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Review

Review on Fast Pyrolysis of Biomass for Biofuel Production from Date Palm

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Abstract: The fast depletion of fossil fuels and growing concerns about environmental sustainability have increased interest in using biomass as a renewable energy source. Fast pyrolysis, a thermochemical conversion process, has emerged as a promising technique for converting biomass into valuable biofuels and bio-based chemicals. The aim of this literature review is to comprehensively analyze recent advances in biomass fast pyrolysis, focusing on the principles, process parameters, product yields, and potential applications of biomass fast pyrolysis. This comprehensive review, based on an in-depth analysis of 61 scientific papers and 4 patents, provides an overview of various biomass technologies (combustion, gasification, pyrolysis) used for biofuel production. It focuses on the principles, benefits and applications of these technologies and serves as a valuable resource for researchers, engineers and policy makers. Based on the wealth of information from rigorously selected sources, we explore the key process parameters and reactor types associated with each technology, providing insight into its efficiency and product composition.

Keywords: fast pyrolysis; bio-oil; bio-fuel; bio-oil composition; biomass; pyrolysis oil; biofuel review; biomass review

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1. Introduction

Energy consumption has been growing in recent years due to population growth and economic development. By 2040, energy demand will increase by 37%, according to the International Energy Agency [1]. Renewable energy resources are composed of lignin, cellulose and hemicellulose and are becoming more popular because of the harmful effect of the use of fossil fuels on the environment.

Biomass comprises organic material derived from plants. This material results from the use of sunlight to convert carbon dioxide and water into organic matter; this natural activity is named photosynthesis [2]. As biomass resources, we can cite wood waste, crops and their by-products, municipal solid waste, food processing waste, and aquatic plants and algae [2], as well as animal by-products and animal waste [3–6]. Biomass technology is one of the best natural substituents for fossil resources, used for heating, generating electricity, and transport fuels production, chemicals, and biomaterials production [2]. It is also a considerable source of sustainable energy because it does not contribute to the accumulation of CO_2 in the atmosphere and, at the same time, helps in the recovery of degraded land and increases biodiversity [2].

Thanks to promising technological developments, biomass applications can be realized at a lower cost and with higher conversion efficiency, having a direct impact on jobs.

The use of biomass for liquid fuel production involves thermochemical technologies, biological strategies, and multiple other strategies. One of the most common downstream biofuel production technologies is pyrolysis, followed by mild and deep hydrotreating [7].

Fast pyrolysis involves the thermal decomposition of biomass in an anaerobic environment; it is characterized by high temperature (above 450 °C) and short residence time, producing biofuel with a high yield of up to 75% on a dry biomass basis.

Pyrolysis has been the subject of several works for the valorization of lignocellulosic biomass [8]. It consists of decomposing organic matter under the effect of heat in an inert atmosphere to produce gases, oils, and char. The three pyrolysis technologies, slow, fast, and flash, allow the process to be oriented towards the production of specific pyrolysis products depending on the processing conditions. Reactor technologies have been developed to produce pyrolysis oils, which have attracted increasing interest since the 1979 crisis. Indeed, these oils present an alternative to polluting fossil fuels. However, their application as fuel remains limited by their low calorific value (16–19 MJ/kg) due to their high water content (30%) and their richness in oxygenated compounds.

Biomass-based economies extension is limited by problems associated with refining fast pyrolysis oils that are highly oxygenated oils. This challenge is preventing the large-scale use of these oils. Oxygen content is not the only problem that affects the performance of bio-oils during storage, handling, and upgrading, however; it also depends on the type and reactivity of these oxygen-carrying functional groups [7].

The main objective of this research work is the valorization of date palms for the production of biofuels. This study will highlight the different stages of the process. We start by studying the pretreatment process for fast pyrolysis and the preparation of the raw materials for biofuel production.

We take into consideration in this review of the literature on fast pyrolysis the different synonyms used to describe the same phenomenon, in particular "fast pyrolysis", "fast pyrolysis", and "flash pyrolysis". From now on, we will use the term fast pyrolysis.

This paper is organized as follows: Section 2 presents the research methodology; Section 3 provides an overview of biomass with different types; Section 4 deals with the fast pyrolysis of date palm biomass with synthesis and depicts a technology watch on the production of biofuel from date palms via fast pyrolysis technology; and Section 5 concludes the paper.

2. Research Methods

In this review, the research methodology followed was as follows (see Figure 1):

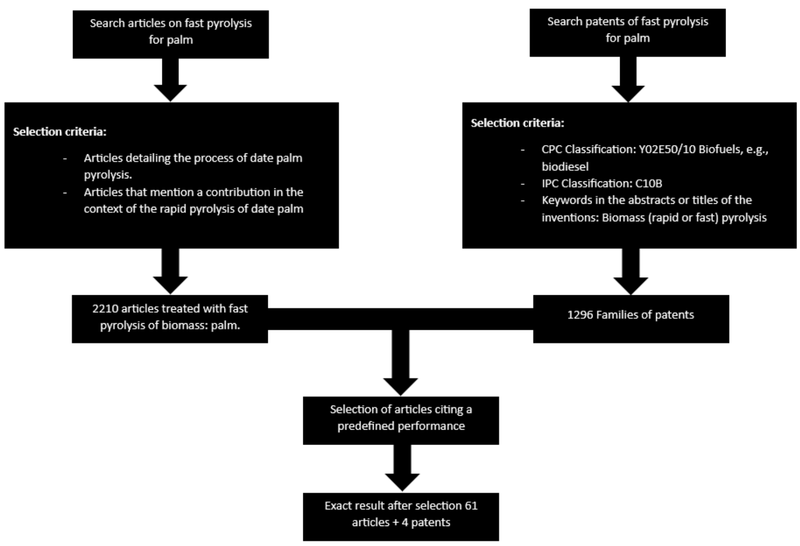


Figure 1. Data extraction strategy.

3. Biomass Generalities

3.1. The Dry Process

The term "biomass" refers to all organic matter. This can include matter of vegetable (microalgae included), animal, bacterial or fungal (mushrooms) origin, which can be transformed into energy. The biomass is present in three forms, with very different physical characteristics: solids (for example, straw, plants, leaves, etc.), liquids (for example, vegetable oils, bio alcohols) and gases (for example, biogas. Produced from organic material undergoing anaerobic digestion, biogas is a combination of methane and carbon dioxide. Although commonly associated with biomass, it is actually a result of the fermentation of biomass and is not considered biomass gas) [9].

