Procedure International Journal of Science and Technology

(International Open Access, Peer-reviewed & Refereed Journal)

(Multidisciplinary, Monthly, Multilanguage)

ISSN : 2584-2617 (Online)

Volume- 1, Issue- 2, Feburary 2024

Website- www.pijst.com

Sustainable Utilization of Oil Palm Residues and Organic Wastes for Transport Fuel Production– A Review

Okoh Elechi

Department of Chemical Engineering Technology, Federal Polytechnic Ekowe, Bayelsa State Nigeria

Oruabena Bernard

Department of Civil Engineering Technology, Federal Polytechnic Ekowe, Bayelsa State Nigeria.

Abstract:

The increasing global demand for cleaner energy sources has made the attainable and innovative conversion of biomass residue from empty palm fruit bundles into compressed fuel a reality. Oil palm-based wastes have become a significant source of renewable fuels and chemicals with high liquid and lower gas yields. In the quest to transition to a renewable energy future, lignocellulosic biomass including oil palm-based biomass is currently the cheapest and least harmful material that offers the prospect of producing clean energy that effectively rivals fossil fuels in terms of efficiency and sustainability fuels can compete. Although the cost of energy production from lignocellulosic biomass cannot currently compete with fossil fuel sources due to the lengthy processing and utilization process, the potential exists to effectively compete with fossil fuels. The fact that biomass is inexhaustible and renewable, low in sulfur and nitrogen, environmentally friendly, and sustainable is a major advantage of its use for energy production. Furthermore, unlike fossil fuels, which contribute to the increase in greenhouse gas emissions (GHGs), biomass energy has no impact on the natural carbon-CO_2 cycle. Thermochemical and

biochemical routes are used to obtain energy from biomass, with thermochemical routes being more convenient and efficient. This article reviews studies on the pyrolysis of empty palm fruit bunch biomass for bio-oil production, to reduce environmental impact and dependence on fossil fuels. It provides a detailed description of the reactors and pyrolysis technology.
Keywords: Biomass; Pyrolysis; Reforming; Fossil Fuel; Oil-Palm Wastes; Bio-oil

1. Introduction-

Lignocellulosic biomass is diverse and accessible and can be utilized as feedstock in the production of transportation fuel. Biomass, a non-fossilized, biodegradable organic material from plants, animals, and microorganisms, is crucial due to the projected 48% increase in global energy consumption by 2040 [2][3]. Scarlat, et al., [4] and Jens, et al., [5], emphasize the need to efficiently utilize the bioenergy capacity of various biomasses, particularly lignocellulosic biomass, as it remains the only renewable energy source that can be easily incorporated into the biofuels industry [6]. Tissot and Welte [7], Kamm et al. [8], and Paul O'Connor [3], reviewed the fossilization of terrestrial and marine biomasses, focusing on local liquefaction and concentration, with fast pyrolysis for liquid fuel developed in North America but has significantly expanded worldwide [9]. The pyrolysis biofuel production platform is undergoing significant improvements due to a better understanding of fundamental processes, enhancing its capability to decompose biomass using heat instead of oxygen. [9, 10]. Biomass pyrolysis produces solid biochar, liquid bio-oil, and non-condensable gas from various waste and biomass sources, achieving a bio-oil yield of 65-75% depending on the process conditions [11, 12, 13]. Pyrolysis is a crucial, non-pretreatment process for producing liquid fuel from biomass, making it a vital pathway in the energy production sector.[14, 15]. Pyrolysis produces bio-oil with various chemicals, including phenol, organic acids, alcohols, esters, guaiacol, and alkanes, used for industrial purposes but causing undesirable properties seen in bio-oil [16] [17, 18]. Fast pyrolysis bio-oil production feasibility depends on biomass used as feedstock for high-value products and petrochemical production, including aromatic hydrocarbons like benzene, toluene, and xylene, making bio-oil attractive for chemical production [19, 20, 21]. Interest in producing bio-oil from EPFB is increasing, with reports of successful pyrolysis and thermochemical conversion in fixed bed reactors advancing towards a sustainable biofuel future [22, 23]. Bio-oil from EPFB biomass pyrolysis contains valuable chemicals, that are separated using solvents of different polarities. Phenols are common products, used in fuel additives, food antioxidants, and chemical synthesis.

In general, the various platforms for biofuel production from lignocellulosic biomass though not in conflict with food sources, differ from the conventional ethanol process, which uses starch and sugar, as it involves additional processing steps. The transportation and handling costs of lignocellulosic biomass are negatively impacted by its high moisture content and low energy density. The use of heat to break down biomass into intermediates like bio-oil, biochar, and fuel gasses, which can then be upgraded into fuel and other products, would help solve the problem of shipping and handling.

When pyrolyzing EPFB biomass, the problem of determining the optimal parameters needed for the full output of desirables has remained a processing issue due to the source-dependent characteristics of EPFB. Another problem is that empty fruit bunch biomass produces a mixture of minerals called ash, some of which enhance bio-oil yield, while others promote char formation [24, 25, 26] . Before pyrolysis, aqueous pretreatments could be used to remove the ash content of EPFB biomass selectively [27, 28, 29]. Fluidized bed reactors are widely used in pyrolysis reactions due to their uniform particle-fluid mixing, excellent heat and mass transfer, absence of moving parts, operational continuity, and improved heat and mass transport.[30]. Sukiran et al., Park et al., Tsai et al., and Radlein & Quignard have all found that the pyrolytic yield of bio-oil and other desirable products is highly dependent on the process operating parameters and biomass characteristics. They achieved the highest bio-oil yield of 42% and 63.9 wt% using a fluidized fixed bed reactor. Other researchers have found that temperature, nitrogen flow rates, heating rates, and particle sizes significantly impact bio-oil yields for soybean biomass and olive oil residue, while others have investigated rapeseed biomass yields under static atmospheric conditions.

2. The global trend in bio-fuel development-

Energy resources are central to the sustainability of the development and technological progress of any nation [38]. Malaysia and Indonesia are exploring biomass pyrolysis to reduce dependency on fossil energy imports. The energy and environmental benefits of biomass pyrolysis are driving interest in producing clean, sustainable energy from agricultural residues.[39]. Biomass-derived energy is environmentally friendly due to its lower greenhouse gas emissions, but it also releases combustion products into the atmosphere.[40, 41]. Biomass, currently accounting for 14% of primary energy sources, primarily from cellulosic starch sources, poses a threat to food supply sources.[42, 43]. Numerous investigations exploiting the feasibility of converting EPFB and other agricultural biomasses to bioenergy are ongoing all over the world [44, 45]. Yaman [46], in a review paper, reported over one hundred biomass species whose pyrolysis behaviour has been studied. The fast pyrolysis method can convert Oil-Palm based wastes (Empty Palm Fruit Bunches (EPFB), Palm Kernel Shell (PKS), Mesocarp Fibres (MF)), a non-woody biomass waste products from the palm oil processing industry, normally discarded because of their high-water content and inability to be used as boiler fuel, can be processed into value-added fuels and renewable chemicals [47, 48]. EPFB and PKS are common feedstock for the pyrolysis process and bioenergy is now clean and sustainable, despite some technological challenges on the path to converting lignocellulosic biomass to liquid fuel. EPFB and PKS, rich in phenolic compounds, is a promising energy source. Commercialization of lignocellulosic biomass is beneficial, and suitable feedstocks like palm shell, mesocarp fibre (MF), and palm kernel shell (PKS) for bio-oil production [49][50].

3. The palm oil industry-

The palm oil industry, a significant agricultural sector in developing countries, is growing due to increased consumer demand for food, cosmetics, and sanitary products. Processing palm oil fresh fruit bunches generates waste biomass, which can be used as fuel in various energy generation systems, including thermal, thermochemical, and other processes [57]. Nigeria, Indonesia, Malaysia, Thailand, and Colombia are major palm oil producers, with empty fruit bunches potentially producing biofuel if processed properly [58].

4.Empty fruit bunch as a biomass feedstock-

EPFB (Empty Palm Fruit Bunch) and Palm Kernel Shell (PKS) are non-woody biomass, a byproduct of the palm oil processing industry, rich in cellulose, hemicellulose, and lignin and represents the possibility for transforming agricultural waste into useful energy recovery valuables [13]. It is a popular feedstock for the pyrolysis process. EPFB is also rich in phenol and other phenolic compounds [49]. Empty palm fruit bunches (EPFB) and other palm tree-derived biomasses have been investigated for use in bio-oil production [59, 60]. EPFB biomass is a known energy source, with a high moisture content of about 65 percent, resulting in a low heating value [61]. Though EPFB biomass is frequently discarded as waste, it is a viable choice for converting it to biofuel. Fast pyrolysis, a thermochemical conversion process, can optimize the biofuel capacity of EPFB solid waste by converting palm tree-derived biomass at a temperature of approximately 500°C and a vapour residence time of approximately 1 second into a dense, compact biofuel with 75% oxygen content [62, 63]. Oil palm biomass holds significant potential as a renewable energy source, with numerous pilot and commercial-scale energy systems being tested [61, 15]. EPFB biomass feedstock, rich in acids, aldehydes, ketones, alcohols, phenols, and oligomers, is a popular fuel and chemical feedstock for pyrolysis [64].

