M. N. et al. An Overview of Recent Developments in Biomass Pyrolysis Technologies. Energies, [S. l.], v. 11, n. 11, p. 3115, 2018. Available at: <https://doi.org/10.3390/en11113115>

WANG, S. et al. Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review. Progress in Energy and Combustion Science, [S. l.], v. 62, p. 33–86, 2017. Available at: <https://doi.org/10.1016/j.pecs.2017.05.004>

WOODS, W. I. et al. Amazonian dark earths: Wim Sombroek's Sombroek's vision introduction. Springer Science + Business Media B.V, 2009.

WOOLF, D. et al. Sustainable biochar to mitigate global climate change. Nature Communications, [S. l.], v. 1, n. 5, p. 1–9, 2010. Available at: <https://doi.org/10.1038/ncomms1053>. Accessed in: 24 abr. 2019.

ZAMAN, C. Z. et al. Pyrolysis: A Sustainable Way to Generate Energy from Waste. In: Pyrolysis. [S. l.]: InTech, 2017. E-book. Available at: <https://doi.org/10.5772/intechopen.69036>

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Correspondência:

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