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TECHNICAL ASSESSMENT OF BIO-OIL PRODUCTION THROUGH THE PYROLYSIS OF EMPTY PALM FRUIT BUNCHES – A REVIEW

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ABSTRACT

Growing global demand for clean energy has led to converting empty palm fruit bunch into compressed fuel, a significant source of renewable fuels and chemicals. Lignocellulosic biomass is a cost-effective and environmentally friendly alternative to fossil fuels. Despite its longer processing and use process, it provides a clean, sustainable energy source that can effectively compete with fossil fuels. Biomass is inexhaustible, renewable, low in sulfur and nitrogen, environmentally friendly and sustainable, and offers significant benefits for energy production. In addition, biomass energy is a sustainable alternative to fossil fuels and reduces greenhouse gas emissions. Unlike traditional biochemical methods, the thermochemical process is more convenient and efficient, converting biomass into products. Fast pyrolysis is the most economical technology for converting biomass into transportation fuel and producing bio-oil and other energy products. Empty palm fruit bunch, a palm oil industrial waste, offers a sustainable energy future. This study attempts to review the numerous developments and studies focusing on biomass pyrolysis in the pyrolytic utilization of empty palm fruit bunch biomass for low-cost bio-oil production to reduce environmental pollution and dependence on fossil fuels. The paper also included a detailed description of pyrolysis reactors. The current status of pyrolysis methods and technical obstacles in converting EPFB biomass into bio-oil, biogas, and biochar.

Keywords: Biomass, Fossil Fuel, Empty Fruit Bunch, Bio-oil, and Phenol.

1. Introduction

Lignocellulosic biomass has become a popular source of renewable energy because of its full accessibility and diversity [1]. According to Mutjtaba et al. [1], by 2040, global energy utilization is expected to expand by 48 % and reach 8.44 x 10^{14} MJ. With the decline in crude oil production, it has become essential to find new ways to produce fuels and chemicals while reducing greenhouse gas, CO_2, and CH_4 emissions. In addition, according to Jens et al. [2], the current bioenergy capacity of the various usable biomass available worldwide must be used efficiently to achieve the global targets for renewable energies. The processing of biofuels from lignocellulosic biomass has become the worldwide trend of renewable energy generation. Biomass, therefore, remains the only renewable energy source and the only option easily integrated into the biofuel industry [3]. Several researchers reviewed the fossilization of terrestrial and marine biomasses, whereby biomass is viewed as a locally liquefied and concentrated source.

Fast pyrolysis of biomass for liquid fuel was developed in North America and has made significant advances since then [4]. The pyrolysis production platform’s basic processes are being resolved due to a lack of understanding, limiting its capabilities as a cutting-edge thermochemical conversion technique. [4]. Biomass pyrolysis produces solid biochar, liquid bio-oil, and non-condensable gas from waste and biomass sources, with a 65-75% yield depending on the process conditions [5]. Pyrolysis is a crucial method for generating liquid fuel from biomass, as it eliminates the need for pre-treatment, offering a significant advantage over enzymatic conversion [6]. Pyrolysis produces bio-oil, which includes chemicals like organic acids, alcohols, esters, guaiacol, and alkanes, used in the resin industry for industrial purposes. [7]. Many bio-oil components are primarily responsible for the undesirable constituents of the oil [8]. Terry et al. [9] demonstrated that the success of a bio-oil generation process relies on its exploration as a high-quality raw material. Other researchers, such as Machado et al. [10], have established that bio-oil can be utilized as a raw material for a wide range of petrochemical products, including aromatic hydrocarbons (benzene, toluene, and xylene), which makes chemical production from bio-oil an appealing option. Interest in bio-oil generation from EPFB is growing, and steps are being taken towards a sustainable biofuel future. Numerous reports on the pyrolysis conversion of EPFB biomass to bio-oil have been published, and the thermochemical conversion has been successfully carried out in fixed beds and other reactors [7]. Bio-oil, a mixture of beneficial compounds, requires extraction using solvents. Phenol is a common by-product used as a fuel additive and food antioxidant. Due to additional processing steps, biofuel production from lignocellulosic biomass differs from conventional ethanol. However, high moisture content and low energy density increase transportation and handling costs. Heat-based biomass breakdown could solve these issues. Optimal parameters for pyrolysis remain a processing problem due to source-dependent properties [10]. Aqueous pre-treatments could be explored before pyrolysis to selectively reduce the ash content of the EPFB biomass [11, 12] Many reactors, including fluidized beds, are regularly used in pyrolysis reaction systems. Fluidized bed reactors have several advantages over other reactor types. These include a uniform particle-liquid mixture with excellent heat and mass transfer, the lack of moving parts, operational continuity, and improved heat and mass transfer [13]. Khatibi et al. [14], employed a fluidized bed reactor to generate bio-oil from a bunch of empty palm fruit and reported the highest yields at 42 % and 63.9 % by weight, respectively.

In a similar study, Park et al. [11], obtained bio-oil and a calorific figure of 21.41 MJ kg-1 by pyrolysis of empty palm fruit bunches at 500°C, a nominal heating rate of 100°C min^{-1}, with a particle size range of 91-106µm in a fixed bed reactor. Lachos-Perez et al. [15], researched the fast pyrolysis of various lignocellulosic biomass in an externally heated fixed-bed reactor for bio-oil production. While conducting pilot-scale demonstrations, Kunia et al. [16] discovered that the pyrolytic yield of bio-oil and other desirable products relies on process operating parameters and biomass properties. Temperature, heating rates, nitrogen flow rates, and particle sizes all impacted bio-oil yields from soybean biomass and olive oil residue, according to Lachos-Perez et al. [15]. Other researchers, such as Osman et al. [17], examined the effect of process parameters on the production of bio-oil produced from rapeseed in a free-fall reactor under static atmospheric pressure.

2. The global trend in bio-fuel development

Energy resources are central to the sustainability of development and technological advancement of any nation [18]. Malaysia and Indonesia are exploring biomass pyrolysis to reduce dependence on fossil fuels, focusing on energy and ecological benefits. Concerns about traditional fossil fuel use are driving interest in clean, sustainable energy from agricultural residues [1]. Biomass-derived energy is environmentally friendly because it emits fewer greenhouse gases, but it has a drawback in such a way that it releases combustion products into the atmosphere [19, 18].

Biomass currently provides at least 14% of primary energy, but mostly from cellulosic starch sources, which harms food supply sources [20] Numerous studies are ongoing worldwide into the feasibility of converting EPFB and other agricultural biomass into bioenergy [21] Ndukwu et al. [22], reported in a review article on more than a hundred types of biomass whose pyrolysis behavior has been studied. Empty Palm Fruit Bunch (EPFB), a non-woody biomass and notable waste product of the palm oil processing industry that is usually disposed of because of the high water content and inability to be used as boiler fuel, and can be improved to value-adding fuels and renewable chemicals with a fast pyrolysis process [23] EPFB, a common feedstock for pyrolysis, is a clean and sustainable bioenergy source despite technological challenges in converting biomass into liquid fuel [16]. Commercialization of lignocellulosic biomass as an energy source is positive, with starting materials like oil palm wastes, palm husks, MF, and PKS suitable for optimal pyrolysis results.