Figure 1: Showing Empty Palm Bunch, Full Palm Bunch, and Ground PKS

5. Composition of oil palm tree derived biomasses-

Biomass is a hydrocarbon content that can be biologically degraded and primarily consists of carbon, hydrogen, oxygen, and nitrogen. [65]. Oil palm tree-derived biomass comprises various compounds including cellulose, hemicellulose, lignin, and others [66, 67, 68]. The proportions of hemicellulose and cellulose in oil palm waste biomass vary based on species and fraction examined [65, 69]. Hemicellulose, a lower molecular weight component of biomass, makes up 12-33% of palm fruit mass and serves as cement for cellulose micelles and fiber, while lignin is a highly polar macromolecule with hydroxyl and carbonyl functional groups [71] [72, 70]. The lignin content in palm oil empty fruit bunch biomass, despite variations in cellulose, hemicelluloses, and lignin content based on the feedstock source, ranges between 7.79 and 37% [73, 74]. The total composition of each component in oil palm biomasses are crucial for determining the quantity of biomass required for bio-oil or other essential chemicals production [75]. Yang et al., [76], and Jahirul et al, [77] found that bio-oil is primarily derived from cellulose and hemicellulose in biomass, while bio-char is derived from lignin. Table 1 summarizes the basic components of biomass extracted from the palm oil tree as found in 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	[73]
EPFB	13.75 – 59.70	12.79 – 22.1 0	7.79 – 30.45	3.45 - 7.54	[79, 74]
Mesocarpfibre (MF)	40	20	30	1 - 11.8	[80]
PKS	27.7	21.6	44	0.87 - 4.6	[81]

6. Analysis and heating values of palm fruit residues

The only renewable energy source that can be converted to liquid fuel is biomass and the diverse physicochemical compositions of palm biomass significantly influence the most suitable conversion technology [73][82]. The conversion process yield is determined by biomass feedstock heating value, and some thermochemical processes convert all biomass fractions to biofuels. Analyses reveal bio-oil chemical and physical properties. Ash is a mixture of several minerals present in biomass, such as sodium and potassium. Iron, copper, and chromium are typically found in ash in concentrations ranging from 1.3 to 22.9 percent, and they increase the yield of bio-oil. The remaining minerals minimize the yield of bio-oil and increase char production [83, 25]. Selective extraction of retardant minerals from biomass before pyrolysis can increase bio-oil extraction. Table 2 summarizes proximate, ultimate, and heating values for palm tree residues.

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**
		[84, 81]	[85, 80]	[86, 81]	[87]
Proximate	**Unit (wt. %)**				
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	**(Wt. %)**				
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	
Lignocellulose	**(wt.%)**				
HHV	(kJ/kg)	15220 – 19350	19331 - 21980	17930 – 20520	18740
Bulk density	(kg/m3)	110 – 144	225	715 - 780	

Table 2 reveals no significant differences in volatile matter and fixed carbon contents among palm tree biomass sources, but significant variations in moisture and ash contents.

Ash is a byproduct of combustion, and the literature suggests that EPFB and PKS contains large amounts of ash, ranging from 0.8 to 12 moisture-free (mf) weight percent [61]. The excess ash content of biomass is correlated with emissions of obnoxious compounds such as NOx with ash acting as a catalyst that aids its processing [88], resulting in environmental problems. Ash content of biomass significantly impacts pyrolysis oil yield, with homogeneous oil obtained when oil palm biomass ash content is less than 3 mf wt percent, and maximum bio-oil yield is 72 mf wt percent.

7. Bioenergy from oil palm tree based biomasses-

The assessment of fossil fuels is becoming more challenging and environmentally damaging, necessitating the creation of an alternative source of energy. One recognized alternative is the conversion of biomass to bioenergy. EPFB, PKS and MF are waste biomasses generated by the palm oil industry that, when burned in open air produces CO_2 or when left to rot in the open produces CH_4 and CO_2 [3]. Depending on the method of processing, EPFB and PKS will yield three different liquid items (Bioethanol, Biodiesel, and Bio-oil). Bioethanol is generated by pretreatment of EPFB biomass, saccharification, and fermentation, while biodiesel is produced by the recovery method. Bio-oil is generated by rapidly pyrolyzing biomass and then purifying it. Bio-oil offers numerous environmental benefits over fossil fuels, including being CO_2-neutral and containing no SOx. Additionally, NOx emissions are low for all biomass liquid items as compared to diesel oil [71]. EPFB has a higher moisture and ash content than palm kernel shells or other forms of biomass extracted from the oil palm tree, resulting in a lower energy content. Researchers have performed a variety of thermochemical studies focusing on the conversion of EPFB and PKS to bioenergy. Several studies have suggested that using an optimized fast pyrolysis process and washing the biomass can increase the bio-oil yield by up to 80% and the distribution of pyrolysis products, including bio-oil, fuel gas, and char, is based on the operating conditions of the process [68][89, 90]. Several researchers have found that the maximum bio-oil yield occurs at temperatures around 500°C, with a yield of around 20 MJ/L, using fixed or fluidized bed reactors [44, 31]. Research indicates that most pyrolysis occurs in fixed bed reactors at 450°C to 600°C, which are more efficient due to ideal plug flow behavior, lower maintenance costs, and minor losses [68]. Bio-oil is a depolymerization result of biomass building blocks that are similar to the mother biomass, but not like petroleum-derived oil and have special properties as compared to other fuels. The bio-oil extracted from EPFB is thermally unstable and polar, making it difficult to separate from the water formed during the pyrolysis process. In comparison to bio-oil from various feedstocks, they are also very acidic and have a high oxygen content (40 percent weight) [91].

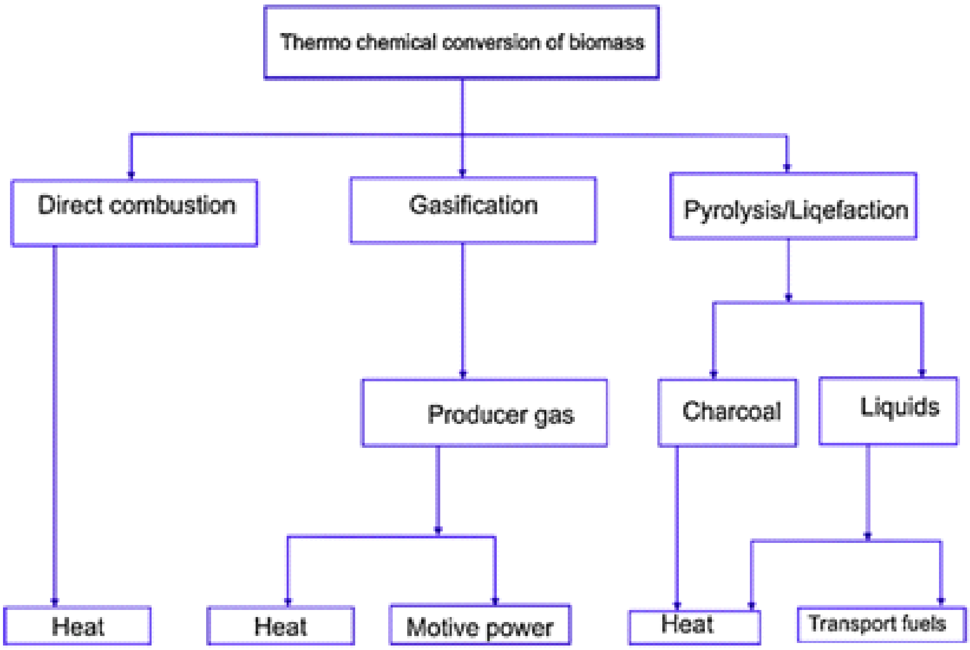
The pyrolysis liquids extracted from EPFB are separated into two stages, roughly 60% organic and 40% aqueous, making it highly unlikely to be used as a fuel commercially [51]. The reactor's operating parameters can improve the production of biochar and biogas, pyrolytic products with high heating values, which have potential as fossil fuel substitutes [92, 93]. Bio-oils can be efficiently utilized as a fossil fuel substitute or directly used in various energy generation systems without further processing.

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

Thermochemical processes are utilized to transform biomass into high-value biofuels like biochar, bio-oil, and volatile materials, which can be utilized as fuel or converted into higher-value biofuels [94]. The literature on thermochemical biomass reutilization is extensive, covering biomass pyrolysis and catalytic upgrading of the resulting bio-oil [71]. The global interest in pyrolysis of oil palm based biomass for bio-oil production has prompted further research into this technology [95, 96, 5]. Pyrolysis offers economic advantages over other thermal conversion processes when used to produce bio-oil from organic wastes [9, 97]. A typical thermochemical bio-oil production route from biomass is as shown in Figure 2.

This process is a unique thermochemical fuel conversion method that produces petroleum-like liquid products from biomass, while also offering environmental benefits. [65, 96]. Fast pyrolysis, a process where biomass feedstock is heated and vapors condensed, has been proven to increase the bio-oil yield of biomass [71]. Catalysis for deoxygenation and upgrading liquid fuel production has been explored, but current FCC conditions and catalysts do not significantly reduce oxygen content, making desired decarboxylation reactions rare [98, 99].

Research by Woulf et al., [94], indicates that with minimal biomass moisture content, the enthalpy needed to dry, heat, and pyrolyze gases and volatiles can serve as the feedstock. The pyrolysis system is generally considered to be cost-effective on a small scale. [100, 101, 102]. The literature provides numerous requirements for optimal pyrolysis plant operation conditions to produce the desired products [71, 103]. Lede [104], argues that authors often set standard criteria, making it challenging to compare experimental systems uniformly, as requirements like heating rate and temperature are often unquantified. The highest bio-oil yield is often assumed to be achieved through high heating rate and short reactor residence time, influenced by the cellulosic content of palm empty fruit bunch biomass [105].