Energy derived from biomass is a renewable energy source that depends on the cycle of living plant and animal matter and is an energy born of the sun's action through the phenomenon of photosynthesis [10]. This energy is reserved in the form of organic carbon, and its valorization requires specific processes according to the component used. Depending on the type of biomass and the technology used, the energetic valorization of the organic matter allows for producing three types of energy: the driving force for displacement, heat, and electricity [11]. According to the above, there are three methods of biomass valorization: the dry route, the wet route, and the production of biofuels.

The dry route of valorizing biomass mainly consists of thermochemical method; this mode include technologies such as combustion, gasification, and pyrolysis:

- Combustion is a physical–chemical process producing heat through the complete oxidation of fuel in the presence of surplus air.
- The hot water or steam obtained during combustion is mainly used in industry or in heating networks. This steam can be used in a turbine or a steam engine to produce mechanical energy. The production of electricity and heat from the combustion of biomass is called cogeneration [12].
- Biomass gasification is a technology that uses plant material, bone meal, etc., to produce synthesis gas after a thermochemical reaction. The gasification process takes place in a specific reactor in four successive phases as follows: drying, pyrolysis, oxidation, and reduction [13]. The gasification of biomass is one of the most important thermo-chemical transformation technologies, offering significant potential for the combination of various energy production systems. The gas generated through the gasification of biomass is an ecological alternative to the use of conventional petrochemical fuels for the generation of hydrogen, synthetic biofuels for transport, electricity and other chemical products. Gas from biomass contains CO, H_2, CO_2, CH_4 and H_2O, together with some organic impurities (tar, light hydrocarbon species) and other inorganic impurities (H_2S, HCl, NH_3), depending on the gasification process and operating conditions [14–16].
- Biomass pyrolysis is the chemical decomposition of organic matter at high temperatures to obtain other products that it did not contain in the initial state; the product is obtained either in the form of gas or in the form of volatile matter. This operation is carried out mainly in the absence of oxygen or in an atmosphere that contains only a little oxygen to avoid oxidation and combustion of the organic matter; this technology does not produce a flame. Another variant of biomass pyrolysis is currently being used to treat contaminated biomass or organic household waste.

3.2. The Wet Route

The wet process of valorizing biomass is mainly represented by the methanation process, which is a technique depending on the decomposition of biomass by microorganisms in a digester heated without oxygen, i.e., a process in an anaerobic environment.

Biogas is a product of the digestion of organic materials in an anaerobic environment. The digestate, which is the residue of the methanation process, is composed of non-biodegradable organic matter.

Supercritical water gasification (SCWG) and hydrothermal liquefaction (HTL), two successful methods for converting biomass into biofuels, have received increasing attention due to their fast reaction speed and the use of moist feed materials without the use of an energy-intensive drying process [17]. Gasification in supercritical water or hydrothermal gasification (HTG) displays the highest temperature and pressure among all hydrothermal conversion processes [18].

3.3. The Generations and Different Forms of Biomass

Biofuels are either solid (char), liquid (e.g., bio-oil from pyrolysis, Fischer–Tropsch products or methanol from synthesis gas, ethanol from sugar/starch fermentation, biodiesel from the transesterification of vegetable oils or animal fats) or gaseous (biogas from anaerobic digestion or methane and other light hydrocarbons from synthesis gas) [1].

If biomass is subjected to an elevated temperature in the absence of oxygen (pyrolysis), it is converted into solid carbon, gaseous and liquid products, which can be used as fuels. Liquid products include pyrolysis oil or bio-oil, with a density of around 1.2 kg/L. Bio-oil has a water content of 14 to 33% by weight, which cannot be easily removed by conventional methods (e.g., wastewater treatment, distillation), but bio-oil can be phase-separated above a certain moisture level, bearing in mind that the gross calorific value of bio-oil is generally between 15 and 22 MJ/kg, which is lower than the calorific values of conventional fuel oil (43.5 MJ/kg) and conventional heating oil (43–46 MJ/kg) [19].

There are three different generations of biofuel production in the biomass field: the first generation involves the production of biofuel from seeds, the second generation involves the production of biofuels from non-food crop residues, and the third generation involves the production of biofuel from microorganisms or from oil generated by microalgae.

The biofuels produced from biomass come in various forms: alcohols, pure vegetable oils, esters and biogas.

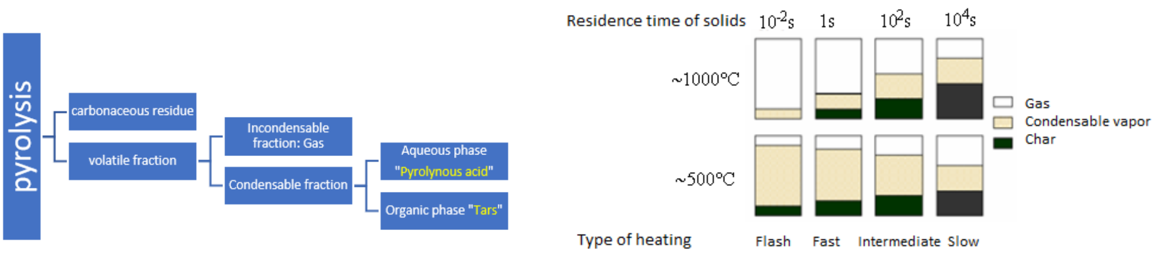
- Alcohols are produced from the fermentation of plant starch or sugar, such as corn, beets, wheat, and sugar cane. The product obtained is called bioethanol.
- Pure vegetable oils are generated through the simple cold pressing of oilseeds, notably rapeseed, sunflower and oil palm.
- Esters are derived from oil plants and are obtained via a complex chemical transformation of the oils resulting from the pressing of the seeds.

Biogas is the gas generated by the fermentation of organic matter in an anaerobic environment. It is a combustible gas consisting mainly of methane and carbon dioxide [12].

