ÁREA TEMÁTICA: Reciclagem

WASTE TO ENERGY AND MATERIALS THROUGH PYROLYSIS: A REVIEW

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ABSTRACT

Waste biomass, such as agro-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: Agrowaste; Pyrolysis; Bioproducts

CONVERSÃO DE RESÍDUOS EM ENERGIA E MATERIAIS POR MEIO DA PIRÓLISE: UMA REVISÃO

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: Agroresíduos; Pirólise; Bioprodutos

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, carbonbased 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 alreadyexisting 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 bespoken advantages of its products, such as the bio-oil for the production of 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, BAȘAK 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 WASTETOENERGY 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*					
	C	H	N	S	O	Ref
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 *et al.*, 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 *et al.*, 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 *et al.*, 2018)

*drybasis Obs:differences in the summation of the analysis is due to ash and othe minor elements not reported.

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

	Proximate analysis					
	M (%H2O)	VM (%w)db	FC (%w)db	Ash (%w)db	HHV MJ kg^{-1}	Reference
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 *et al.*, 2014)
Sugarcane bagasse	8.5	84	1.64	6	18.17	(AL ARNI; BOSIO; ARATO, 2010; UDDIN *et al.*, 2018)
Miscanthus	11.5	66.8	15.9	2.8	18.5	(MCKENDRY, 2002; NACHENIUS *et al.*, 2013)
Sorghum	6.2	69.1	18.5	6.3	16.9	(NASIR EL BASSAM, 2010; PANDEY *et al.*, 2015)
Switchgrass	7.9	72.6	16.4	3.1	17.4	(PANDEY *et al.*, 2015)

Obs: differences in the summation on the analysis is due to ash and othe 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, waterbased 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 agrowaste and energy crop

Agrowaste	Specific growth rate (ton/ha/year)	Type of waste	Waste (%)	Specific waste generation (ton/ha/year)	Reference
Rice	11.7×10^6	Rice husk	21	2.5×10^6	(EMBRAPA – 2017)
Sugarcane	665×10^6	bagasse	27	179.3×10^6	(NOVA CANA, 2016)
coconut	2.8×10^6	shell	57	1.6×10^6	(ROCHA *et al.*, 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)

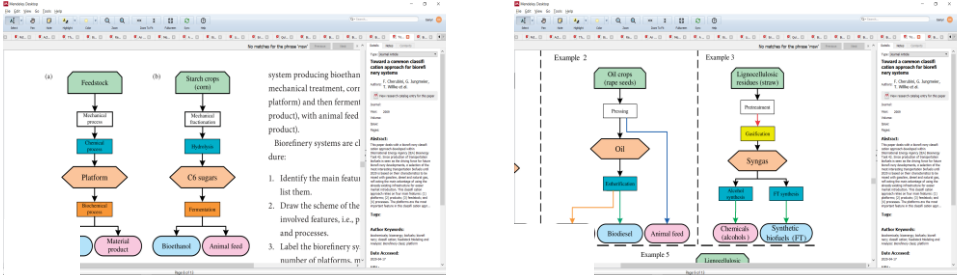
Table 5 Total generation for organic MSW

MSW	Generation rate Total (ton/year)	Organic Waste (%)	Organic waste generation (ton/year)	Reference
Organic	62.78×10^6	51.4	32.3×10^6	(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 particular 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)



system producing bioethan
mechanical treatment, corr
platform) and then ferment
product), with animal feed
product).
Biorefinery systems are cl
dure:

1. Identify the main featu
list them.
2. Draw the scheme of the
involved features, i.e., p
and processes.
3. Label the biorefinery sy
number of platforms, m

Toward a common classifi cation approach for biorefi nery systems

F. Cherubini, G. Jungmeier, T. Wellisch et al.

According Cherubini (2009), the production of transportation biofuels is seen as the driving force for future biorefinery developments reflecting the main advantage of using the alreadyexisting 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 CO_2CO_2 emissions.

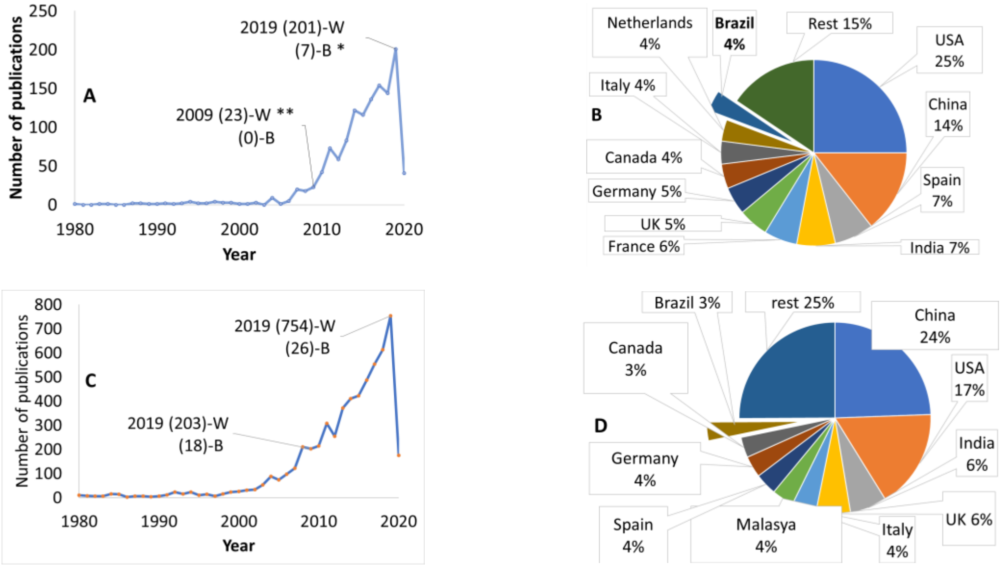
2.3 The relevance of biomass pyrolysis in the world