9. The fast Pyrolysis Processes-

Advanced thermal processing techniques have been developed for the pyrolysis of woody biomasses, breaking bonds to form solid, liquid, and gaseous products, and optimizing organic vapours for oxygenated liquid products. Researchers have investigated various methods for converting biomass into densified energy products, including gasification, torrefaction, pyrolysis, direct combustion, densification, and shedding [106, 107]. Pyrolysis is a thermochemical process that converts biomass into vaporized organic products through rapid heating, high temperatures and a short residence time. A sequential processing of biomass feedstock using the pyrolysis technology is depicted in Figure 3. Oil palm based organic materials are popular feedstock for pyrolysis technology, with most of the process occurring in a fixed bed reactor at 450-600^{o}C atmospheric pressure [68]. Fixed bed reactors are more efficient due to their ideal plug flow behavior, lower maintenance costs, and reduced attrition and wear loss [68]. For optimal performance, feedstock particles should be less than 2mm in diameter, and 10% moisture content and heated to produce vapor and condense into liquid bio-oil [50]. Pyrolysis utilizes biomass components like cellulose, lignin, and hemicellulose for energy generation, converting solid biomass into bio-oil and increasing energy density through deoxygenation [14]. The bio-oil production process involves pyrolysis, char formation, and condensing into a liquid. It is cleaned and stabilized by filtering out particulates and ash for storage, refining, and end-use.

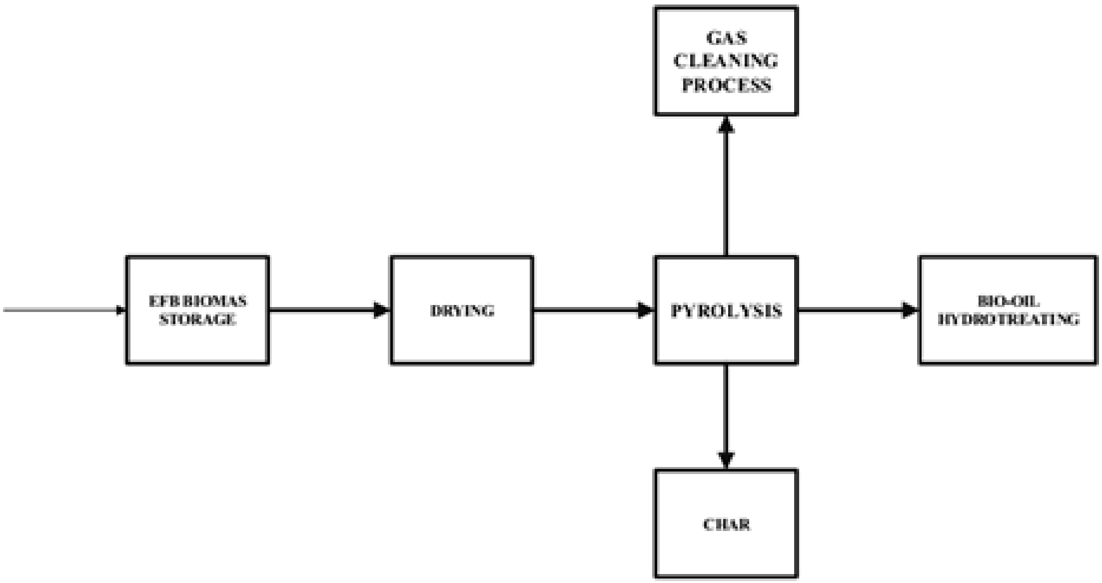


Figure 3: Sequence of the bio-oil production process for EPFB biomass

9.1 Four stages of pyrolysis-

The biomass feedstock is dried to reduce moisture content and water content in the fast pyrolysis liquid product. It is then ground to a particle size of about 2-6 mm to produce small enough particles for the pyrolysis reactor to react quickly. Inside the feeder, the biomass is pre-dried using cross-flows of hot, dry air. The biomass is pre-charged and pre-heated in the pyrolysis reactor, where it undergoes the following processes:

9.2.Moisture Evaporation process-

The de-carbonization process requires the removal of accumulated moisture in biomass, which can take seconds depending on the type and amount of moisture, and the high temperature in the reactor.

9.3.The degasification processes-

Biomass is degasified at 390-400oC for volatiles extraction, consuming 40% of energy in pyrolysis. The remaining gas can be used for energy after combining with heated air.

9.4.The de-carbonization processes-

High-temperature treatment of degassed and dried biomass increases elemental carbon concentration, reduces fibrous structure, and increases grindability, with calorific values varying from 21 to 29 MJ/kg.

10.Classification of the pyrolysis process-

The pyrolytic process can be categorized into flash, fast, and slow pyrolysis, with product yield influenced by feedstock and process conditions [92, 77][104]. Fast pyrolysis is a widely used method that uses high temperatures in an inert atmosphere to degrade organic biomass without oxygen, producing char, bio-oil, and gases [108]. The proportion of products in pyrolysis can be adjusted by adjusting process parameters such as the composition of the starting material, the heating rate, the residence time of the solid, the particle size of the biomass and the operating temperature[109]. Fast pyrolysis is a method for producing high-quality liquid fuels from biomass [110, 111]. Table 3 shows a summary of the standard operating parameters for optimal product yield.

Table 3: Typical operating parameters and products for pyrolysis process

Pyrolysis process	Gas residence time (s)	Heating rate (K/s)	Particle size (mm)	Temperature (K)	Product Yield		
					Oil	Char	Gas
Slow	450-550	0.1-1	5-50	550-950	30	35	35
Fast	0.5-10	10-200	<1	850-1250	50	20	30
Flash	<0.5	>1000	<0.2	1050-1300	75	12	13

Adapted from [77]

10.1. Slow pyrolysis.

Slow pyrolysis is a conventional charcoal kiln method for producing char from biomass at low temperatures and heating rates, typically operating between 550 and 950 K. The slow pyrolysis reaction's high residence time often leads to primary product cracking, affecting bio-oil yield, efficiency, and energy consumption [112, 113].

10.2. Fast pyrolysis

The application of high temperature allows biomass to decompose into vapours, aerosols, and some charcoal, and the substance is characterized by properties that influence its use, such as its ability to be easily stored or transported. Compared to other biomass conversion processes, the fast pyrolysis process provides major economic and processing benefits [9]. Rapid heating, short vapour residence times, and relatively high temperatures in the range of 400°C to 650°C are used to achieve fast pyrolysis, accompanied by rapid quenching of the emitted gaseous stream [114, 115]. Fast pyrolysis involves finely ground biomass feed, controlled reaction temperature, short vapour residence period, and rapid cooling of pyrolysis vapors to produce bio-oil products [47]. The liquid produced is a mixture of bio-oil, solid char, non-condensable gases, and a homogeneous hydrophilic mixture of polar organics and water, depending on the feedstock used [77].

10.3. Flash pyrolysis

Flash pyrolysis, characterized by rapid devolatilization, high particle heating, high reaction temperatures, and short gas residence time, is utilized to produce bio-oil with up to 70% yield efficiency [116]. Flash pyrolysis operates at 777-1027 %C, producing bio-oil with pyrolytic water, low thermal stability, and corrosive properties, which are significant disadvantages. [117].

11.Pyrolysis Reactors

Pyrolysis reactors in bio-oil production account for 10% to 15% of the total capital cost, with reactor configuration significantly influencing product distribution [118]. The development of a reactor system for liquids is crucial for ensuring high heating rates, moderate temperatures, and short vapor and substance residence time. [9]. Developing and analyzing various reactor systems for the pyrolysis of lignocellulose biomass has taken considerable research effort over the years. Different reactor configurations were tested on a variety of feedstock, including EPFB. The tested reactors are categorized into slow, intermediate, fast, and microwave pyrolysis reactors, each with similar designs and complementary technologies [119]. Slow pyrolysis reactors produce char from larger biomass, while fast reactors process small particles for bio-oil and other materials. Intermediate reactors may be needed for large-scale production without preprocessing. Microwave pyrolysis is a cost-effective solution for managing solid waste and generating energy in modular, autonomous devices, enhancing the quality of value-added products.

Based on the starting dry biomass weight, it has been demonstrated that the majority of reactor configurations achieve a liquid-product yield of approximately 70-80%. [71]. Research is underway to improve and extend pyrolysis reactors to increase heating rates and reduce power consumption, thereby enhancing product yield. Vamshi & Qi [118], emphasized the significance of a fast pyrolysis reactor with high heat transfer rate, controlled temperature, short vapour residence times, and rapid cooling for efficient operation and scale-up capability. Numerous reactor designs have been designed to meet the critical requirements for fast pyrolysis [71]. Several authors have studied and listed these pyrolysis reactors as fluidized-bed reactors [120], transported and circulating fluidized-bed reactors [121, 122], ablative reactors, rotating cone reactors, and vacuum reactors [123], as well as bubbling fluidized beds [124].

The pyrolysis of EPFB biomass has been demonstrated in various reactors and several vessels using various technologies, such as slow heating under vacuum [77], quartz fluidised fixed bed reactor [31], entrained coiled tube reactor [125], stainless steel fixed bed reactor under atmospheric pressure [64], entrained ablative vortex reactors [123]and ablative mill reactors [47] fluidised bed reactors [97, 87], and in a vertical fixed bed reactor [126]. Vamshi & Qi [118], classified and discussed reactors used in the fast pyrolysis of empty palm fruit bunch biomass materials. In Table 4, the characteristics of the various reactor types, as well as their complexity and status, are discussed and summarized.