3.4. Pyrolysis of Lignocellulosic Materials

Pyrolysis involves the decomposition by heat in the absence of air of an organic substance. It can be achieved under a vacuum or in the presence of an inert gas.

The pyrolysis products of lignocellulosic materials are a solid residue, charcoal, while the other products constitute a volatile fraction containing condensable and non-condensable materials (Figure 2a) [20]. The quality and quantity of the pyrolysis products and the composition of the volatiles depend on several parameters, among which are the characteristics of the treated material and the operating conditions. Indeed, three parameters are inseparable—the temperature, the heating rate, and the residence time. They greatly condition the yield and the distribution of solid, liquid, and gaseous products (Figure 2b). Pyrolysis processes are associated with either slow heating rates or fast heating rates. Fast pyrolysis processes at low temperatures are of great interest for oil production. Indeed, Figure 2b [20] indicates that the best oil yield is achieved at 500 °C under flash or fast pyrolysis conditions.



(a) (b)

Figure 2. (**a**) Diagram showing the different categories of pyrolysis products [20]. (**b**) Influence of heating rate (for the two temperatures of 773 K and 1273 K) on pyrolysis products as a function of temperature [20].

Fast pyrolysis at a high temperature is of great interest when one is interested in fluidized bed gasification processes, where the temperature is around 1173 K and the heating rate is high [21]. Fast pyrolysis offers several advantages, including maximizing gas production. Fast pyrolysis can also produce large quantities of gas, which can then be reformed to produce syngas. However, it is important to note that syngas itself is not directly used by many energy sources as it is considered a secondary energy source [22]. The resulting syngas, composed primarily of hydrogen (H_2) and carbon monoxide (CO), can be used in a variety of other energy systems and applications. It can be used as a versatile feedstock for other processes such as methanol synthesis, methane production or Fischer–Tropsch synthesis [23]. These downstream processes convert syngas into final energy products that can be used by various energy utilizations, including power plants, industrial applications or transportation systems [22,24].

3.5. Influence of the Parameters on the Products Used during Fast Pyrolysis

3.5.1. When the Temperature Increases

As we have seen previously, the biomass decomposes into three phases under the action of heat:

- Condensable phase with oils composed of H_2O, a number of organic substances and a number of inorganic substances. The inorganic substances are present in several forms. They include Ca, Si, K, Fe, Na, S, N, P, Mg and heavy metals [25]. The organic substances, frequently referred to as "tars", are mostly polyaromatic hydrocarbons (molar mass between 78 and 300 g/mol) and aromatics [25,26]. The gaseous phase mainly includes H_2O, CO, CH_4, CO_2, C_2H_4, H_2, C_2H_2, and other heavier hydrocarbons, and the solid (char) phase mainly contains carbon with small amounts of hydrogen and oxygen. It also contains inorganic species.

With an increase in temperature, the quantity of gas produced by the various technologies increases [27], the amount of CO trained increases [28], the amount of hydrogen formed in the reaction increases with increasing temperature due to the gas phase cracking of the hydrocarbons, the amount of hydrocarbons formed diminishes in the temperature range 1873–2073 K [28], the amount of CH_4 produced diminishes, and the amount of CO_2 generated during the reaction increases.

Effect of residence time.

In the literature, the effect of residence time is found to be related to the temperature parameter in biomass pyrolysis technology [29]. The interactive effect of the residence time and temperature is the not necessarily well-accepted reduction caused by biomass pyrolysis for biomethanation. Boroson et al. [30] observed that as temperature and residence time increase, secondary reactions increase and tar molar mass decreases. A long residence time favors tar cracking and reforming [31]. On the contrary, a low residence time leads to a partial depolymerization of the lignin and encourages the production of bio-oils [32].

Fassinou et al. [33] discovered that when the vapor residence time is long, H_2, CH_4 and CO_2 concentrations increase.

The C_2H_4 and C_2H_6 concentrations remained weakly influenced. Uddin et al. [34] described that a syngas produced via the pyrogasification of biomass for biomethanation favors the production of H_2 with long residence times and high temperature [25,35,36].

Effect of pressure.

The work of Wafiq et al. [37] showed that pyrolysis of biomass is generally performed at high pressures compared to coal. Unlike temperature, the effect of partial pressure, as well as total pressure, is not a well-studied parameter in the literature.

The total pressure is fixed, on the one hand, in order to keep the system in the liquid state (light products, aqueous phase) at the reaction temperature and, on the other hand, in order to ensure solubility of hydrogen in the bio-oil [38]. The yield of CO_2 increases with pyrolysis pressure, while the yield of high molecular weight gases like C_2H_4 and C_2H_6 decreases with increasing pyrolysis pressure up to 30 bar [38].

3.5.2. Influence of the Heating Rate

As the heating rate increases at a low temperature of about 773 K, the yield of biofuels produced in gases decreases, that of biofuels produced in condensable gases increases, and that of biofuels produced in carbon decreases [27].

When the heating rate increases at high temperatures, the efficiency of biofuel production in gases decreases. When the heating rate is high, it leads to the fast formation of gas, and thus a fast elevation of the pressure inside the particle with a sudden ejection of the gases produced. Meanwhile, the efficiency of biofuel production in condensable gases and coal decreases with an increasing heating rate [27].

According to a study that was conducted by Li et al. [39], the yield is low when the fast pyrolysis is performed at a temperature that varies between 773 K and 1073 K, while a high yield of H_2 rich gas is obtained at a high temperature (1073 K).

Another hypothesis was provided by Rolando Zanzi et al. [40]. Pyrolysis of oil palm husks was studied by using thermogravimetric analysis. The influence of heating rate on kinetic parameters (activation energy, frequency factor and reaction order) was investigated. Pyrolysis of oil palm shells was carried out in an inert atmosphere, using nitrogen as the medium gas. Experience shows that the kinetic behavior of the samples can be divided into three zones. The first zone lies within the temperature range 300–380 °C, the second between 380 and 450 °C and the third between 450 and 850 °C. The experimental results also showed that the activation energy was relatively constant despite the variation in heating rate. The different pyrolyzed biomasses and coal in a drop furnace showed that the heating rate had a significant effect on the distribution of pyrolysis products. The difference observed in the amounts of char formed by the biomass and coal is mainly attributed to the cellulose contained in the biomass. Indeed, the dehydration of cellulose into anhydrous cellulose, the intermediate compound responsible for the high char yields, takes place at temperatures below 573 K. Above this temperature, it is the volatile products that are formed in the majority. When the heating rate is very high, the residence time of the biomass at temperatures below 573 K is very low, and the dehydration of the cellulose does not take place. Little anhydrous cellulose is formed, and consequently, little char is formed. On the other hand, these conditions of high heating rate favor the formation of char with high porosity and high reactivity [40].