3. The palm oil industry

The palm oil sector is growing due to increased consumer demand for food, cosmetics, and hygiene products, and it is a significant agricultural industry in developing countries [16]. Palm oil has been rated the second global leading source of vegetable oil products, after soybean oil, in global production [23]. The processing of fresh palm oil fruit bundles (PFFB) creates significant waste, including empty palm fruit bundles (EPFB) and other solid residues. This waste can be used as fuel and in different energy generation systems through several energy conversion processes, such as thermal and thermochemical [24]. Ash, biochar, and compost are other by-products of processing fresh palm fruits [25] Nigeria, Indonesia, Thailand, Colombia, and Malaysia are the leading palm oil producers, accounting for more than 92 % of global production [26] Empty palm fruit bunches are high in energy and, if properly processed, can produce biofuel. The optimal use of energy and other valuable materials would be ensured by using the biomass obtained from the palm oil tree.

4. Empty palm fruit bunch as a biomass feedstock

Empty Palm Fruit Bunch (EPFB) is a non-woody biomass from palm oil processing, rich in cellulose, lignin, and hemicellulose, offering the potential for agricultural waste conversion into energy recovery [5]. It is a popular starting material for the pyrolysis process. EPFB is also rich in phenol and other phenolic compounds [16]. Empty palm fruit bunch (Plate 1) and other palm-derived biomasses have been explored for bio-oil generation. EPFB biomass is a well-known energy source with a high moisture content of around 65 %, resulting in a low calorific value. Although EPFB biomass is often disposed of as waste, it is a viable choice for conversion to biofuel. Fast pyrolysis, a thermochemical conversion process, can optimize the biofuel capacity of EPFB waste by burning palm biomass at 500°C for 1 second, resulting in 75% bio-oil. Palm oil biomass holds significant potential as a renewable energy source, with numerous pilot and commercial-scale energy systems being tested [6]. EPFB biomass raw material, with its compositions, moisture content, and higher calorific value before pyrolysis, is used as valuable fuels and chemical raw materials. [27].

Plate 1: Showing oil palm tree, shredded oil palm EPFB, and whole EPFB

5. Composition of oil palm EPFB Biomass

Biomass is a biodegradable hydrocarbon consisting primarily of carbon, hydrogen, oxygen, and nitrogen. Biomass from oil palm comprises cellulose, hemicellulose, lignin, and several forms of compounds [28, 29]. The composition of oil palm waste biomass varies, with hemicellulose, a mixture of polymerized monosaccharides and galacturonic acid residues, making up 12-33% of the mass and serving as the cement for cellulose micelles and fibers, and lignin, an aromatic polymer with various functional groups [30].

The lignin content in palm oil empty fruit bunch biomass varies between 7.79 and 37%, despite variations in cellulose, hemicelluloses, and lignin content depending on the source of EPFB raw material [31]. When determining the amount of biomass required to make bio-oil or other essential chemicals, the total amount of each component in the EPFB biomass is critical [25]. Bio-oil is primarily extracted from cellulose and hemicellulose components of biomass, while biochar is extracted mainly from the lignin component, exhibiting an elementary structure similar to lignin. [9]. Table 1 provides a comprehensive overview of the fundamental elements of the biomass derived from the palm oil tree, as per the literature.

Table 1: Composition of Biomass-derived from oil palm tree

Fibre	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)	References
EPFB	43-65	17-33	13-37	1-6	
EPFB	13.75 – 59.70	12.79 – 22.10	7.79 – 30.45	3.45 - 7.54	[31, 32]
Mesocarpfibre (MF)	40	20	30	1 - 11.8	[32]
PKS	27.7	21.6	44	0.87 - 4.6	[33]

6. Analysis and heating values of palm fruit residues

Biomass is the only renewable energy source that can be converted into liquid fuel, with palm biomass's diverse composition affecting conversion technology. Bio-oil's physical and chemical characteristics, including moisture, ash content, volatiles, and bound carbon, can be improved by selectively extracting inhibitory minerals before pyrolysis. Table 2 summarizes literature values and calorific values for palm remains. Table 2 shows that palm tree volatile and solid carbon content don't significantly differ, but moisture and ash content do. EPFB contains high ash, leading to harmful NOx emissions and environmental issues. Studies show that biomass ash percentage significantly impacts bio-oil yield, with homogeneous bio-oil attainable when EPFB ash content is less than 3 mf wt%, indicating the importance of biomass ash percentage. According to Awoh et al. [23], The maximum bio-oil yield achieved by washing EPFB is 72 mf wt% with an ash content of 1 mf wt%.

Table 2: Proximate and ultimate analysis of heating values of palm tree residues from literature

Analysis	**Empty Palm fruit bunch (EPFB)**	**Mesocarpfibre (MF)**	**Palm kernel shell (PKS)**	**Fresh fruit bunch (FFB)**
	Reference	**Reference**	**Reference**	**Reference**
	[33]	[32]	[33]	
Proximate				
Volatile matter	67.59 –83.86	67 – 79	53.38 – 77.5	78.7
Fixed carbon	8.36 – 21.80	9.3 – 28	18.84 – 20.3	15.44
Moisture content	5.18 – 8.31	4.98 – 5	8.4 – 9.55	7.38
Ash	3.45 - 7.54	1 - 11.8	0.87 -4.6	4.64
Ultimate				
Carbon	43.52 – 49.07	30.02 - 52.2	43.8– 60.9	51.78
Hydrogen	5.72 - 6.48	3.81 – 11	5.27 – 12.76	7.01
Nitrogen	0.25 – 1.65	0.7 – 1	0.36 – 0.66	0.72
Sulphur	0.04 - 1.06	0.07 – 1	0.03 – 0.19	0.1
Oxygen	38.29 – 48.9	23.35 – 42	31.18 - 37.7	40.31
Chlorine		0.06	0.05	
HHV (kJ/kg)	15220 – 19350	19331 - 21980	17930 – 20520	18740
Bulk density (kg/m^3)	110 – 144	225	715 - 780	

7. Bioenergy from the empty fruit bunch (EPFB)

The increasing demand for alternative energy sources, such as biofuel, is prompting the exploration of biomass conversion. EPFB, a waste biomass from the palm oil industry, produces bioethanol, biodiesel, and bio-oil. Bioethanol is produced through pre-treatment, saccharification, and fermentation, while biodiesel is produced through recovery. Bio-oil offers environmental benefits like carbon neutrality and low NOx emissions [30] EPFB, with higher moisture and ash content, has been studied for bioenergy conversion. The pyrolysis method is promising, but the high ash percentage produces poor output. Optimized fast pyrolysis can increase bio-oil yield by up to 80% [29] The pyrolysis products (bio-oil, fuel gas, and char) are distributed according to the process operating conditions [34, 35]. Most researchers used fixed or fluidized bed reactors, and it was discovered that the highest output of bio-oil occurs at temperatures around 500 ° C with a yield of around 20 MJ/L [14]. Also, according to research, most pyrolysis occurs in a fixed bed reactor at temperatures between 450°C and 600°C. Fixed bed reactors are more efficient at pyrolysis than other reactor designs because of their ideal plug flow behavior, lower maintenance costs, and fewer losses from abrasion and wear [29]. Bio-oil, derived from biomass building blocks, is thermally unstable, polar, acidic, and high in oxygen, making it difficult to separate from pyrolysis-produced water and other raw materials. [7]. The pyrolyzed liquids extracted from EPFB are split into two phases, about 60% organic and 40% aqueous, which makes commercial use as fuel very unlikely [23]. The reactor’s parameters can be adjusted to increase biochar and biogas yield, which are pyrolytic products with high heating values and potential as fossil fuel replacements. They can be used directly in boilers, furnaces, diesel engines, and turbines.