11.1. Fluid bed reactors

A fluidised bed reactor is a continuous flow reactor that maintains a nearly constant temperature in the reaction system. It is commonly used in the chemical industry, but it has been modified for organic wastes pyrolysis. Fluidised bed reactors are widely used due to their ease of operation and rapid scale-up, aimed at increasing the production of bio-oil. Due to the low thermal conductivity of biomass particles, ample heat transfer between the gas and the solid is achieved by making them extremely small. Fluidised bed reactors are more efficient for continuous bio-oil production than other reactor designs and have higher overall reaction effectiveness factors than other reactors. They are frequently employed in solid-fluid reaction schemes. They have a range of advantages, which include uniform particle-fluid mixing, superior heat and mass transfer, continuous operation without moving parts, and increased reaction rates due to improved heat and mass transport.

11.2. Circulating fluid beds and transported beds

A riser and a down-comber, similar to the FCC unit of a crude oil refinery, are used in a circulating fluidized-bed reactor, with a solid particle circulating between them. A circulating fluid bed was initially developed for coal combustion to achieve lower pollutant emissions. Since the char's residence, time is shorter in the CFB technology, the char will invariably be contained in the pyrolysis oil. The technology of CFB reactors is well understood; they are designed to use larger particles, have a high throughput, and have excellent temperature control.

However, CFB reactors consume a large amount of inert carrier gases, thereby diluting the pyrolytic gases and preventing bio-oil recovery [119]. CFBs initiate pyrolysis in a fluidised bed unit, then feed char into a second unit to combust in an inorganic heat carrier, generating most energy needed in the first unit [127]. CFBs' utility is demonstrated when the inorganic heat carrier has catalytic properties, enabling the char to adhere to its surface and perform an effective reaction. Bio-oil yields from a circulating fluid bed are estimated to range between 54 and 71% by weight [128, 119].

11.3. Bubbling fluid beds

The bubbling fluidised bed reactor is a pure technology that uses gas at low velocity and does not expand much beyond its volume at minimum fluidisation (solids are stationary). Because of its high particle density, the bubbling fluidised bed has excellent temperature control and effective heat transfer [129]. The process involves transferring heat from hot sand to biomass particles, with particle size less than 2 mm, aiming for high heat transfer rate. The bubbling fluidised bed reactor was historically used for coal gasification, and many of them are still in use today. An inert medium, such as sand, or a catalyst material, such as CaO, is used as the bed material. The fluidisation of the solid fuel increases the heat transfer between solids and gases [130].

11.4. Rotating cone

Biomass pyrolysis is achieved in a rotating cone reactor by transporting a particulate heat carrier containing biomass particles into a heated cone, passing heat to the feedstock. The bubbling-bed char combustor uses residual char from pyrolysis to heat sand in a rotating-cone reactor, acting as a transported-bed reactor. The rotating cone initiates pyrolysis by contacting particulate heat carriers and biomass, which are then combusted in a fluidized bed to burn off the char.

11.5. Ablative pyrolysis

The ablative reactor is a compact and efficient reactor device that uses heat transfer from the hot reactor wall to melt the biomass particles that come into contact with it under pressure, with the residual oil evaporating [9]. Ablative reactors are distinguished from fluidized bed reactors by the fact that heat is transmitted through a molten layer at the hot reactor surface, obviating the need for a carrier gas [77]. The rate of pyrolysis is restricted by the amount of heat supplied to the reactor. Because the ablative reactor is a surface area-controlled system, heat transfer is improved by using small biomass particles on a large heat transfer surface. The heat transfer through the biomass particles does not limit the reaction rates in ablative reactors, thereby allowing for the use of larger-sized particles. Two common types of ablative reactors are the revolving disk and the ablative vortex.

11.6. Fixed bed fast pyrolysis

The first drawback of fixed bed fast pyrolysis is its batch-wise inefficiency. However, it satisfies the fundamental requirements of rapid pyrolysis and has been demonstrated to be efficient and useful for producing biomass feed with consistent particle size and low ash content [127]. This system consists of a reactor and a fixed bed of pyrolyzed feedstock [118]. While fixed bed reactors and associated systems are unlikely to produce large amounts of liquid, they often produce phase-separated liquids [131]. The solids are heated externally, falling down a vertical shaft and encountering a counter-current upward-moving product gas stream..

11.7. PyRos Reactor technology

PyRos reactor technology is an optimized flash pyrolysis technique for producing high-quality bio-oil from various biomasses, using a cyclone, rotating particle separator, and centrifugal force to isolate char.[118].

11.8. Microwave pyrolysis.

Traditionally, pyrolysis has been described as a biomass heating process that generates char, oil, and gas in an oxygen-free environment with the assistance of an external heat source. Microwave pyrolysis, on the other hand, is a term that refers to the same process of heating biomass through microwave radiation. Microwave heating is a unique pyrolysis technique that heats biomass particles internally, unlike other methods that use external heat transfer from a high-temperature source. It is a relatively new thermochemical technology that is still in its infancy, but it offers many advantages over conventional pyrolysis. Microwave pyrolysis of biomass can assist in energy recovery, waste management, biomass conversion to usable energy products, and reaction time reduction during pyrolysis [132]. The starting material is thoroughly mixed with a microwave adsorbing material (charcoal) that can absorb an acceptable amount of microwave energy. Microwave heating uses a high dielectric constant material like water, offering processing advantages when wet biomass is used. Microwave pyrolysis of biomass produces a low liquid yield of about 30% but is relatively free of entrained material due to the absence of carrier gas, agitation, and fluidization, rendering the process much cleaner and more controllable. Numerous studies have explored microwave pyrolysis of biomass using various feedstocks, including wood [133], corn stover [134], rice straw [135], oil palm biomass [136, 137], and oil palm empty fruit bunches [138, 137, 139, 140] compared microwave pyrolysis to conventional pyrolysis and found significant differences in the purity of the bio-oil produced between the two techniques.

Table 4: 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 %	Medium	High	High	Medium	Easy	Low
CFB and Transported bed	Commercial	75 wt%	High	High	High	Medium	Easy	Low
Rotating Cone	Demonstration	70 wt %	High	High	Low	low	Medium	High
Ablative	Laboratory	75 wt %	High	Low	Low	Low	Difficult	High
Screw or Auger	Pilot	65 wt %	Medium	Medium	Low	Low	Medium	High
Entrained flow	Laboratory	60 wt %	Medium	High	High	Easy	Easy	Low
Vacuum	None	60 wt %	High	Low	Low	High	Difficult	Medium

Adapted from [118]

12.Pyrolysis Products

Pyrolysis of lignocellulose biomass, including oil palm wastes, produces biogas, bio-oil, and biochar, with composition and distribution determined by feedstock composition, moisture content, and pyrolysis process characteristics.

12.1.Bio-oil

Pyrolysis is a new technique for extracting liquid bio-oil from empty palm fruit bunches and solid char and gaseous products, yielding up to 75% wt with significant water extraction from both the initial biomass moisture content and reaction product [141]. Bio-oil, a liquid mixture of water and chemicals, is extracted from oil palm biomass building blocks like cellulose, hemicellulose, and lignin, used for transportation fuels and other value-added products.[47, 142, 143, 144]. Bio-oil, a dark brown liquid produced through pyrolysis, is similar to mother biomass in character and can be used in boilers, engines, and gas turbines for heat and electricity generation [145, 112]. Bio-oil's characteristics, including thermal stability, combustion properties, and corrosiveness, require careful attention in pyrolytic oil processing, despite extensive research on biomass feedstock, reactor sizes, and quality control [46]. Yaman, S [46], in his work, suggested hydrogenation and catalytic cracking as potential methods to enhance the bio-oil product by reducing oxygen content and eliminating alkalis. Dynamotive utilizes fast pyrolysis technology to convert biomass into primary liquid fuel, which can be blended with hydrocarbon fuels or converted into transportation-grade liquid hydrocarbon fuels like gasoline/diesel [150].

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 [151, 152]. The pyrolysis oil product and tar undergo secondary reactions like decarboxylation, decarbonylation, dehydrogenation, deoxygenation, and cracking to produce gas components [153]. The pyrolysis temperature significantly impacts gas production during the reaction, with high temperatures resulting in increased gas production due to the transformation of tar into gases [46].

12.3. Biochar

Pyrolysis produces biochar, a dense material containing metals and contaminants. It's formed when lignin and hemicellulose are thermally degraded, containing 10%-35% of biomass. Biochar is a mixture of carbon, hydrogen, and inorganic species [77]. Pyrolysis residues accumulate in reactors, but exit gases remove some during cleaning, preventing secondary reactions. Increased temperature decreases biochar production. Sukiran et al. [31] found that the highest biochar yield of EPFB and MF occured at 300 °C, while the lowest is at 700 °C, primarily due to the biomass's lignin content. Pyrolysis, a method of generating biochar, is particularly advantageous due to its versatility, especially when performed at moderate temperatures and a short residence time [131]. Biochar, a soil amendment, retains mineral components during pyrolysis, benefiting agriculture and domestic use. It functions similarly to activated carbon in gas cleaning and water treatment systems. According to [154, 155], the likely usage of biochar depends on its surface area, carbon recalcitrance, and high nutrient content, as illustrated in Figure 4.