3.5.3. Influence of Particle Size

Wei, L [41] studied the effect of particle size (0.10 mm to 1.2 mm) on the formation of products of the fast pyrolysis of pine sawdust and apricot kernels at 1073 K. Mass and heat transfer have little influence on the formation of pyrolysis products in the case of particles with diameters less than 0.20 mm [41].

This is in accordance with the results in Figure 3. In contrast, for particles larger than 0.20 mm in diameter, pyrolysis is primarily controlled by mass and heat transfer within the particle [41]. This is in disagreement with the results in Figure 3, which indicate a transition regime, not a thermal regime, for particles with diameters between 0.2 and 1.2 mm.

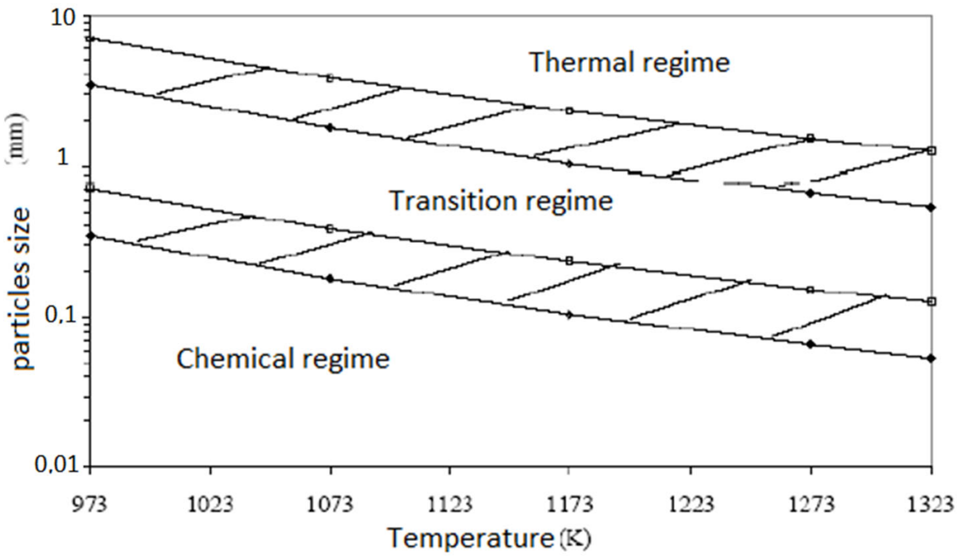


Figure 3. Pyrolysis regimes as a function of temperature and particle size [27].

In the literature, one finds many works concerning the influence of the size of the particles on the formation of the pyrolysis products. These works are generally carried out with particles whose size is between 0.1 and 2 mm. The results show that the smaller the particle size [28,42,43]:

- The higher the gas yield.
- The higher the H_2 and CO yield
- The more the quantity of CO + H_2 synthesis gas increases
- The larger the H_2/CO molar ratio is
- The more the yield of CO_2 decreases
- The more the hydrocarbon yield decreases. The gases are quickly expelled from a small particle, and therefore their residence time in the reactor is higher.
- The more the yields of condensable gases and char decrease.

Several pyrolysis regimes are to be considered depending on particle size and temperature. In his work on biomass stratification, Dupont determined the boundaries between pyrolysis regimes as a function of temperature and particle size [35].

Figure 3 shows the pyrolysis regimes as a function of temperature and particle size [44]. The limits are not lines but thick hatched areas because they take into account uncertainties. This shows that the chemical reaction of pyrolysis is limiting for particles smaller than 0.1 mm at temperatures between 973 and 1100 K. In this case, the reaction is in the intrinsic regime.

Between 1173 and 1323 K and for particles between 0.1 mm and 1 mm, the reaction is in an intermediate situation, called the transition regime, which is neither a chemical nor a thermal regime. We are in the thermal regime for particles of several millimeters, with limitations caused by internal heat transfer.

3.5.4. Bio-Oil Composition

Biofuels offer an interesting alternative to traditional fossil fuels, which can be produced from different biomass feedstocks such as municipal, forestry, agricultural and industrial waste. The main component of biofuels is bio-oil, which contains a wide range of compounds. These can be categorized as acids, alcohols, esters, aldehydes, phenols, ketones, syringes, guaiacols, sugars, alkenes, aromatics, furans and various oxygenates. In addition, some nitrogen compounds can also be present. In the last decade, a large number of research groups have carried out in-depth studies on pyrolysis oil, a type of bio-oil, with a view to understanding its composition as well as its chemical and physical characteristics. This research has contributed to our knowledge of this increasingly complex substance and its potential applications as a renewable energy source [43–47]. Table 1 depicts the principal pyrolysis oil compounds determined and quantified.

Table 1. Principal pyrolysis oil compounds determined and quantified by GC/MS (wt%) [44].

N°	Compound	Range
1	Glycolaldehyde	1–13.7
2	Acetol	2.6–8.6
3	Ethanoic acid	2.5–8.7
4	4-ethylguaiacol	0–0.1
5	Methyl	0.3–0.5
6	Propanoic acid monophenols and monofurans	0.2–2.8
7	Syringol	0–0.4
8	2(5H)-furanone	0.1–0.8
9	Guaiacol	0.1–0.5
10	Creosol	0.1–0.5
11	Eugenol	0.1–0.6
12	Methyl-2(5H)-furanone	0–0.2
13	Levoglucosan	3–6.5
14	Syringylaldehyde Monosugars	0–0.1
15	Cyclopenten-one	0.1–0.2
16	Phenol	0–0.9
17	Catechol	0.2–0.9
18	4-methylcatechol	0–0.5
19	Vanillin	0–1.5
20	Furfural	0.1–0.6

The date palm exists in Morocco. The palm groves cover an area of 50,000 hectares and are populated by 5 million plants. Morocco is thus ranked third in the Maghreb and seventh in the world for date palms [20], and in this context, the next section will be on the valorization of palm waste for biofuel production.