8. Pyrolysis as a core technology in bio-oil production

Thermochemical methods are commonly employed to convert biomass into high-quality biofuels like biochar, bio-oil, and gaseous and volatile components, which can be burned as fuel or directly converted [36]. The literature on thermochemical biomass reuse is extensive, covering biomass pyrolysis and catalytic processing of bio-oil [30]. The global interest in the pyrolysis of EPFB biomass to produce bio-oil has led to further research into the process [2]. Pyrolysis, a cost-effective and environmentally friendly method for producing bio-oil from EPFB, involves heating biomass feedstock and condensing vapor, enhancing bio-oil output. [30]. Current FCC settings and catalysts do not significantly lower bio-oil oxygen concentration, making deoxygenation reactions nearly impossible.

The pyrolysis system is cost-effective when run on a small scale. Standard criteria can make it challenging to compare test methods. High heating rates and short reactor duration are believed to result in the highest bio-oil output.

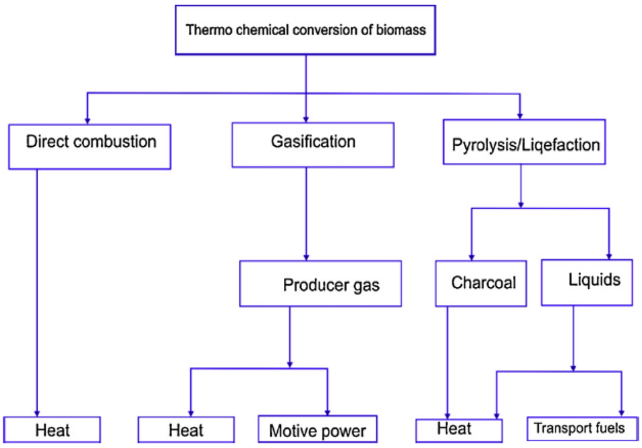

Figure 1: Thermochemical conversion route

9. The fast pyrolysis process

Lignocellulosic biomass is heated to 300-600°C, forming solid, liquid, and gaseous products from cellulose, hemicellulose, and lignin. Advanced thermal processing techniques have been developed for the pyrolysis of woody biomasses, optimizing organic vapours for oxygenated liquid products. Pyrolysis techniques are used fast. Heating rates, high-temperature heat sources, and short residence times to convert biomass into vaporized organic products [29]. Pyrolysis is a thermal decomposition method that converts solid biomass into liquid bio-oil, a transportation fuel. It increases energy density through deoxygenation and forms char. The gasses are purified and stabilized, making them suitable for storage, refining, and end-use.

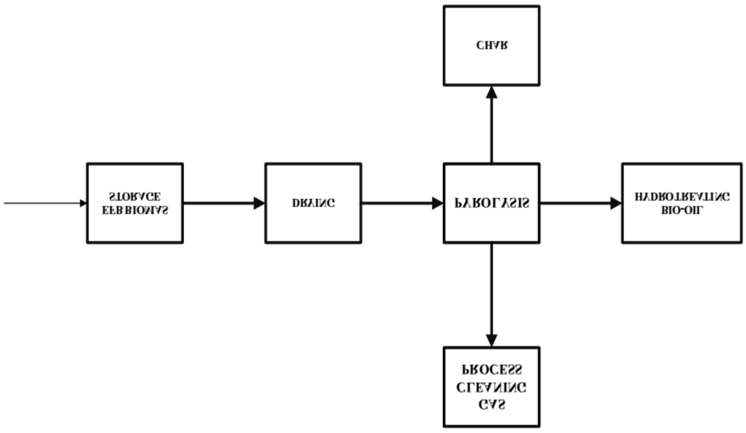

Figure 2: Sequence of the bio-oil production process for EPFB biomass

9.1. Four stages of pyrolysis

To reduce the moisture composition of the biomass material by a few percent and to lower the quantity of water in the fast pyrolysis liquid product, the biomass feed is dried. It is then pulverized to the particle size of about 2-6 mm to produce small particles for the pyrolysis reactor to react quickly. The biomass is pre-dried in a cross-flow of hot, dry air in the feeder. The biomass is pre-charged and preheated in the pyrolysis reactor and goes through the following processes:

9.2. Moisture Evaporation process

Before the decarbonization process begins, all moisture accumulated in the biomass must be removed. Depending on the form of biomass and the amount of moisture in the process material, the process can take several seconds. The high temperature that has been accumulated in the upper part of the reactor also helps to improve the dehumidification quality.

9.3. The degasification process

At this point, the biomass is degassed at 390 - 400 °C, which is most effective for the extraction of volatile substances. Chemicals such as CO_2, H_2, N_2, and others are flammable, and the pyrolysis process consumes around 40% of the energy utilized. The residual gas can be used for energy after merging with the hot air from the preceding phase.

9.4. The decarbonization processes

First, the biomass was degassed and exposed to a high temperature. The high-temperature treatment of dried and degassed biomass leads to a quick concentration of elemental carbon and eliminates the fibrous structure, increasing the grindability. The calorific value of the material varies from 21-29 mJ/kg, subject to the reactor’s temperature and the decarbonization process’s length.

10. Classification of the pyrolysis process

Pyrolysis is divided into flash, fast, and slow groups based on end product and operating conditions, with product yield influenced by feedstock and process conditions. The most popular method is fast pyrolysis, which uses high temperatures in an inert atmosphere to break down organic biomass in the non-inclusion of oxygen to generate char, bio-oil, and gases as products [37] Adjusting the process parameters changes the proportion of these products. The compound makeup of the starting material, the solids residence time, the biomass particle size, the heating rate, and the operating temperature all influence the ranking. Fast pyrolysis regulates fractionated product yield by heating rate and gas retention period, while slow pyrolysis produces significant carbon yields at lower temperatures and longer vapor retention durations. [38].