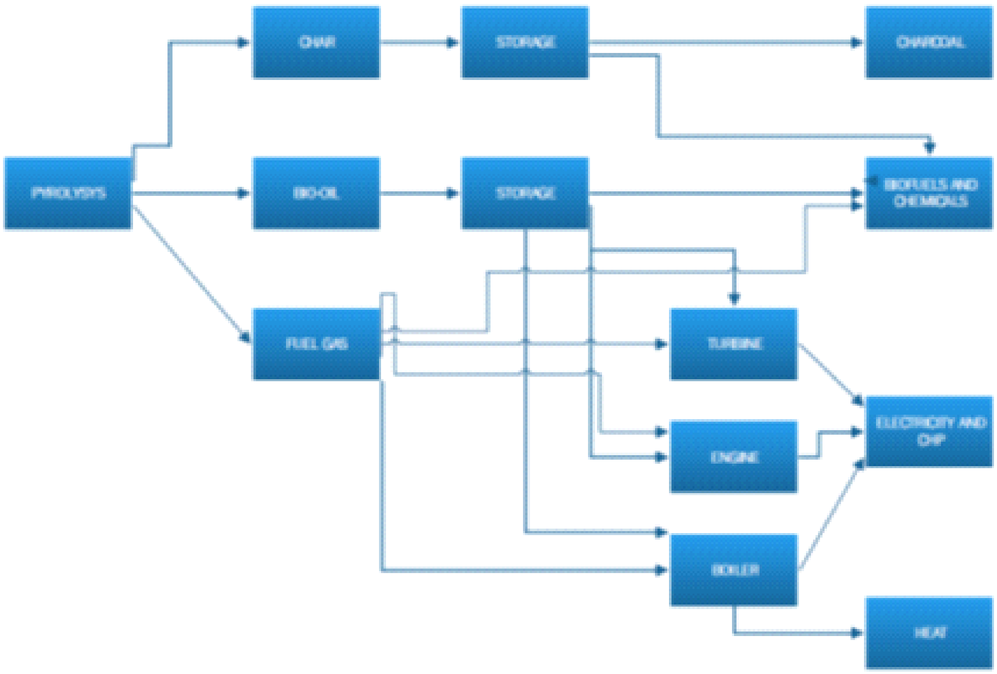


Figure 4: Products from the pyrolysis of EPFB biomass
Adapted from [131]

13. Pyrolysis product distribution

Pyrolysis, a complex process involving biomass heating in a non-reactive environment, is influenced by parameters like reactor temperature, heating rate, system pressure, reactor configuration, and feedstock type [156]. The temperature is the key factor in pyrolysis product distribution [157, 158]. The process involves the thermal decomposition of organic components in biomass at temperatures ranging from 350°C to 800°C, without the presence of air or oxygen [159]. The influence of temperature on the yield of the pyrolysis product is depicted in Figure 5. Pyrolysis breaks down large biomass into gases, oils, and solid char, with char production favoring low temperatures and long residence times. Bio-oil, the key product, has higher density and heating benefits but is easier to handle [114, 5]. Bio-oil with high oxygen content can be removed through catalytic cracking and hydrodeoxygenation, with a maximum yield of around 500 °C depending on feedstock.

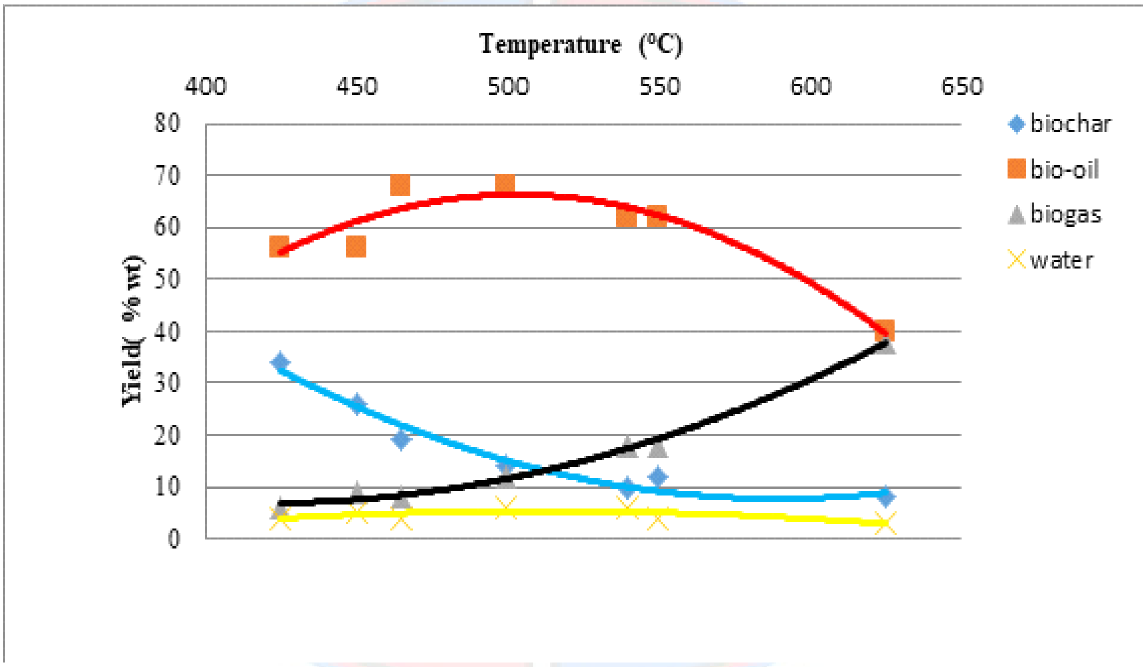


Figure 5: Relative proportion of products in pyrolysis of biomass
Adapted from [160]

14.Bio-oil stabilization and Upgrading

Improvements in the ignition properties of bio-oils are the focus of comprehensive studies. 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, fractionation, and new products are transforming biorefineries to enhance, stabilize, and improve the properties of bio-oil [161] [162, 163]. Biomass pretreatment and hot vapour filtering can enhance the stability of bio-oil by reducing oxygen content, eliminating the carboxylic acid group, and lowering char content [141]. To produce stabilized bio-oil, a bio-oil recovery system and a catalyst are needed. Mild hydrotreating extracts pollutants like sulphur, nitrogen, and oxygen, while other methods for extracting O2 and producing less reactive bio-oil are being studied. Initially, efforts to stabilize biomass pyrolysis products focused on using microfiltration membranes for char removal and catalytic processing for transportation fuel production.[164, 165]. Zeolite, a low-cost catalyst, is widely utilized under atmospheric pressure to convert oxygenated bio-oil into renewable gasoline and diesel fuels [166, 80]. Ro, et al., [167], demonstrated the selectivity of aromatic hydrocarbons through catalytic pyrolysis of oil palm waste over zeolite, optimizing the molecule sizes of hydrotreated bio-oil for gasoline, diesel, and jet fuel.

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

The biofuel industry's growth is hindered by a lack of knowledge of pyrolysis technologies, as the process is influenced by various variables [119]. The composition of the biomass and the process conditions have a direct impact on the production of bio-oil from oil palm wastes and other biomasses. Sand as a heat carrier with smaller particle size, shorter vapor residence time, and an average temperature of 500°C maximizes bio-oil yields without relying on product quality carrier [168] [169, 170], [171], [172]. Experimental studies reveal various operating conditions, designs, and parameters impacting final product yield and quality. These include initial biomass moisture content, flow rate, feedstock composition, reactor form, reaction temperature, heating rate, and particle sizes. These factors are summarized as follows:

15.1. Biomass Feedstock Composition and Particle Size

Lignocellulose biomass components, cellulose, hemicellulose, lignin, and extractives, influence pyrolysis product yield and distribution. The bio-oil properties are greatly affected by the composition of the biomass feedstock and particle size [169, 170]. Studies indicate that the size of biomass particles directly impacts heating rate, aerosol release, and product distribution. Garcia-Nunez, et al. [119] found that particle size increases mass transfer limitations, leading to higher char and gas yields in fast pyrolysis reactors. Fast pyrolysis reactors typically utilize tiny particles to achieve high heating rates and high bio-oil yields.

15.2. Effect of biomass moisture content

Studies by Beaumont and Schwab [169], have revealed that increased moisture content in biomass leads to charring and lowers bio-oil yield, necessitating pre-heating and grounding of feedstock before pyrolysis. Generally, biomass performance in biofuel production is influenced by its specific properties such as its elemental composition, calorific value, moisture content, ash content, volatile matter, and bulk density.

15.3. Effect of temperature

The temperature is crucial in the pyrolysis of lignocellulose biomass as its degradation is influenced by it [36]. Various authors suggest that the optimal temperature for fast pyrolysis of lignocellulose biomass is around 500°C and this temperature encompasses the degradation ranges for the three major biomass constituents. [173]. The physicochemical properties of the pyrolyzed products of EPFB, including bio-oil and biochar, are improved with increasing pyrolysis temperature, while yield, cation exchange capacity, and H, C, and N contents decrease.

15.4. The Impact of Biomass Ash Content.

Ash content in biomass affects pyrolysis product distribution, affecting bio-oil production. The ash content also affects pyrolysis product distribution, affecting bio-oil production by reducing bio-oil yield, according to Venderbosch [78]. Similarly, Abdullah & Gerhause [176], analysis of empty fruit bunch pyrolysis revealed that organic yield can vary from 60% at 1 wt. percent ash to 35% at 3.5 wt. percent ash content.