3.6. Oil Palm (Elaeis guineensis) Waste

Solid waste from the palm tree includes trunks, leaves, empty bunches, fruit waste, and the cake that is a co-product of oil extraction from the nuts of the palm fruit. The press cake contains 6–15% oil, while the solvent-extracted cake contains no more than 3% oil [45]. The main components and some of the work carried out on oil palm waste are given in the tables below (Tables 2 and 3).

Table 2. Main constituents of oil palm waste [48,49].

Composition (%db)	OPT	OPF	EFB	Presscake of Mesocarp
Lignin	18.1	18.3	21.2	14.1
Hemicellulose	25.3	33.9	24	-
Holocellulose	76.3	80.5	65.5	-
α-cellulose	45.9	46.6	41	20.5
Alcohol-benzene	1.8	5	4.1	-
Ashes	1.1	2.5	3.5	4.7

OPT: Oil palm trunk = tronc de PAH; OPF: Oil palm fronds = frondes de PAH; and EFB: empty fruit bunch = grappes vides de PAH.

Table 3. Existing works on the pyrolysis of waste from oil palm cultivation.

<table>
<tr><th>Oil Palm Waste</th><th>Type of Pyrolysis</th><th colspan="2">Results</th><th>Ref</th></tr>
<tr><td>Shell</td><td>ATG-Slow</td><td colspan="2">Volatile matter (77.6)</td><td>[45]</td></tr>
<tr><td>DAP waste</td><td>Fast</td><td colspan="2">Bio-oil yield is 23% at 600 °C</td><td>[50]</td></tr>
<tr><td>Fronds</td><td>ATG-slow</td><td colspan="2">-</td><td>[51]</td></tr>
<tr><td>mesocarp and palm frond</td><td>Fixed bed—Slow</td><td colspan="2">Maximum oil yield by mass is 48% at 500 °C with mesocarp and 47% at 600 °C with palm frond</td><td>[52]</td></tr>
<tr><td>Shell</td><td>slow</td><td colspan="2">-</td><td>[53]</td></tr>
<tr><td>OPT</td><td>Fixed bed—Slow</td><td colspan="2">Bio-oil yield is 20% at 600 °C</td><td>[54]</td></tr>
<tr><td>OPT</td><td rowspan="4">Fixed bed</td><td>40.87</td><td rowspan="4">500 °C</td><td rowspan="4">[55]</td></tr>
<tr><td>OPF</td><td>43.50</td></tr>
<tr><td>PL</td><td>16.58</td></tr>
<tr><td>PLR</td><td>29.02</td></tr>
<tr><td>OPT and EFB</td><td>TGA</td><td colspan="2">-</td><td>[56,57]</td></tr>
</table>

4. Summary of Existing Work on Fast Pyrolysis of Biomass

4.1. Synthesis of Recent Articles

A summary of recent articles on this subject is given in the following table (Table 4).

Table 4. Recent papers on fast pyrolysis of biomass.

Subject	Author	Summary
A review of the Chemical and physical mechanisms of the Storage stability of Fast pyrolysis bio-oils [58]	Diebold, J.P.	This article examines the chemical and physical mechanisms responsible for the storage stability of fast pyrolysis bio-oils. Fast pyrolysis is a thermochemical conversion process used to produce biofuels from biomass. However, fast pyrolysis bio-oils can be unstable and undergo undesirable reactions that affect their quality and shelf life. The article starts by explaining the factors that influence the storage stability of fast pyrolysis bio-oils, such as chemical composition, the presence of oxygenates, oxidation reactions, polymer formation, thermal degradation processes and the influence of impurities. It highlights the importance of understanding these mechanisms to improve the stability of bio-oils and extend their shelf life. The authors also review the various approaches and strategies used to improve the storage stability of fast pyrolysis bio-oils, such as modification of the chemical composition, use of stabilizing additives, heat treatment, dehydration, filtration and purification. They also highlight the importance of developing effective stabilization processes to make fast pyrolysis bio-oils more marketable and promote their use in a diverse range of applications. The review offers an overview of the chemical and physical mechanisms affecting the storage stability of fast pyrolysis bio-oils. It highlights the challenges associated with bio-oil stability and proposes strategies for improving their shelf life. This information is critical for the development and use of fast pyrolysis bio-oils as a source of renewable energy.

Table 4. *Cont.*

Subject	Author	Summary
PYROLYSIS KINETICS OF OIL-PALM SOLID WASTE [59]	Mohd Din, A.T. et al.	This paper describes a study on the pyrolysis process kinetics of oil palm solid waste. Oil palm solid waste is an important source of residual biomass from the palm oil transformation industry. Pyrolysis is a technique of thermochemical transformation used to convert this biomass into useful products such as charcoal, pyrolysis gases and bio-oils. This article analyzes the pyrolysis kinetics of solid oil palm waste. The pyrolysis kinetics are important to understanding the decomposition mechanisms of biomass and to optimizing the parameters of the pyrolysis in the process. The present study offers different kinetic scenarios, such as the zero-order model, the first-order model and the reaction-complex model, in order to describe the thermal degradation profiles of oil palm waste solids. The researchers tested pyrolysis experiments using lab scale instrumentation and measured degradation processes and output rates at different temperatures and over reaction times. The resulting experimental data were used to adjust kinetic model parameters and to predict the thermal decomposition profiles of oil palm solid residues under different reaction conditions. The kinetic values found in the models showed a good match with experimental data, validating the proposed models. To summarize, this paper offers an extensive background on the pyrolysis process kinetics of solid oil palm waste.
Thermogravimetry and pyrolysis of date stones [60]	Al-Badri, H.T. et al.	In this article, the authors have carried out a study of the thermal decomposition and pyrolysis of date pits, which are considered as agricultural waste, as well as a potential source of biomass for the production of renewable energy. The study is based on thermogravimetry, a technique that measures changes in the mass of a test sample when it is exposed to a controlled heat increase. The findings show that date pits undergo a complicated thermal decomposition process involving several distinct stages. The stages of the thermogravimetry experiment are mainly based on the following steps: the first is initial moisture loss with low temperatures, and then organic material decomposition at higher temperatures. The decomposition of organic matter releases various by-products such as gas, liquids and solid waste. The results of this article show that pyrolysis of date pits mainly produces biochar, charcoal, pyrolytic liquids and combustible gases. The gases and pyrolytic liquids can be converted into fuels or valuable chemicals, and the biochar can be used as a soil improver, while the pyrolytic liquids can be used as a fertilizer. The present study finds that date pits have considerable potential for energy production and can be processed by both thermogravimetric and pyrolysis techniques.
Porosity Characteristics of Chars Derived from Different Lignocellulosic Materials [61]	Khalil, L.B.	This article focuses on using date stone as a medium for filtering automobile exhaust particulates. Automobile emissions include various pollutants which are toxic to the environment and human health, such as oxides of nitrogen and small particulates. The findings demonstrated that date stone charcoal was effective in absorbing these types of pollutants, helping to minimize their presence in the exhaust gas. In summary, the paper concludes that the utilization of date stone carbon as an emission filtration material may be a viable possibility for the reduction of vehicular pollution.