10.1. Slow pyrolysis.

The traditional charcoal furnace process for producing char from biomass at poor temperatures and low heating rates is slow pyrolysis. With slow pyrolysis, the operating temperature is usually between 550 and 950 K, with a long vapor retention time. The long residence time of the slow pyrolysis reaction often leads to the cracking of the primary product, which has a significant contribution to bio-oil yield and efficiency and excessive energy consumption [39].

10.2. Fast pyrolysis

High temperatures allow biomass to break down into vapors, aerosols, and some charcoal, and the fabric has properties that affect its use, such as: Compared to other biomass conversion processes, the rapid pyrolysis process offers significant economic and processing advantages. Rapid heating, short vapor residence times, and relatively high temperatures in the 400-650 ° C range are used to achieve fast pyrolysis and rapid quenching of the vapor generated. Fast pyrolysis additionally necessitates a biomass source that has been finely ground, a temperature-controlled pyrolysis reaction, a short vapor residence duration to limit secondary reactions, and rapid cooling of the pyrolysis vapors to extract the bio-oil product [4]. The final liquid, varying based on the feedstock, consists of 60-75% bio-oil, 15-25% solid coal, 10-20% non-condensable gases, and a homogeneous hydrophilic mixture of polar organic molecules and water [9].

10.3. Flash pyrolysis.

Flash pyrolysis produces bio-oil from biomass, yielding up to 70% due to rapid degassing, high particle heating rate, high temperatures, and a short gas retention period.

The technique involves rapid degassing in an inert atmosphere, a high particle heating rate, high reaction temperatures, and a short gas retention period [39]. The flash pyrolysis temperature ranges from 777 ^{o}C to 1027 ^{o}C. Aboelela et al. [37] found that the bio-oil produced has significant drawbacks, such as pyrolytic water, poor thermal stability, and corrosive properties.

11. Pyrolysis Reactors

Pyrolysis reactors, accounting for 10-15% of integrated pyrolysis system costs, are crucial for bio-oil production from EPFB biomass, with reactor layout influencing product distribution [40]. It is critical to design a liquid reactor system that allows quick heating, considerable temperatures, and short vapour and material residence periods [4]. Significant efforts have been made over the years to develop and evaluate various reactor systems for the pyrolysis of lignocellulosic biomass. Various reactor configurations were assessed on a variety of feedstocks, including EPFB. The reactors evaluated fall into four categories: slow, moderate, fast, and microwave pyrolysis reactors. They all share a typical design and use complementary technologies [41]. Fast pyrolysis reactors process small particles to expand the bio-oil yield and other products, while slow pyrolysis reactors produce char from larger biomass. Intermediate pyrolysis reactors may be required to create char and bio-oil on a large scale from EPFB and other agricultural wastes without pre-treatment. For modular small autonomous devices, microwave pyrolysis is a waste management and power-generating solution. Pyrolysis reaction time and energy consumption are reduced with microwave-based technology, while the quality of value-added products created from various types of raw materials improves. Most reactor configurations obtain a liquid product yield of roughly 70-80 %, based on the dry matter biomass’s original weight [30]. Much research is underway to improve and expand pyrolysis reactors to increase heating rates and reduce energy consumption for a higher product yield. According to Vamshi & Qi [40], the critical properties of a fast pyrolysis reactor include a rapid rate of heat transmission, a moderate temperature that is accurately controlled, a short steam residence period, and quick quenching of the pyrolysis vapors, and at the same time being easy to operate and scale-up. Several reactor configurations have been devised to meet the severe pyrolysis criteria, [30]. Several authors have reviewed fluidized bed pyrolysis reactors [9], transported and circulating fluidized-bed reactors [42], ablative reactors, rotating cone reactors, and vacuum reactors [42], as well as bubbling fluidized beds [9].

Various technologies have been used to demonstrate the pyrolysis of EPFB biomass, including slow heating under vacuum [9], quartz fluidized fixed bed reactor [14], entrained coiled tube reactor [43], stainless steel fixed bed reactor under atmospheric pressure [27], entrained ablative vortex reactors. Vamshi and Qi [40] categorized and discussed the diverse forms of reactors utilized in the fast pyrolysis of empty palm fruit bunch biomass materials. Table 4 summarizes and discusses the characteristics of various reactor types and their complexity and status.

11.1. Fluid bed reactors

A fluidized bed reactor is a continuous flow reactor that keeps the reaction system at an almost constant temperature. It has been modified for EPFB pyrolysis and is widely utilized in the chemical sector. Due to the simplicity of use and easy scale-up, fluidized bed reactors are the most often utilized reactor configuration.

They're made to boost the amount of bio-oil produced. Because biomass particles have a low thermal conductivity, significant heat transmission between gas and solid is obtained by making them exceedingly thin. Fluidized bed reactors are more efficient than other reactor designs for continuous bio-oil production and have higher overall reaction effectiveness factors than other reactors. They are widely used in solid-liquid reaction schemes. They have several advantages, including a uniform particle-liquid mixture with superior heat and material transport, continuous operation without moving parts, and increased reaction speeds due to improved heat and material transport.

11.2. Circulating fluid beds and transported beds

Circulating fluidized bed reactors use risers and downcombers to circulate solid particles, similar to crude oil refinery systems. Developed for coal combustion, CFB technology reduces pollutant emissions. The technology of CFB reactors is well understood. They are designed to use larger particles, have high throughput, and have excellent temperature control. CFB reactors, on the other hand, use a lot of inert carrier gases, which dilute the pyrolytic gases and make bio-oil recovery impossible [41]. CFBs start the pyrolysis reaction in one fluidized bed unit, then transfer the produced coal into the second fluidized bed unit, which is burned in the inorganic heat carrier, providing heat that meets most of the energy requirements in the first unit. When the heat carrier is inorganic and contains catalytic qualities that allow the carbon to attach to its surface and react effectively, CFBs are helpful. The weight yields of bio-oil from a circulating fluidized bed are predicted to be 54 to 71 % [41].

11.3. Bubbling fluid beds

The bubbling fluidized bed reactor utilizes low-velocity gas, minimal fluidization, and high particle density for temperature control and effective heat transfer. [44]. The particle size of the heat source (hot sand) should be less than 2mm to generate a high heat transfer rate, and the heat should travel to the substrate by convection and conduction. The bubbling fluidized bed reactor, used for coal gasification, utilizes an inert medium like sand or a catalyst material like CaO, enhancing heat transfer between solids and gases [45].

11.4. Rotating cone

Biomass pyrolysis is a process in a spinning cone reactor where biomass particles are conveyed into a heated cone. The char is oxidized in a char burner, and the reaction occurs when the particulate heat transfer medium and biomass contact the cone.