15.5. Heating rate

Studies show that heating rate affects biomass pyrolysis temperature, with increased heating rates increasing the H/C ratio and a decrease in the O/C ratio. The heating rate increases the conversion of bio-oil and enhances biomass decomposition and production in all pyrolysis pressure regions. At higher heating rates the bio-oil obtained has chemical properties similar to diesel oil.

15.6. Vapour residence time

The vapor residence time in a biomass pyrolysis reactor significantly influences the distribution of pyrolysis products, with prolonged residence time and high temperatures leading to secondary cracking. Long vapor residence times over 1 second enable secondary reactions, leading to char production and decreased bio-oil yield. [78, 177]. A short vapour residence time in the reactor, on the other hand, would result in inadequate biomass fragmentation, resulting in the output of a highly viscous oil with a lower yield [178]. If biochar and biogas are the desired pyrolysis products, a longer residence time is preferred since studies show that the yield of char and gasses increases with a longer residence time.

16. Modeling and Optimization of fast pyrolysis systems

Fast pyrolysis processes are complex, with no consensus on reaction mechanisms, making reactor design and pilot industrial-scale operation challenging due to the lack of a comprehensive model [6]. Energy systems optimization and process modeling aim to plan, design, and execute future energy systems. Model design, implementation, and validation are aided by understanding the theoretical context of the model. Construction of a model, according to Lund, et al. [179], entails defining and focusing on a single feature, thus modeling the dynamic interdependencies and characteristics of an engineering system. For the pyrolysis of empty fruit bunch biomass, a variety of energy optimization models have been developed, each with its own set of features and outcomes [180, 181]. By optimizing the operating conditions, the catalytic pyrolysis of oil palm based wastes could achieve the maximum yield of pyrolytic products at a higher efficiency. Different methodologies have been used by various researchers to improve the process conditions, with varying degrees of success. Many have used the Design of the experiment (DOE) response surface technique to achieve the full yield of products by considering the effect of each pyrolysis parameter as well as their interaction [182, 183]. Yun, et al, [125] developed a detailed Aspen Plus model for an industrial plant generating biomethane from palm fruit bunches, achieving 80.6 percent thermal efficiency and a final gas product of 99.2 wt% CH_4 and 0.8 wt% H_2.

17. Pyrolysis of EPFB Case Studies

EPFB, lignocellulose biomass from the palm oil industry, has potential as a bioenergy source, reducing waste and fossil fuel reliance. Pyrolysis conversion to bio-oil, bio-gas, and char is the most effective method for maximizing its energy production, with pyrolysis char being ideal for solid fuel use due to its high calorific value. Abdullah and Bridgwater [44], conducted a lab-scale experiment to extract pyrolytic oil from EPFB biomass, evaluating its potential as a renewable energy source, while Abdullah and Gerhause, [176], compared the properties of EPFB-derived oil with wood-derived bio-oil.

Khor and Lim [184], studied the impact of pyrolysis parameters on product yield in EPFB pyrolysis. They found optimal conditions for achieving a char product with 74.8 percent fixed carbon and a calorific value of 28.61MJ/kg. Mohamed, et al, [185], optimized a pyrolysis process using EPFB feedstock and Central Composite Design, achieving a 46.2% bio-oil yield at 442.15 oC, 866 µm EPFB particle size, and 483 seconds reactor holding time. Similarly, Mahmood et al. [186] successfully optimized bio-oil production using an ablative pyrolysis reactor by comparing the best kinetic parameters for pyrolytic processes. Shahlan, et al., [187], developed a gasification system for hydrogen gas production from oil palm empty fruit bunches, achieving optimal temperatures and pressures of 850°C and 1 atm, while Widiatmoko et al., [188], utilized two-stage pyrolysis of oil palm fruit bunch to increase graphene yield to 70% at 350°C, characterized using SEM, TEM, Raman Scattering, and X-ray.

18. The Role of Heterogeneous Catalysis in pyrolysis of EPFB

Catalyst pyrolysis is the most promising method for upgrading bio-oil to transportation fuel, but its necessity depends on biomass cellulosic content and reactor type [2][116]. Research by Thangalazhy-Gopakumar, et al, [189], Zabeti, et al. [190], Mansur, et al, [191], and others have demonstrated that catalytic pyrolysis is a promising method for various biomass feedstock applications. Other researchers [193, 194] show that catalytic pyrolysis, a method involving high heating rates and short gas residence times, maximizes product yield and improves bio-oil quality by removing oxygenated compounds, increasing calorific value, and decreasing viscosity. Catalytic cracking and hydrodeoxygenation are processes where bio-oil reacts with hydrogen at high pressure and moderate temperature, resulting in the production of hydrocarbon compounds and water. Catalytic cracking and hydrodeoxygenation are widely utilized methods to enhance bio-oil for fuel applications [195].

19.Extraction of chemicals from bio-oil

As a result, the chemicals derived from bio-oil contribute significantly to the economic benefit of bio-oil. By conducting an accurate assessment of the bio-oil, both qualitatively and quantitatively, the most important components of bio-oils would be identified, allowing us to analyze and identify bio-oils with desired characteristics for downstream production of fuels or chemicals. Chemical extraction from bio-oil involves adsorption, distillation, and fractionation, with acetone as the adsorption solvent and phase separation and aqueous extraction as the fractionation process [196].

Bio-oils are divided into two fractions: a water-insoluble phase for fuel or chemical manufacturing, and a water-soluble aqueous phase constituted by oxygenates. The aqueous phase of bio-oil is highly heterogeneous in composition, with the main constituents being acids (19-25 wt %), ketones (12-20 wt %), phenols (wt %), and furans (1 wt %). [197, 198]. Phenolic compounds extracted from biomass are a critical feedstock for the sustainable development of hydrocarbon biofuels. Due to the high concentrations of phenol groups (phenol, 2-methoxy-) and furfural, they are especially well suited as value-added chemicals for extraction from bio-oil. Separation of bio-oil can be achieved in stages by precipitation and extraction, or by deoxygenating the oil to produce a higher-grade transportation fuel. The aqueous fraction of bio-oils can be reformed through valorisation to add additional value and gain.

20. Future Challenges

1. The primary challenge of oil palm wastes pyrolysis is to refine the process to increase product quality and quantity while lowering costs and minimizing environmental impact.

2. Research should be focused on improving bio-oil quality and developing high-grade pyrolysis oil techniques while exploring alternative biomass forms for pyrolysis feedstock.

3. Biomass pyrolysis produces bio-oil with high oxygen content, causing low calorific value, corrosion, and instability. The cost of oxygen removal is still higher than in fossil-based oil production.

21. Conclusions

1. The environmental effects of continued use 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 the search for alternative and sustainable energy sources.
2. Fast pyrolysis of empty palm fruit bunches and 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.
3. However, while the technology for converting food crops to ethanol is well developed, converting lignocellulose biomass to bio-oil through pyrolysis faces numerous challenges.
4. Pyrolysis technology offers technical advantages over traditional biological conversion processes, utilizing biomass for biofuel production. It produces volatile gases, vapour fractions, tar elements, and carbon-rich residues. Commercial viability is limited, requiring further research for improved reliability and efficiency.
5. 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.
6. Various reactor configurations are being studied, and a few have already been scaled up to large demonstration units. Fast pyrolysis for fuel oil production is on the verge of being commercially viable.
7. Research suggests ideal parameters like 500°C temperatures, high heating rates,

and short volatile residence time maximize the bio-oil yield, making fluidised bed reactors the most common reactor type.

8. 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 oil palm based wastes are held in high regard as a widely distributed biomass with enormous potential for biofuel generation via pyrolysis processes.

Conflict of interest-

The authors declare no conflict of interest.

References-

[1]. M. Akia, F. Yazdani, E. Motaee, D. Han and H. Arandiyan, “A review on the conversion of biomass to biofuel by nanocatalysts,” Biofuel Research Journal, vol. 1, pp. 16-25, 2014.

[2]. B. Sibel and H. ªeyma, “Catalytic Pyrolysis of Biomass,” in Catalyst, IntecOpen, 2017, pp. 167-196.

[3]. P. O’Connor, “A General Introduction to Biomass Utilization Possibilities,” in The Role of Catalysis for the Sustainable Production of Bio-Fuels and Bio-Chemicals, Amsterdam, The Netherlands, Elsevier B.V, 2013, pp. 1-24.

[4]. N. Scarlat, J. Dallemand, F. Monforti-Ferrario, and V. Nita, “The role of biomass and bioenergy in a future bio-economy: policies and facts.,” Environ Dev, vol. 15, p. 3–34, 2015.

[5]. F. Jens, W. Scott, V. Anthony, Bridgwater, and D. Javier, “A kinetic reaction model for biomass pyrolysis processes in Aspen Plus,” Applied Energy, vol. 188, p. 595–603, 2017.

[6]. J. Montoya, F. Chejne-Janna and M. Garcia-Pérez, “ Fast pyrolysis of biomass: A review of relevant aspects. Part I: Parametric study,” DYNA, vol. 82, no. 192, pp. 239-248, 2015.

[7]. B. Tissot and D. Welte, Petroleum Formation and Occurrence, Berlin/New York: Springer-Verlag, 1984.

[8]. B. Kamm, P. Gruber, and M. Kamm, Biorefineries-Industrial Processes and Products: Status Quo and Future Directions, Weinheim: Wiley-VCH, 2006.

[9]. A. Bridgwater, D. Meier, and D. Radlein, “An overview of fast pyrolysis of biomass.,” Organic Geochemistry, vol. 30, no. 12, p. 1479–93, 1999.