Table 4. *Cont.*

Subject	Author	Summary
USING DATE STONE CHARCOAL AS A FILTE-ING MEDIUM FOR AUTOMOBILE EXHAUST GASES [62]	Shahad, AHK. et al.	This paper explains that a thermal reactor has been used and was built to produce charcoal from date stones using pyrolysis technology. The project authors took five charcoal samples to prepare for different maximum carbonization temperatures. During the experiment, it was observed that, as the temperature is increased, the characteristics of the charcoal are refined (the % carbon improves). It was also noted that at 700 °C, the percentage of carbon content remained constant. Charcoal made at this temperature was used as a filter medium in an adsorption filter to purify exhaust gas from a two-stroke spark-ignition internal combustion engine. The experimental results demonstrated that the filter has a high adsorption capacity for CO and CO_2 gases. An ORSAT was used to measure the concentration of CO and CO_2 in the engine exhaust gases before and after the filter. The filter reduces CO and CO_2 concentrations by 62% and 59%, respectively.
Energy from biomass [63]	Quaak, P. et al.	This article examines the use of biomass as a renewable energy source. Biomass is made up of organic materials of plant or animal origin, such as agricultural residues, forestry waste and energy crops grown specifically for this purpose. Using biomass as an energy source has several advantages. First, it is renewable because plants and trees can be replanted and grown continuously. In addition, the use of biomass reduces greenhouse gas emissions, because burning biomass only releases the amount of carbon dioxide that was recently absorbed by plants during their growth. This makes it a cleaner alternative to fossil fuels. The article also discusses the various methods used to convert biomass into energy. One of the commonly used methods is direct combustion, where biomass is burned to generate heat, which can then be used to generate electricity or for heating. Another method is the conversion of biomass into biofuels such as ethanol and biodiesel. These biofuels can be used as substitutes for fossil fuels in vehicles. The article, however, highlights some challenges associated with using biomass as an energy source. For example, the availability and collection of large quantities of biomass can be expensive and require adequate logistics. In addition, the conversion of biomass into energy can lead to polluting emissions if the appropriate technologies are not used. In conclusion, the article highlights the potential of biomass as a source of renewable energy. Its use can help reduce greenhouse gas emissions and diversify the energy mix. However, further efforts are needed to develop more efficient technologies and to ensure the sustainable management of biomass to maximize its environmental usefulness.
Fast Pyrolysis of Stored Biomass Feedstocks [64]	Agblevor, F.A. et al.	This article presents a comprehensive review of the research conducted by Agblevor, F. A.; Besler, S. and Wiselogel, A. E. on fast pyrolysis of stored biomass feedstocks. The authors' work is focused on the conversion of biomass into valuable energy based products by Fast heating of biomass under controlled conditions. The study emphasizes the importance of fast pyrolysis as a potentially promising technology for biomass utilization, especially for renewable energy production. The authors highlight the potential of this process to address the challenges associated with storing biomass feedstocks, such as agricultural residues, wood waste and energy crops. By quickly heating biomass materials to high temperatures in the absence of oxygen, fast pyrolysis enables the production of a variety of energy-rich products, including bio-oil, biochar, and syngas.

Table 4. *Cont.*

Subject	Author	Summary
Extraction of oil from palm seeds (phoenix) Dactylifera [65]	Ali, M.A. et al.	In the article "Extraction of oil from palm seeds (phoenix Dactylifera)" by Ali, M.A. et al., fast pyrolysis of palm [65] seeds was carried out for seeds of size 0.425 mm with a residence time of 2 h; the researcher used the solvent "n-hexane" in the reaction to produce the biofuel with a yield of 8.5% by weight Seed size: 0.425 mm. Time 2 h. Solvent: n-hexane. Max yield: 8.5% by weight.
Study of biogas production from date palm fruit waste [66].	Lattieff, F.A. et al.	Lattieff, F.A. [66] showed in their paper "Study of biogas production from date palm fruit waste" the possibility of producing biogas as a source of energy from date palm fruit waste using reactor batches and that the maximum biogas production was 203 L/kg. VS was obtained when the substrate was mixed with recycled digestate, so with regard to the solid concentration of 0.15 (w/w), the volumes of biogas obtained were estimated at 133 L/kg volatile solids (VS) at thermophilic and mesophilic conditions, respectively, and therefore after the study perfomed in this direction, the adoption of a mesophilic system of biomass remains the best choice to produce biogas from this type of waste.
Study of the thermal behavior of different date palm residues: characterization and devolatilization kinetics under inert and oxidizing atmosphere [67].	Jeguirim, M. et al.	In [67], Jeguirim, M et al. studied the thermal behavior of different date palm residues (date palm leaflets (DPL), date palm rachis (DPR), date palm trunk (DPT), dates (DS), and fruit stems sizes (FP)) under inert and oxidizing atmosphere, so common approach was used to model the kinetic parameters of devolatilization of different samples under 2 atm. Jeguirim, M et al. [67] showed that among the studied samples, DCT was the most reactive material under pyrolysis and an oxidation atmosphere, while DS was the least reactive fuel.
Evaluation of the combustion of date palm residues in a fixed bed laboratory reactor: comparison with the behavior of sawdust [68].	Elmay, Y. et al.	Under a temperature of 600 °C and with pyrolysis technology, Yassine et al. [68] in his paper "Evaluation of the combustion of date palm residue in a fixed bed laboratory reactor: Comparison with the behavior of sawdust" showed that the stone residue date is among the best biofuels produced, with the highest calorific value, bulk density and the lowest ash content, near 1.2%, as well as volatile matter content. It also has an energy density of 11 GJ per m^3, which is four times higher than that of other date residues and for other biomasses, namely the rachis of the date palm (DPR), the trunk of the date palm (DPT) and the fruit stem prunings (FP), for which characteristics were obtained such as chemical composition and energy density. It was also shown that the high amounts of chlorine for DPR and DPT would introduce both potential risks of corrosion in exchange and boiler tubes and the formation of persistent organic pollutants in the form of dioxins [68].
Overview of paraffin-based biofuel production by catalytic hydrodeoxygenation [69].	Mohammad, M. et al.	Under high temperature and hydrogen pressure, Mohammad, M. et al. showed that the process of hydrodeoxygenation of vegetable oil is one of the promising routes for the production of future fuels, and thus reducing metal catalysts, supported noble metal catalysts and sulfurized metal catalysts are used in this reaction to produce biofuel.
Conversion of lignin into aromatics-based chemicals (L-chems) and biofuels (L-fuels) [70].	Beauchet, R. et al.	This paper demonstrated that sodium hydroxide as a catalyst is effective in producing maximum yields of the monomer-rich fraction and high depolymerization of lignin origin particles of 8.4 wt% at 315 °C.