11.5. Ablative pyrolysis

The ablative reactor is a small and effective reactor system that uses heat transmission from the hot reactor wall to liquefied biomass particles being exposed under pressure, with the residual oil evaporating [4]. In contrast to fluidized bed reactors, heat is transported through a molten layer on the heated reactor surface, which eliminates the need for a carrier gas [9]. The quantity of heat provided to the reactor limits the rate of pyrolysis. Placing small biomass particles on a large heat transfer surface optimizes heat transfer because the ablative reactor is a surface-controlled device. The heat transfer through the biomass particles in ablative reactors does not limit the reaction rates, allowing for the use of bigger particles. In ablative reactors, the heat transfer through the biomass particles does not limit the reaction rates, allowing larger particles to be used. The rotating disk and the ablative vortex are two common forms of ablative reactors. Fixed bed fast pyrolysis The disadvantage of fixed bed rapid pyrolysis is its batch inefficiency. However, it meets the basic requirements of rapid pyrolysis and is efficient and helpful in making biomass feed with constant particle size and low ash content. This system consists of a reactor and a fixed bed of pyrolyzed feedstock [40]. While fixed bed reactors and associated systems are unlikely to produce large amounts of liquid, they often produce phase-separated liquids. The solids are heated from the outside and fall a vertical shaft, colliding with a countercurrent upward flow of product gas.

11.6. Fixed bed fast pyrolysis

The disadvantage of fixed bed rapid pyrolysis is its batch inefficiency. However, it meets the basic requirements of fast pyrolysis and is efficient and helpful in making biomass feed with constant particle size and low ash content [78]. This system consists of a reactor and a fixed bed of pyrolyzed feedstock [73]. While fixed bed reactors and associated systems are unlikely to produce large amounts of liquid, they often produce phase-separated liquids [81]. The solids are heated from the outside and fall a vertical shaft, colliding with a countercurrent upward flow of product gas.

11.7. PyRos Reactor technology

PyRos reactors use a flash pyrolysis method to generate a solid-free, reasonable-quality bio-oil from various biomasses. The pyrolysis reaction occurs in a cyclone, and a revolving particle separator extracts the steam. Centrifugal force is then used to separate the coal in the hurricane [40].

11.8. Microwave pyrolysis.

Pyrolysis is a traditional biomass heating process using external heat to produce char, oil, and gas in an oxygen-free environment, while microwave pyrolysis uses microwave radiation. As some primary research has revealed, microwave heating differs fundamentally from all other pyrolysis procedures. It heats the biomass particles from the inside rather than the exterior by transferring heat from a high-temperature source. A relatively new thermochemical technology and still in its infancy, but it offers many advantages over conventional pyrolysis. Microwave pyrolysis of biomass is a method that aids in energy recovery, waste management, and conversion of biomass into usable energy products while reducing reaction time. The feed is mixed with a microwave-adsorbent material like carbon, which absorbs the microwave energy, enhancing the processing of wet biomass. Microwave pyrolysis of biomass produces a low liquid yield of around 30%. Still, it is relatively free of entrained material due to the lack of carrier gas, agitation, and fluidization, making the process much cleaner and more controllable. Many investigations on microwave pyrolysis of biomass have been conducted with a variety of raw materials, including wood Shvet et al. [46], corn stover [47], rice straw [48], oil palm biomass [49] and oil palm empty fruit bunches [50]. These studies compared microwave pyrolysis to conventional pyrolysis and found significant differences in the purity of the bio-oil generated between the two techniques.

Table 3: Overview of Fast Pyrolysis Reactor Characteristics and Status for Bio-oil Production

Reactor Type	Status	Bio-oil yield	Complexity	Feed size specification	Inert gas requirements	Specific reactor size	Scale-up	Gas quality
Fluid bed	Commercial	75 wt %	M	H	H	M	E	L
CFB and Transported bed	Commercial	75 wt%	H	H	H	M	E	L

Rotating Cone	Demonstration	70 wt%	H	H	L	L	M	H
Ablative	Laboratory	75 wt%	H	L	L	L	D	H
Screw or Auger	Pilot	65 wt%	M	M	L	L	M	H
Entrained flow	Laboratory	60 wt%	M	H	H	E	E	L
Vacuum	None	60 wt%	H	L	L	H	D	M

Where M represents Medium, H represents High, L represents Low, E represents Easy, and D represents Difficult.

Adapted from Vamshi & Qi [73]

12. Pyrolysis Products

Pyrolysis of lignocellulosic biomass, including EPFB, produces biogas, biochar, and bio-oil, the composition and distribution of which are determined by starting material constituents, moisture content, and pyrolysis process properties.

12.1. Bio-oil

Pyrolysis is a new technology for producing bio-oil, solid char, and other gaseous products from empty palm fruit ash and other biomasses. It can recover up to 75% bio-oil with significant water content, utilizing building blocks like cellulose, hemicellulose, and lignin [51]. EPFB pyrolysis produces bio-oil, a dark brown liquid similar to mother biomass. Quality monitoring is crucial for heat and electricity use in boilers, engines, and gas turbines [52]. The bio-oil yield from EPFB is shown in Table 5 compared to other palm waste biomasses.

Bio-oil properties require special attention in pyrolytic oil processing, including biomass feedstock, reactor sizes, and quality control, but thermal stability, combustion properties, and corrosiveness are not adequately considered [22]. Ndukwu et al. [22], suggested hydrogenation and catalytic cracking to raise the quality of the bio-oil product by minimizing the oxygen content and eliminating alkalis. Dynamotive uses fast pyrolysis technology to convert biomass into a primary liquid fuel mixed with hydrocarbon fuels or into transport-grade liquid hydrocarbon fuels (gasoline/diesel) [54].

Table 4: Bio-oil liquid yield from different palm oil waste-derived biomass using different reactor types

S/No	Reactor type	Type of Biomass	Bio-oil Yield	References
1	Fixed and stirred bed	Oil palm shell	-	[87]
2	Fixed bed reactor	Empty fruit bunch	52%	[90]
3	Fixed bed reactor	EPFB, Palm Kernel Shell (PKS), Palm Meso carp Fiber (PMF)	58.2 % for EPFB, 49.8% for PKS and 53.1% for PMF	[91]
4	Fixed bed reactor	Trunk, Frond, palm leaf and palm leaf rib	40.87% (Trunk), 43.50% (Frond), 16.58% (Palm leaf) and Palm leaf rib (29.02%)	[92]
5	Fluidized bed reactor	Palm oil shell	58% (at 500 °C)	[91]
6	Fixed and stirred bed	Palm shell waste	46.40%	[92]
7	Fluidized Bed	Empty Fruit Bunch (EPFB)	72% for washed EPFB and 55% for unwashed EPFB	[62]
8	Fluidized Bed	Empty Fruit Bunch (EPFB)	55% depending on the particle size	[25]

Adapted from Kurnia et al. [28]

12.2. Biogas

Non-condensable gases, produced after pyrolysis, consist of carbon dioxide, carbon monoxide, methane, hydrogen, and trace amounts of ethylene, propylene, chloromethane, butane, propane, and ethanol [55]. The volatile species in the pyrolysis reactor and the tar will undergo a series of secondary reactions to generate gas components, including decarboxylation, decarbonylation, dehydrogenation, and deoxygenation [56]. The pyrolysis temperature, which controls the product distribution, significantly affects the amount of gas generated during the pyrolysis reaction. Additionally, at elevated temperatures, the gas production rate increases due to the transformation of tar into gases [22].