[10]. J. Kawser, J. Hayashi and C. Li, “Pyrolysis of a Victorian brown coal and gasification of nascent char in CO2 atmosphere in a wire-mesh reactor.,” J. Fuel, vol. 83, pp. 833-843, 2004.

[11]. D. Laird, R. Brown, J. Amonette and J. Lehmann, “Review of the Pyrolysis Platform for Producing Bio-oil and Biochar: Technology, Logistics and Potential Impacts on Greenhouse Gas Emissions, Water Quality, Soil Quality and Agricultural Productivity.,” Biofuel Bioprod Bioref, vol. 3, p. 547–562, 2009.

[12]. C. Cardoso, M. Machado, and E. Caramao, “Characterization of bio-oils obtained from pyrolysis of bocaiuva residues.,” Renew Energy 1., vol. 91, pp. 21-23, 2016.
[13] M. D. Solikhah, F. Pratiwi, Y. Heryana, A. Wimada, F. Karuana, A. Raksodewanto and A. Kismanto, “Characterization of Bio-Oil from Fast Pyrolysis of Palm Frond and Empty Fruit Bunch,” in IOP Conf. Series: Materials Science and Engineering, Tangerang Selatan, Indonesia, 2018.
[14] M. Mettler, D. Vlachos and P. Dauenhauer, “Top ten fundamental challenges of biomass pyrolysis for biofuels,” Energy Environ. Sci., vol. 5, p. 7797–7809, 2012.
[15] E. Okoh, B. Oruabena and E. Nelson, “Bioproducts Engineering Solution to Sustainable Energy - Retrospection,” in Lecture notes in civil engineering, K. Arvind, R. Reddy and A. Bansal, Eds., Singapore, Springer Nature Singapore Pte Ltd, 2019, pp. 291-306.
[16] J. Cao, X. Zhao, K. Morishita, L. Li, X. Xiao, R. Obala, X. Wei and T. Takarda, “Triacetonamine formation in a bio-oil from fast pyrolysis of sewage sludge using acetone as the absorption solvent.,” Bioresour. Technol. , vol. 101, pp. 4242-4245, 2010.
[17] X. Lian, Y. Xue and Z. Zhao, “Progress on upgrading methods of bio-oil: A review,” Int. J. Energy Res., vol. 41, pp. 1798-1816, 2017.
[18] Y. Xu, Y. Li and C. Wang, “ In-situ hydrogenation of model compounds and raw bio-oil over Ni/CMK-3 catalyst.,” Fuel Process. Technol. , vol. 161, pp. 226-231, 2017.
[19] J. Bozell, “ Feedstocks for the future – bio-refinery production of chemicals from renewable carbon.,” Clean , vol. 36, no. 8, p. 641–647, 2008.
[20] T. Vispute, H. Zhang, A. Sanna, R. Xiao and G. Huber, “Renewable chemical commodity feedstocks from integrated catalytic processing of pyrolysis oils.,” Science, vol. 330, no. 6008, pp. 1222-1227 , 2010.
[21] R. Brown, Y. Zhang, G. Hu and R. Brown, “Modeling and Analysis: Technoeconomic analysis of biobased chemicals production,” Biofuels, Bioprod. Bioref. , vol. 6, p. 73–87, 2012.
[22] M. Misson, R. Haron, M. Kamaroddin and N. Amin, “Pretreatment of empty palm fruit bunch for production of chemicals via catalytic pyrolysis.,” Bioresour. Technol., vol. 100 , no. 11 , pp. 2867-2873 , 2009.
[23] X. Lim and J. Andrésen, “Pyro-catalytic deoxgenated bio-oil from palm oil empty fruit bunch and fronds with boric oxide in a fixed-bed reactor,” Fuel Process. Technol. , vol. 92, no. 9, pp. 1796-1804, 2011.
[24] T. Lin and C. Kuo, “Study of products yield of bagasse and sawdust via slow pyrolysis and iron-catalyse,” Journal of Analytical and Applied Pyrolysis, vol. 96, pp. 203-209., 2012.

[25] R. Lou, S. Wu, G. Lv and A. Zhang, “Factors related to minerals and ingredients influencing the distribution of pyrolysates derived from herbaceous biomass, fast pyrolysis factors for gases,” Bio Resource, vol. 8, no. 1, pp. 1345-1360, 2013.
[26] L. Edye, G. Richards and G. Zheng, “ Transition metals as catalysts for pyrolysis and gasification of biomass,” Wood Chemistry Laboratory, University of Montana, Missoula, MT 59812, 2014.
[27] C. Pittman, D. Mohan, A. Eseyin, Q. Li, L. Ingram, E.-B. Hassan, B. Mitchell, H. Guo and P. Steele, “Characterization of bio-oils produced from fast pyrolysis of corn stalks in an auger reactor,” Energy Fuels,, vol. 26, pp. 3816-3825, 2012.
[28] E. Bensah and M. Mensah, “Chemical Pretreatment Methods for the production of Cellulosic Ethanol: Technologies and Innovations,” International J. of Chemical Engineering, Article ID 719607,, p. 21pages, 2013 .
[29] I. Park, J. Heo, H. Ly, J. Kim, H. Lim and S. Kim, “Fast pyrolysis of acid-washed oil palm empty fruit bunch for bio-oil production in a bubbling fluidized-bed reactor,” Energy, vol. 179, pp. 317-527, 2019.
[30] M.-A. Razzaque, “ Development and assessment of a fast pyrolysis reactor for bio-oil, syngas and bio-char production from biomass residues.,” PhD thesis, University of Nottingham, Nottingham, 2016.
[31] M. Sukiran, C. Chin and N. Abu Bakar, “Bio-oils from Pyrolysis of Oil Palm Empty Fruit Bunches,” Am. J. Applied Sci, vol. 6 , no. 5, pp. 869-875, 2009.
[32] W. Tsai, M. Lee and Y. Chang, “Fast pyrolysis of rice straw, sugarcane bagasse and coconut shell in an induction-heating reactor.,” J.Anal. Appl. Pyrol., vol. 76 , pp. 230-237, 2006.
[33] D. Radlein and A. Quignard, “A Short Historical Review of Fast Pyrolysis of Biomass,” Oil & Gas Science and Technology – Rev. IFP Energies nouvelles, , vol. 68 , no. 4, pp. 765-783 , 2013.
[34] B. Uzun, P. A.E. and E. Putun, “Fast pyrolysis of soybean cake: Product yields and compositions.,” J. Biores. Technol, vol. 97, pp. 569-576, 2006.
[35] B. Uzun, A. Putun and E. Putun, “Composition of products obtained via fast pyrolysis of olive-oil residue: Effect of pyrolysis temperature.,” J. Anal. Appl. Pyrol., vol. 79 , pp. 147-153, 2007.
[36] O. Onay and O. Kockar, “Pyrolysis of rapeseed in a free fall reactor for production of biooil,” J. Fuel, vol. 85, pp. 1921-1928., 2006.
[37] D. Ozcimen and F. Karaosmanoglu, “Production and characterization of bio-oil and biochar from rapeseed cake.,” J. Renew. Energ., vol. 29 , pp. 779-787, 2004.
[38] D. G. Pillay and E. Da-Silva, “Sustainable development and bioeconomic prosperity in Africa: Bio-fuels and the South African

gateway," African Journal of Biotechnology, vol. 8 , no. 11, pp. 2397-2408, 2009.
[39] A. Ghaly and A. Ergudenler, " Thermal Degradation of Cereal Straws in Air and Nitrogen," Journal of Applied Biochemistry and Biotechnology, vol. 27, no. 1, pp. 111-126, 1991.
[40] Y. Chiew and S. Shimada, " Current state and environmental impact assessment for utilizing oil palm empty fruit bunches for fuel, fiber and fertilizer: a case study of Malaysia.," Biomass Bioenergy, vol. 51, pp. 109 -124, 2013.
[41] H. Joselin, G. Unn and A. Krishnan, "Quantifying environmental performance of biomass energy.," Renew Sust Energy Rev, vol. 59, p. 292–308, 2016.
[42] P. Kumaran, N. Mazlini, I. Hussein, M. Nazrain and M. Khairul, "Technical feasibility studies for Langkawi WCO (waste cooking oil) derived-biodiesel.," Energy , vol. 36 , pp. 1386-1393, 2011.
[43] J. Mabrouki, A. Abbassi, K. Guedri, A. Omri and M. Jeguirim, "Simulation of biofuel production via fast pyrolysis of palm oil residues," Fuel , vol. 159 , pp. 819-827, 2015.
[44] N. Abdullah and A. Bridgwater, "Pyrolysis liquid derived from oil palm empty fruit bunches.," J. Phys. Sci. , vol. 17, p. 117–129., 2006.
[45] F. Sulaiman and N. Abdullah, "Optimum conditions for maximising pyrolysis liquids of oil palm empty fruit bunches.," Energy , vol. 36 , no. 5, pp. 2352-2359, 2011.
[46] S. Yaman, "Pyrolysis of biomass to produce fuels and chemical feedstocks," Energy Convers Manage, vol. 45, p. 651–671, 2004.
[47] A. Bridgwater and G. Peacocke, "Fast pyrolysis processes for biomass.," Renewable and Sustainable Energy Reviews, vol. 4, pp. 1-73, 1999.
[48] Z. Husain, Z. Zainal and M. Abdullah, " Analysis of biomass-residue-based cogeneration system in palm oil mills.," Biomass Bioenerg, vol. 24, pp. 117-124, 2003.
[49] J. Kurnia, S. Jangam, S. Akhtar, A. Sasmito and A. Mujumdar, "Prolysis advances in biofuel from oil palm and palm oil processing waste: a review.," Biofuel Research Journal, vol. 9, pp. 332-346, 2016.
[50] A. Nuru, A. Nasrin, S. Loh and Y. Choo, "Bioethanol production by fermentation of oil palm empty fruit bunches pretreated with combined chemicals.," J Appl Environ Biol Sci, vol. 4 , no. 10, pp. 234-242, 2014.
[51] N. Abdullah, H. Gerhauser and F. Sulaiman, "Fast pyrolysis of empty fruit bunches," Fuel, vol. 89, p. 2166–2169, 2010.
[52] S. Loh and Y. Choo, "Prospect, challenges and opportunities on biofuels in Malaysia.," in Advances in biofuels, New York, Springer, 2013, p. 3–14.
[53] S. Hosseini and M. Wahid, "Utilization of palm solid residue as a source of renewable and sustainable energy in Malaysia.," Renew Sust Energy Rev, vol.