Table 4. *Cont.*

Subject	Author	Summary
Investigation of oil palm wastes' pyrolysis by thermogravimetric analyzer for potential biofuel production [71].	Noor haza Binti Alias et al.	In [71], Noor haza Binti Alias et al. showed that there are several parameters that influence the pyrolysis process, including the heating rate, the particle size, and the properties of the biomass itself. The smallest yield is obtained for the OPT, with 0.04–0.86% more volatile product when pyrolyzed at two heating rates. In contrast, EFB shows an increase from 3.81 to 9.81%. The high heating rates accelerate maximum degradation from 1.42 to 1.56 mg/s. This also causes the biomass to be degraded in a narrow temperature range of 21 °C.
Bio-oil from the pyrolysis of palm and jatropha waste in a fluidized bed [72].	Kim, S.W.	The pyrolysis of palm kernel shells (PKS) was valorized to produce bio-fuel in the study conducted by Sung Won Kim; the study was carried out in an optimized laboratory bed reactor: The maximum yield given in this reaction for palm kernel shell is 48% at 470 °C [72].
A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil [73].	Abnisa, F. et al.	Faisal Abnisa et al. [73] showed in their paper "A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil" the possibility of mixing between palm shells and polystyrene waste to increase the rate of liquid pyrolysis, which could be used as a fuel, so they showed that high liquid yields were obtained in the temperature range of 400 to 700 °C with palm shell/polystyrene ratios of 40: 60 and reaction times of 15–45 min. The characterization results studied in this paper demonstrated that the heating value of the liquid of 40.34 MJ/kg was obtained with a water content of 1.9% by weight and oxygen content of 4.24% by weight. The liquid consisted mainly of aromatics, hydrocarbons, and aliphatics.
Valorization of pruning biomass of date palm (*Phoenix dactylifera* L.) by co-composting with urban and agri-food sludge [74].	Vico, A. et al.	This paper describes a study to assess the recovery potential of date palm pruning residues using the technique of co-composting with municipal and agri-food sludge. The technique of co-composting is a method of treating organic waste to produce a nutrient-rich, environmentally beneficial soil amendment [74]. The results of the study used different proportions of date palm prunings, urban sludge and agri-food sludge. Phase II tested the physico-chemical characteristics of the compost produced to determine its quality and ability to supply nutrients to plants. The results demonstrate that the co-composting of palm pruning residues with municipal and agri-food sludge was effective in producing quality composts. Analysis revealed high organic material and high organic carbon levels in the resultant compost and nutrient (nitrogen, phosphorus, potassium) [74] In parallel, compost made from this mix of residues exhibited favorable physical properties, with good texture and water-holding capacity [74]. The authors also tested the impact of compost application on plant growth using field trials. The results demonstrated that the utilization of the compost improved plant growth, increased soil nutrient content and reduced nutrient loss through leaching [74]. This study demonstrated the efficacy of co-composting date palm pruning with urban and agri-food processing sludge as a method of valorizing agricultural waste. The compost generated has chemical and physical parameters beneficial for the improvement in soil fertility and plant growth. It also contributes to sustainable organic waste treatment by converting it to a useful product for agriculture [74].

Table 4. *Cont.*

Subject	Author	Summary
Waste biorefinery in arid/semi-arid regions [75].	Bastidas-Oyanedel, J.R. et al.	The paper "Waste biorefinery in arid/semi-arid regions" by Juan-Rodrigo Bastidas-Oyanedel, Chuanji Fang, Saleha Almardeai, Usama Javid, Ahasa Yousuf and Jens Ejbye Schmidt examines waste biorefinery in arid and semi-arid regions [75]. In such regions, the management of waste poses a challenging task, due to constraints linked to the limited availability of raw materials and water resources. This study shows the importance of waste biorefinery as a sustainable approach to produce value-added products and valorize waste. It examines the various forms of waste available in these regions, such as food waste, agricultural waste and wastewater. They point out the biological conversion technologies that can be used to process these wastes to produce biobased chemicals, biofuels and fertilizers [75]. The benefits of waste biorefineries in limiting greenhouse gas emissions, minimizing dependence on outside resources and creating new economic opportunities are also presented [75].
Pyrolysis and combustion kinetics of date palm biomass thermogravimetric analysis [76].	Sait, H.H. et al.	The authors used date palm kernels to produce bio-oil and activated carbon in a fixed bed reactor using the fast pyrolysis technique, so they provided some information on the use of date palm biomass as a source of energy or fuel [76].