12.3. Biochar

Pyrolysis produces biochar, a dense material with a biomass content ranging from 10% to 35%, formed through thermal degradation of lignin and hemicellulose, containing metals and contaminants [9]. During pyrolysis, the residues often accumulate in the reactor, and they are partly carried away by the exhaust gases and removed in the second cleaning stage, which prevents side reactions. Khatibi et al. [14], found that the highest biochar yield of EPFB occurs at 300 ^{o}C, while the lowest is at 700 ^{o}C, primarily due to the presence of lignin in the biomass.

Pyrolysis has traditionally been utilized for producing biochar, but its versatility and short residence time at moderate temperatures have garnered particular interest [57]. Biochar is a beneficial soil improvement due to the mineral components retained during pyrolysis, and it can also be used in agriculture and the household, similar to activated carbon in gas cleaning and water treatment plants. According to Lee et al. [58] and Xu et al. [8], the surface of biochar, its carbon recalcitrance, and its high nutritional content determine its likely use. In general, the pyrolysis products of EPFB biomass can be represented as shown in Figure 3.

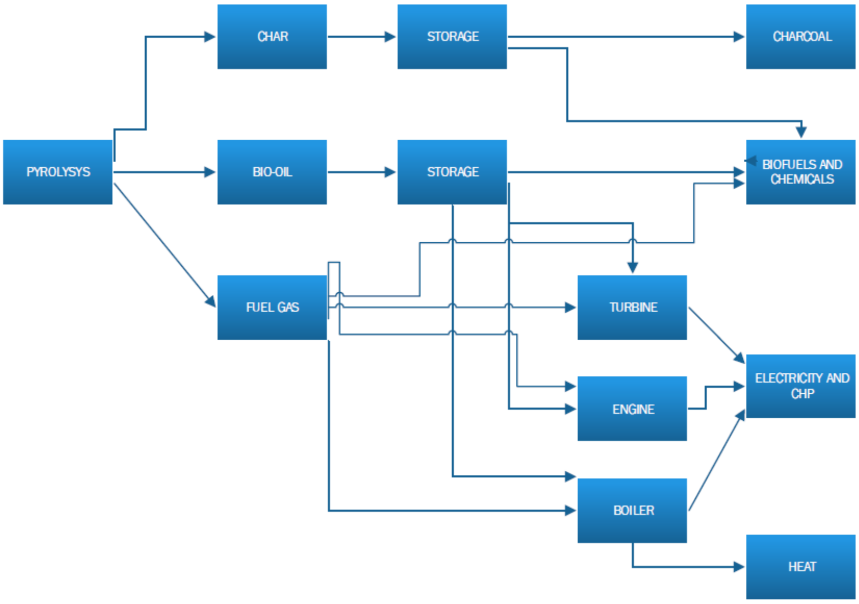

Figure 3: Products from the pyrolysis of EPFB biomass

13. Pyrolysis product distribution

Pyrolysis, a complex process involving multiple reactions, is influenced by various parameters like reactor temperature, heating rate, system pressure, reactor layout, and feed type [46]. The distribution of pyrolysis products is significantly influenced by the temperature [59]. Biomass breaks down at 350°C-80°C, converting more significant components into char, gases, and oils. Char development favors long residence times and low pyrolysis temperatures, while liquid generation favors higher temperatures and short residence times [2]. Bio-oil, often low energy and unstable, can be deoxygenated using catalytic cracking and hydrodeoxygenation. Wood biomass yield and temperature variation vary, with the highest yield at 500°C.

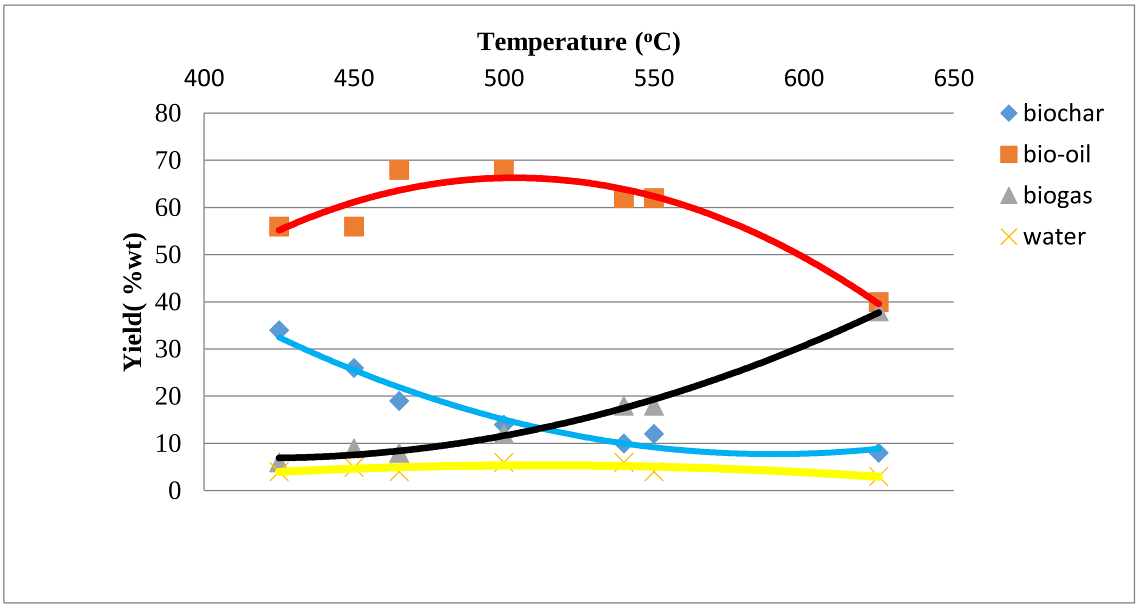

Figure 4: Relative proportion of products in pyrolysis of biomass Adapted from IEA [60]

14. Bio-oil stabilization and Upgrading

. Although bio-oil has better characteristics than other traditional biomass fuels, its properties are inferior to those of fossil fuels. Advances in bio-oil hydrotreatment, bio-oil fractionation [61, 62] and improvement in the ignition properties of bio-oils including the derived products are catalyzing the development of biorefineries to boost, stabilize and upgrade the properties of the produced bio-oil. By reducing the oxygen content, eliminating the carboxylic acid group and lowering the char content through biomass pre-treatment and superheated steam filtration, the firmness of the bio-oil produced can be improved [63] To ensure a stabilized bio-oil, both fractionation with a bio-oil recovery system to separate the produced oil and a catalyst post-treatment are necessary. Mild hydrotreating (a method that uses hydrogen to extract pollutants like sulfur, nitrogen, or oxygen) takes place in the existence of a catalyst and with high hydrogen pressure. Mainly oxygen and some CO_2 are emitted as vapour. Other methods of extracting O_2 and making a less reactive bio-oil with less acidity are still being investigated. According to Riesco-Avila et al, [39] initial efforts to stabilize biomass pyrolysis products centred on the application of microfiltration membranes for char removal and catalytic processing to make transportation fuels. Under atmospheric pressure, low-cost catalysts such as zeolite are widely used in the conversion of produced oxygenated bio-oil into renewable gasoline and diesel fuels [64, 32]. Ro, et al., [65], demonstrated the selectivity of aromatic hydrocarbons over other hydrocarbons by catalytic pyrolysis of EPFB over zeolite. The molecule sizes of the hydrotreated bio-oil are optimized to be in the ideal range of gasoline, diesel, and jet fuel using an existing refinery's hydrocracking process.