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)

Pyrolysis / Lignocellulosic biomass

Pyrolysis / Biomass / Energy



Pyrolysis / Biomass / Biochar

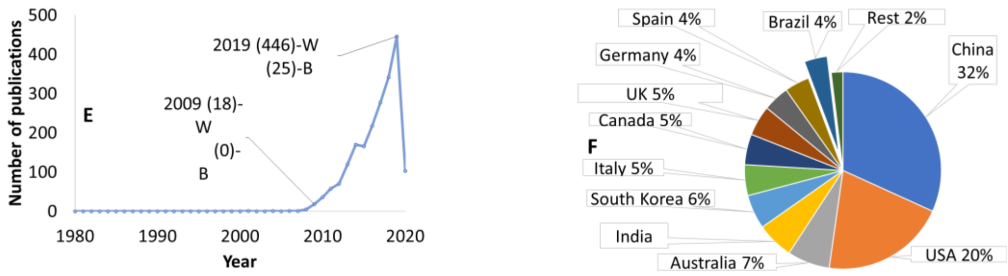
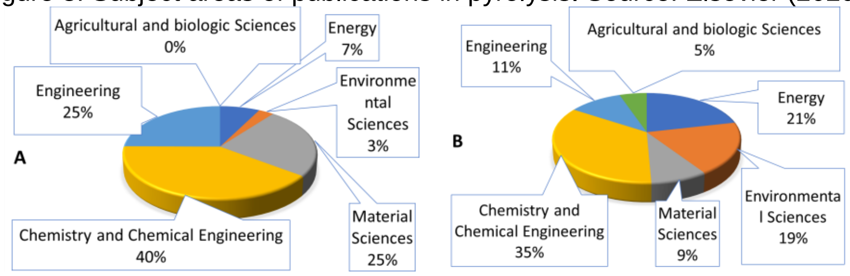


Figure 3: Subject areas of publications in pyrolysis. Source: Elsevier (2020)

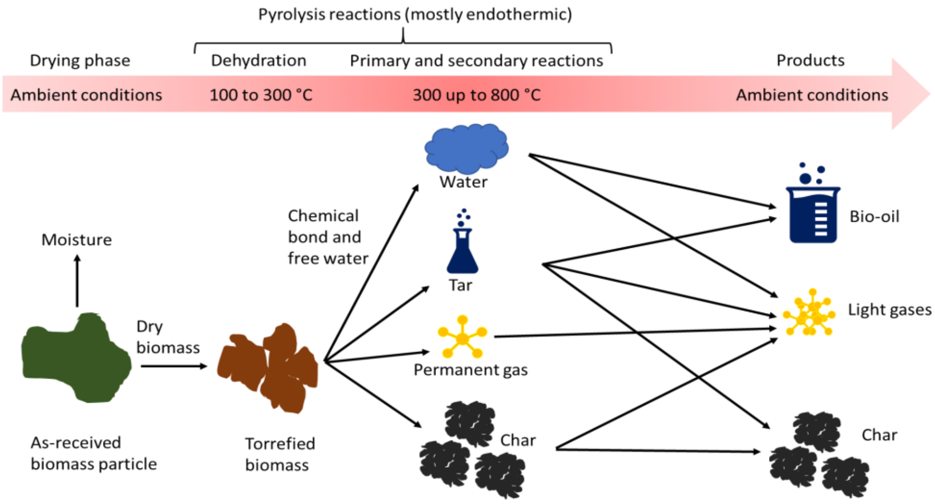


2.4 Pyrolysis reactions and influencing factors

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 oxygenlimiting 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.