4.2. Technology Watch on the Production of Biofuel from Date Palms Using Fast Pyrolysis Technology

To construct a global perception of the fast pyrolysis of biomass, we conducted research ont the patents registered in this field.

The following table (Table 5) gathers the patents with the process used and the classification of the fast biomass pyrolysis: Y02E50/10 biofuels, e.g., bio-diesel, C10B, biomass (fast or fast) pyrolysis in titles, abstracts, the objective of the invention, palm in titles, abstracts, the objective of the invention, claims and three patents have been filed in the field of biomass pyrolysis.

Table 5. Recent patents on fast pyrolysis of biomass.

Patents Number	Title	Current Assignees	Process Description
EP3388498A1 [77].	Method for producing bio-oil using torrefaction and fast pyrolysis process.	Univ industry foundation yonsei univ wonju campus	The present invention relates to a method of producing a bio-oil, in which torrefaction and fast pyrolysis processes are used, which includes (a) introducing a target raw material into a torrefaction apparatus and torrefying the target raw material; (b) pulverizing the torrefied raw material in a sample pulverizer; (c) quickly pyrolyzing the pulverized and torrefied raw material in a circulating fluidized bed reactor; and (d) condensing a gas obtained by the Fast pyrolysis to obtain a bio-oil, and by which a bio-oil with a low moisture content rate and a high heating value is finally produced. In an exemplary embodiment, the produced bio-oil according to the method has a moisture content rate of 20% by weight or less. Thus, torrefraction is an alternative and promising approach produce high-quality bio-oil. This invention has been filed as a PCT international application and is in force in Europe and Korea.

Table 5. *Cont.*

Patents Number	Title	Current Assignees	Process Description
WO2017201598A1 [78].	Integrated process for the pre-treatment of biomass and production of bio-oil	FIBRIA CELULOSE SA	The present invention is aimed at providing an integrated process for the pre-treatment of biomass and to the use of biomass as the raw material in a process for producing biochemicals and bio-fuels, with the present integrated method preferably allowing the production of high-quality bio-oil from biomass such as wood, forestry waste, waste from the sugar and alcohol industries, and energy cane. This invention mentions that many studies in the literature proposed pretreatment steps using acids and bases as well as mechanical fractionation of the material. But these techniques require a high quantity of chemical inputs and considerable investment in equipment. This invention suggests an integrated process for the pretreatment of high-impurity biomass for the production of high-quality raw material using low-cost solvents and/or effluents discarded in existing plants. This invention has been filed as a PCT (Patent Cooperation Treaty) international application and is legally in force in many countries (Australia, South Africa, Brazil).
WO2022063926A2 [79]	SYSTEMS AND METHODS FOR RENEWABLE FUEL	ABUNDIA BIOMASS TO LIQUIDS LTD	The present application generally relates to the introduction of a renewable fuel oil as a feedstock into refinery systems or field upgrading equipment. For example, the present application is directed at methods of introducing a liquid thermally produced from biomass into a petroleum conversion unit (for example, a refinery fluid catalytic cracker (FCC), a coker, a field upgrader system, a hydrocracker, and/or a hydrotreating unit) for co-processing with petroleum fractions, petroleum fraction reactants, and/or petroleum fraction feedstocks and the products, e.g., fuels, and the uses and value of the products resulting therefrom.
WO2013090229A2 [80].	SYSTEMS AND METHODS FOR RENEWABLE FUEL	Ensyn Renewables, Inc.	The present application generally relates to the introduction of a renewable fuel oil as a feedstock into refinery systems or field upgrading equipment. For example, the present application is directed at methods of introducing a liquid thermally produced from biomass into a petroleum conversion unit (for example, a refinery fluid catalytic cracker (FCC), a coker, a field upgrader system, a hydrocracker, and/or a hydrotreating unit) for co-processing with petroleum fractions, petroleum fraction reactants, and/or petroleum fraction feedstocks and the products, e.g., fuels, and the uses and value of the products resulting therefrom.

This literature study allowed us to develop a better understanding of this subject, in particular, to determine the parameters of fast pyrolysis which influence the yield of bio-oil, which include temperature, residence time, pressure and the size of the studied particles. The literature describes several scenarios by varying these parameters. The best yields obtained vary between 70% and 80%. The table below (Table 6) shows the articles where the yield is high.

Table 6. High yield research articles.

Item	Technology	Temperature °C	Residence Time	Yield
Pyrolysis of date palm waste in a fixed bed reactor: characterization of the pyrolysis of the products [64].	Fast pyrolysis of date palm waste using a fixed bed reactor	500 °C	15 °C/min	25.99% by weight
Valorization of date palm (*Phoenix dactylifera* L.) pruning biomass by co-composting with urban and agri-food sludge [74].	Composting technology	47 °C	30 days	0.52 à 0.87% by weight
Pyrolysis and combustion kinetics of date palm biomass using Thermogravimetric. Analysis [76].	Fast pyrolysis of date palms such as seeds, leaves and leaf stems	400 °C	20 °C/min	40% by weight

5. Conclusions

This review consists of recovering date palm waste through the process of fast pyrolysis to improve the liquid yield produced using this technology. There are several technologies that can be used to produce biogas: combustion, gasification, and pyrolysis.

According to a technology watch on biomass patents, there are 1296 patent families and 2210 articles on the subject of fast biomass pyrolysis of palm residues. Fast pyrolysis of date palms represents one of the most innovative and promising methods for biofuel production. Several experiments have shown that this technique provides a high yield of biofuel from date palm residues, which are considered an abundant and renewable source of biomass. However, it is important to take into account several parameters that have a direct influence on biofuel yield and the refining process. The chemical composition of date palm residues plays an important role in biofuel yield.

As explained in the article, the efficiency and yield of biofuel produced via fast pyrolysis depend on several key parameters, such as temperature, which directly influences the yield and quality of the biofuel produced. High temperatures can increase gas production, while low temperatures can favor biochar production. It is therefore important to strike a balance between these two aspects to maximize biofuel production while minimizing the formation of undesirable by-products. This process stabilizes the product, eliminates impurities and adjusts its properties to meet market requirements and standards. Various refining techniques can be used to purify and improve biofuel quality and performance, such as hydrogenation, distillation and deoxygenation.

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