15. Process conditions affecting the pyrolysis process and bio-oil yield

The growth of the biofuels industry is hindered by a lack of understanding of pyrolysis technologies despite increasing interest in this field. The pyrolysis process is influenced by a wide range of factors, making it challenging to create a unique design that can be applied to all conceivable raw materials and applications [41]. The biomass content and process parameters directly influence bio-oil production from EPFB and other biomass.

The use of sand as a heat transfer medium [39], a particle size of less than 2 mm, a vapour residence time of about 2 s [55] and an average temperature of around 500 °C [3] are essential process conditions for maximizing products. Researchers have also found that various operating conditions, designs, and other factors influence product yield and quality in experimental testing. The initial moisture content, biomass flow rate, material composition, reactor shape, reaction temperature, carrier gas flow rate, heating rate, vapour residence time, and particle sizes are all variables that directly impact the secondary reactions that form condensable volatiles. These elements are summarized as follows:

15.1. Biomass Feedstock Composition and Particle Size

Lignocellulosic biomass, consisting

of cellulose, hemicellulose, and lignin and their extracts, plays a crucial role in determining the yield and distribution of pyrolysis products. Numerous research efforts have been made to assess the influence of feedstock composition and particle size on bio-oil products. According to these data, the size of the biomass particles has a precise impact on the heating rate, aerosol emission, and product distribution. According to Garcia-Nunez et al. (2017), mass transport limitations become more severe as particle size increases. Additionally, the studies showed that coarser particles produce more carbon and gas than smaller particles. Fast pyrolysis reactors usually use tiny particles to achieve high heating rates (> 1000°C/s) and high bio-oil yields.

15.2. Effect of biomass moisture content

Osman et al. [17] showed that expanding the moisture amount of biomass accelerated charring, decreased the output, and improved the standard of the processed bio-oil. Increasing the moisture level of biomass increases charring and lowers the output and quality of processed bio-oil, according to Osman et al. [17]. The feedstock is frequently preheated and pulverized before entering the pyrolysis reactor since a higher moisture content reduces the yield of organic compounds, volatile matter, and bulk density of biomass all play a role.

The feed is usually warmed and pulverized before entering the pyrolysis reactor since a higher moisture content lowers the output of organic compounds. The elemental mix, calorific value, moisture content, ash content, volatiles, and bulk density of biomass all contribute to its efficiency when used to make biofuels.

15.3. Effect of temperature

Temperature is essential in the pyrolysis of lignocellulosic biomass since the degradation of the biomass is temperature-dependent [17] According to several studies published in various publications, the ideal temperature for quick pyrolysis of lignocellulosic biomass is around 500 degrees Celsius [66].

The pyrolysis temperature affects the degradation of biomass components, with increased temperatures improving physicochemical parameters like porosity, ash amount, electrical conductivity, and pH value of bio-oil and biochar. Wang et al. [56] found that temperature significantly influences microwave pyrolysis, with it controlling the end products.

15.4. The Impact of Biomass Ash Content.

The biomass's ash content significantly influences the distribution of the pyrolysis product, thus affecting the production of the desired bio-oil product. The presence of ash in the feed reduces the yield of bio-oil. Similarly, the analysis of the pyrolysis of empty fruit bunches using unwashed and washed biomass has shown that the organic material recovery could range from 60% for 1% ash to 35% for 3.5% ash

15.5. Heating rate

Studies indicate that the heating rate of biomass is directly linked to the temperature of pyrolysis, leading to an increase in the H/C ratio and a decrease in the O/C ratio, resulting in a higher conversion rate of bio-oil.

15.6. Vapour residence time

The distribution of pyrolysis products in biomass reactors is influenced by vapour residence time, with higher temperatures leading to secondary cracking and lower organic liquid yields. A longer vapour retention time of more than a second tends to promote side reactions, leading to char formation and a reduction in bio-oil yield [3]. Short vapour residence time in reactors results in insufficient biomass fragmentation, producing highly viscous oil with lower yield. If biochar and biogas are the desired pyrolysis products, a longer residence time is preferred, as studies show that the longer the residence time, the greater the increase in the yield of char and gases.

16. Modeling and Optimization of fast pyrolysis systems

Fast pyrolysis processes are complicated, with phenomenological changes related to reaction rates but no consensus on reaction mechanisms. There is no comprehensive, broadly applicable model to explain the processes within a biomass particle, which enables pyrolysis reactors to be designed and piloted on an industrial scale [3]. The optimization of energy systems and process modelling aims to plan, design, and implement future energy systems. An understanding of the theoretical context of the model supports the model design, implementation, and validation. According to Lund, et al. [67], the construction of a model includes the definition and focus on a single characteristic to model the dynamic dependencies and properties of an engineering system. Many energy optimization models, each with its characteristics and results, have been developed to pyrolyze empty palm fruit bunches [57]. By optimizing the operating conditions, the catalytic pyrolysis of EPFB could achieve a maximum yield of pyrolytic products with a higher efficiency. Researchers have used various methods to improve process conditions with varying degrees of success. Many have used the Design of the Experiment (DOE) reaction surface technique to achieve total product yield by considering the effect of each pyrolysis parameter and how they interact. Yun et al. [43] created a detailed Aspen Plus model for an industrial plant that produces biomethane without external heating from empty palm fruit tufts (50% by weight initial moisture).

17. Pyrolysis of EPFB Case Studies

Biomass has infinite potential as a bioenergy source that will help minimize waste and reduce The simulation results were expected with an auto thermal system with an 80.6 % thermal efficiency and a final gas product which is made up of 99.2 wt% CH_4 and 0.8 wt% H_2 reliance on fossil fuels. EPFB, a large-scale palm oil biomass produced in tropical countries like Nigeria, Indonesia, and Malaysia, has the potential for energy and revenue. Pyrolysis conversion is the most efficient method for converting it into bio-oil, biogas, and char. Awad et al. [68] conducted a laboratory experiment to derive pyrolytic oil from EPFB biomass, comparing its attributes with wood-derived bio-oil and evaluating reactor temperature and feedstock ash level. Osman et al. [17]studied the impact of pyrolysis settings on product yield in a laboratory reactor. They found that optimal temperature and heating rate, 550°C and 5°C/min, resulted in a char product with 74.8 % fixed carbon.