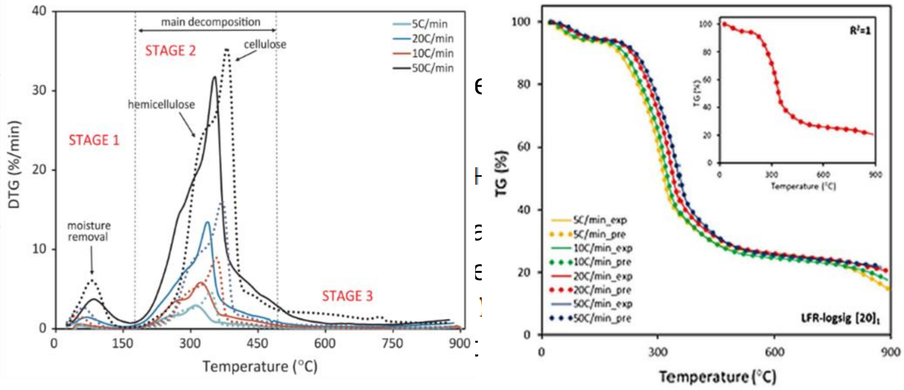
Figure 4: Thermal degradation of a solid biomass particle under pyrolysis. The arrows indicate the main routes for the formation of products. Source: Adapted from (NEVES et al., 2011)



The temperaturedependent 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. CO_2, CO, CH_4) 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)



:

$+ Y_{biooil} + Y_{gas} + Q_{out} + H_2O$

$_{ut} + H_2O$ (1)

of the feedstock; Q_{in} Q_{in} in (
the reactions to take place;
products; and, Q_{out} Q_{out} in (
igh 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:

$$Q_{net} = m_{fs} \sum H_{LHV\,char,biooil,gas} - \sum Q_{in_m,out_n} Q_{net} = m_{fs} \sum H_{LHV\,char,biooil,gas} - \sum Q_{in_m,out_n} \tag{2}$$

where, Q_{net} Q_{net} is the net energy in $kJ.kg^{-1}kJ.kg^{-1}$ for a general pyrolysis process; $m_{fs}m_{fs}$ in kg kg is the mass of original feedstock; $\sum H_{LHV\,char,biooil,gas}\sum H_{LHV\,char,biooil,gas}$ is the summation of the energy of the three products, and $\sum Q_{in_m,out_n}\sum Q_{in_m,out_n}$ is the amount of energy in $kJ.kg^{-1}kJ.kg^{-1}$ 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, biooil, 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 3o 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/Biooil

Figure 6 and Fig. 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 biorenewables system. Source: (RONSSE; NACHENIUS; PRINS, 2015)

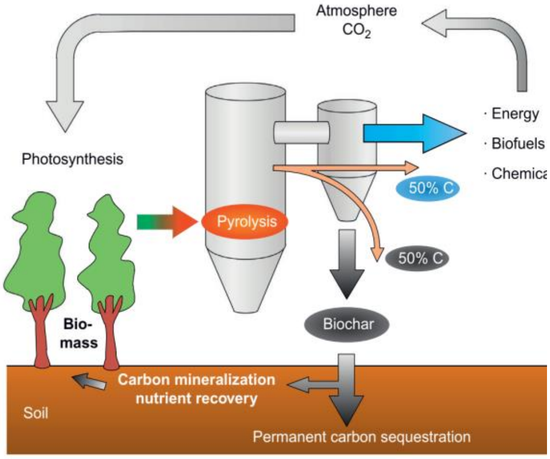
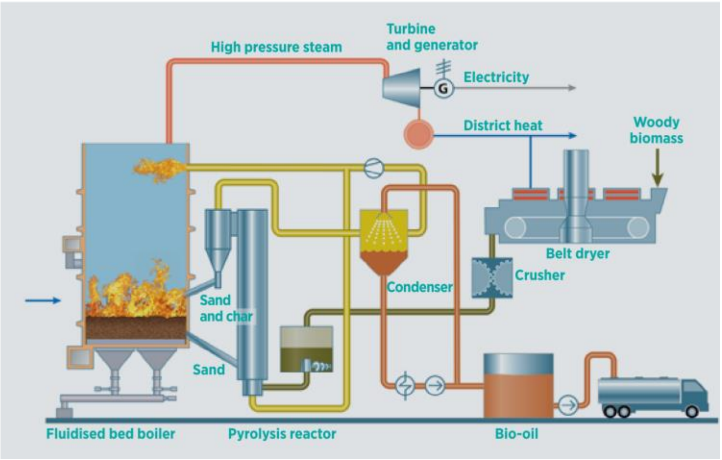


Figure 7: Integration of fast pyrolysis with circulating fluidized bed combustion boiler. Source: (IRENA, 2018)



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 biooil 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)
ABRITech	Canada	50 dry tonne per day - Heavy fuel oil	Under construction	TRL 6-7 Demonstration	Auger	Forest residues softwood bark (2,000 kg/h)	Pyrolysis oil (1,300 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
Carbofex Oy	Finland	EBC* Carbonizes 400-500 kg of wood chip per hour	Operational	TRL 9	Auger	Forest residues Wood chips	Biochar-700 tons/Y. Bio-oil-600tons/y 1-2 MW heat

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 biooil 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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