Mohamed et al. [69] employed EPFB as a feedstock in the procedure of pyrolysis employing a fixed-bed reactor in an optimization study. Process parameters such as biomass particle size, the temperature of pyrolysis, and the holding time were optimized using Central Composite Design (CCD). They discovered that the average bio-oil yield was 46.2% at a pyrolysis temperature of 442.15 ^{o}C and a reactor holding time of 483 seconds using an EPFB particle size of 866 µm. Similarly, Mahmood et al. [70] optimized bio-oil processing using an ablative pyrolysis reactor, while Shahlan et al. [71], developed a gasification device for hydrogen gas production from oil palm empty fruit bunches, determining optimal temperature and pressure. To ascertain the influence of pre-treatment with a dilute nitric acid solution on the biomass, Park et al. [11], used a bubbling fluidized-bed reactor to rapidly pyrolyze acid-washed oil palm empty fruit bunch for bio-oil generation. They discovered that acid-washed EPFB bio-oil had higher levels of levoglucosan, D-Allose, and 3-methyl hydantoin.

Yun et al. [43] and Widiatmoko et al. [72] utilized pyrolysis-direct methanation to generate Bio-CH_4 from empty palm fruit bunches, increasing graphene yield to 70% at 350°C. SEM, TEM, Raman Scattering, and X-ray spectroscopy were used to characterize the graphene product.

Mohamed et al.'s 2014 study utilized the Central Composite Design to optimize pyrolysis using EPFB feedstock in a fixed bed reactor, achieving an average bio-oil output of 46.2%.

Similarly, Mahmood et al. [70] optimized bio-oil processing using an ablative reactor, finding optimal pyrolytic parameters for pure hydrogen gas processing at 850°C and 1 atm for 16.3% of EPFB biomass raw material. Park et al. [11] used a bubbling fluidized bed reactor to rapidly pyrolyze acid-washed empty fruit bundles from oil palm for bio-oil making to maximize the effect of pre-treatment with a. to determine dilute nitric acid solution on the biomass. They discovered that levoglucosan, D-allose, and 3-methyl hydantoin increased in acid-washed EPFB bio-oil. Yun et al. [43], proposed a pyrolysis direct methanation process for the generation of bio-CH_4 from an empty palm fruit bundle, while Widiatmoko et al. [72] in two-step pyrolysis of an oil palm used empty fruit bunches to increase the grapheme yield at 350 ° C to about 70%. SEM, TEM, Raman scattering, and X-ray spectroscopy were explored to characterize the graphene product

18. The Role of Heterogeneous Catalysis in pyrolysis of EPFB

Catalyst pyrolysis is a promising method for improving bio-oil into transport fuel, but it may not always be necessary during the pyrolysis phases [73, 16]. Bio-oil generation from EPFB biomass is influenced by the amount of cellulose in the biomass and the reactor's geometry [37] Some industrial-based researchers have shown that catalytic pyrolysis is promising for various biomass feedstocks. Researchers, including Clemente-Castro et al. [57] and Kurnia et al. [16], have shown that biomass pyrolysis using a catalyst at high heating rates and short gas durations maximizes product production. By studying the effects of different types of catalysts on the pyrolysis process for most biomass feedstocks, catalytic pyrolysis was a viable method for bio-oil quality improvement [56]. Catalytic pyrolysis and catalytic cracking are chemical reactions that enhance bio-oil quality by eliminating oxygen compounds, boosting calorific value, decreasing viscosity, and improving stability [37]. Hydrodeoxygenation and catalytic cracking are commonly employed to enhance bio-oil's potential for fuel applications.

19. Extraction of chemicals from bio-oil

As a result, the chemicals extracted from bio-oil contribute significantly to the economic benefits of bio-oil. A precise assessment of the bio-oil, both qualitatively and quantitatively, would identify the most critical components of bio-oils, which enables us to analyze and identify bio-oils with desired properties for the downstream generation of fuels. Adsorption, distillation, and fractionation are methods used to extract chemicals from bio-oil, with acetone being the primary solvent, followed by phase separation and aqueous extraction [74]. Bio-oils can be divided into two groups: a phase that is insoluble in water, which is suitable for use as fuel or for the manufacture of chemicals, and a water-soluble aqueous phase, which contains oxygenates in total concentrations of 15 to 60% by weight, differentiated by a broad polarity and molecular weight distribution and in most cases only a few uses. The composition of the aqueous phase of the bio-oil is very heterogeneous; the main components in acids (19-25 wt%), ketones (12-20 wt%), phenols (5 wt%) and furans (1wt%). Bio-oil's aqueous fraction can be repurposed for added value and profit, while phenolic compounds extraction from biomass is crucial for long-term hydrocarbon biofuel development. They are particularly appropriate as value-added chemicals for extraction from bio-oil due to the large amount of phenolic groups (phenol, 2-methoxy-) and furfural. Bio-oil separation can occur in stages by precipitation and extraction or by deoxygenation of the oil to a higher-quality transport fuel.

20. Future Challenges

The most challenging aspect of EPFB pyrolysis is fine-tuning the procedure to increase product quality and quantity while lowering costs and minimizing environmental impact.

The quantity of bio-oil produced from EPFB and other biomass has been addressed, and additional research into improving oil quality is needed. At the moment, the study's strengths are focused on developing an appropriate technique for generating improved-grade pyrolysis oil and examining alternative forms of biomass for use as pyrolysis feedstock.

21. Conclusions

The environmental influences of continued utilization of fossil fuels, the realization that the world's petroleum reserves may soon be depleted, and rising crude oil prices have thrown a wrench into means to detect alternative and sustainable energy sources.

Fast pyrolysis of empty palm fruit bunches, besides other lignocellulose biomasses, as well as related processing, is a rapidly developing technology sector with many participants from various countries, mainly from Malaysia, Indonesia, and India, where the palm oil tree is a popular plant.

However, whereas the method for converting food crops to attain ethanol is well developed, converting lignocellulose biomass to bio-oil through pyrolysis faces numerous challenges.

Fast pyrolysis of biomass appears to be commercially viable, but many parts of the process are still in the infancy phases of development. More study is needed to enhance dependability, efficiency, product quality, product features, and scale-up.

It is hoped that an innovative breakthrough would result in a higher quality bio-oil, lower subsequent upgrading costs, allow for more storage space, and increase commercial viability, as this will help bring a safe, sustainable transportation fuel to market that can be used as a replacement for crude oil.

Various reactor configurations are being studied, and a few have already been scaled up to large demonstration units. Fast pyrolysis for the manufacture of fuel oil is nearing commercial viability.

Fluidised bed reactors are now the most widely utilized reactors for generating bio-oil from biomass because they provide technological advantages while still having some disadvantages compared to other reactor types.

Using edible crops for biofuel production, such as corn, sugarcane, and soybeans, is not sustainable because it depletes food supplies. Currently, lignocellulose biomass such as EPFB is held in high regard as a widely distributed biomass with enormous potential for biofuel generation via pyrolysis.

Conflict of interest

The authors declare no conflict of interest.

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