40, p. 621–632, 2014.

[54] P. Ninduangdee and V. Kuprianov, “Combustion of palm kernel shell in a fluidized bed: optimization of biomass particle size and operating conditions.,” Energy Convers Manage, vol. 85, p. 800–808, 2014.

[55] S. Chang, “An overview of empty fruit bunch from oil palm as feedstock for bio-oil production.,” Biomass Bioenergy, vol. 62, p. 2–9, 2014.

[56] M. Awalludin, O. Sulaiman, R. Hashim and W. Wan Nadhari, “An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion specifically via liquefaction.,” Renew Sust Energy Rev, vol. 50, p. 1469–1484., 2015.

[57] K. Anyaoha, R. Sakrabani, K. Patchigolla and A. Mouazen, “ Evaluating oil palm fresh fruit bunch processing in Nigeria.,” Waste Management & Research, p. 1–11, 2018.

[58] K. Anyaoha, R. Sakrabania, K. Patchigolla and A. Mouazen, “Critical Evaluation of Oil Palm Fresh Fruit Bunch Solid Wastes as Soil Amendments: Prospects and Challenges,” Resour, Conser. & Recyl, vol. 136, pp. 399-409, 2018.

[59] B. B. Nyakuma, A. Johari and A. Ahmad, “Analysis of the Pyrolytic Fuel Properties of Empty Fruit Bunch Briquettes.,” Journal of Applied Sciences, vol. 12, no. 24, pp. 2527-2533, 2012.

[60] B. B. Nyakuma and A. A. A. Johari, “Thermochemical Analysis of Palm Oil Wastes as fuel for Biomass Gasification.,” Jurnal Teknologi., vol. 3, p. 62, 2013.

[61] S. Loh, “The potential of the Malaysian oil palm biomass as a renewable energy,” Energy Conversion and Management, vol. xxx, pp. 1-14, 2016.

[62] T. Bridgwater, “Biomass for energy,” J Sci Food Agric, vol. 86, p. 1755–1768, 2006.

[63] H. Heo, H. Park, Y. Park, C. Ryu, D. Suh and Y. Suh, “Bio-oil production from fast pyrolysis of waste furniture sawdust in a fluidized bed.,” Bioresour. Technol., vol. 101, pp. 91-96, 2010.

[64] B. Sutrisno and A. Hidayat, “Pyrolysis of palm empty fruit bunch: Yields and analysis of bio-oil,” in MATEC Web of Conferences 154, 2018.

[65] M. Balat, M. Balat, E. Kýrtay and H. Balat, “Main routes for the thermo-conversion of biomass into fuels and chemicals. Part 1. Pyrolysis systems.,” Energy Convers Manage , vol. 50, p. 3147–57, 2009.

[66] C. Williams, T. Westover, R. Emerson, J. Tumuluru and C. Li, “Sources of biomass feedstock variability and the potential impact on biofuels production.,” BioEnerg. Res., vol. 9, pp. 1-14, 2015.

[67] P. Ravindra, S. Hardinge, H. Vuthaluru and A. Amir, “Production of bio-oil from oil palm empty fruit bunch by catalytic fast pyrolysis: a review,” Biofuels,

vol. 7, no. 6, pp. 647-660, 2016.
[68] S. Ahmad, F. Md Ali and K. Md Isa, "Compilation of liquefaction and pyrolysis method used for bio-oil production from various biomass: A review," Environ. Eng. Res., vol. 25, no. 1, pp. 18-28, 2019.
[69] J. Saini, R. Saini and L. Tewari, "Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: Concepts and recent developments.," 3 Biotech, vol. 3, pp. 337-353., 2014.
[70] A. Demirbas, "The importance of bioethanol and biodiesel from biomass," .Energy Source Part B, vol. 3 , pp. 177-185, 2008.
[71] D. Mohan, C. Pittmann and P. Steele, " Pyrolysis of wood/biomass for bio oils: a critical review,," Energy Fuels , vol. 20 , pp. 848-889., 2006.
[72] D. Feldman, D. Banu, A. Natansohn and J. Wang, "Structure–properties relations of thermally cured epoxy-lignin polyblends.," J App Polym Sci, vol. 42, pp. 1537-1550, 1991.
[73] K. Law, D. W. Wan and A. Ghazali, "Morphological and chemical nature of fiber strands of oil palm empty-fruit-bunch (OPEFB).," BioResources., vol. 2, no. 1, pp. 352-362, 2007.
[74] J. Idris, Y. Shirai, Y. Anduo, A. Ali, M. Othman, I. Ibrahim and M. Hassan, "Improved yield and higher heating value of biochar from oil palm biomass at low retention time under self-sustained carbonisation.," Journal of Cleaner Production, 104,, vol. 104, pp. 475-479, 2015.
[75] C. Welker, V. Balasubramanian, C. Petti, K. Rai, S. DeBolt and V. .. Mendu, "Engineering plant biomass lignin content and composition for biofuels and bioproducts," Energies, vol. 8 , pp. 7654-7676, 2015.
[76] H. Yang, R. Yan, H. Chen, D. Lee, D. Liang and C. Zheng, "Pyrolysis of palm oil wastes for enhanced production of hydrogen rich gases.," Fuel Proc. Technol., vol. 87, pp. 935-942, 2006.
[77] M. Jahirul, M. Rasul, A. Chowdhury and N. Ashwath, "Biofuels production through biomass pyrolysis—a technological review.," Energies, vol. 5, no. 12, p. 4952–5001, 2012.
[78] P. W. Venderbosch R, " Fast pyrolysis technology development.," Biofuels Bioprod. Biorefining, vol. 4 , no. 2, p. 178208, 2010.
[79] M. Mohammed, A. Salmiaton, W. Wan-Azlina and A. M. Mohamad, " Gasification of oil palm empty fruit bunches: A characterization and kinetic study," Bioresource Technology, Vols. 110,, p. 628–636, 2012.
[80] W. Khanday, ,. G. Kabir and B. Hameed, "Catalytic pyrolysis of oil palm mesocarp fibre on a zeolite derived from low-cost oil palm as," Energy Conversion and Management, vol. 127, pp. 265-272, 2016.
[81] N. Zainal, A. J. Aziz, R. Mamat, M. Hassan, E. Bahrin and S. Abd-Aziz, " Microwave-assisted pre-carbonisation of palm kernel shell produced charcoal

with high heating value and low gaseous emission.," Journal of Cleaner Production,, vol. 142, pp. 2945-2949, 2016.

[82] D. J. Hayes, "Biomass Composition and Its Relevance to Biorefining," in The Role of Catalysis for the Sustainable Production of Bio-Fuels and Bio-Chemicals , Amsterdam, The Netherlands, Elsevier B.V, 2013, pp. 25-39.

[83] P. Patwardhan, J. Satrio, R. Brown and B. Shanks, "Influence of inorganic salts on the primary pyrolysis products of cellulose," Bioresource Technology,, vol. 10, no. 1, pp. 4646-4655., 2010 .

[84] P. Lahijani, Z. Alimuddin, A. Rahman and M. .. Mohammadi, "Ash of palm empty fruit bunch as a natural catalyst for promoting the CO2 gasification reactivity of biomass char," Bioresource Technology, vol. 132 , pp. 351-355, 2013..

[85] L. Wilson, W. Yang, W. Blasiak, G. John and C. Mhilu, "Thermal characterization of tropical biomass feedstocks," Energy Conversion and Management, vol. 52 , pp. 191-198, 2011.

[86] M. Jamaluddin, K. Ismail, I. M. Mohd, G. Z. Ab, M. Abdullah, M. Safian, Mohd and N. Hakimi, "Microwave-assisted pyrolysis of palm kernel shell: Optimization using response surface methodology (RSM).," Renewable Energy, vol. 55 , pp. 357-365, 2013.

[87] S. Kim, B. Koo and R. JW, "Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed.," Fuel Process.Technol., vol. 108, pp. 118-124., 2013.

[88] R. Dodson, E. Cooper, A. Hunt, A. Matharu, J. Cole and A. Minihan, " Alkali silicates and structured mesoporous silicas from biomass power station wastes: the emergence of bio-MCMs.," Green Chem, vol. 15, pp. 1203-1210, 2013.

[89] S. Hameed, A. Sharma, V. Pareek, H. Wu and Y. Yu, "A review on biomass pyrolysis models: Kinetic, network and mechanistic models," Biomass and Bioenergy, vol. 123, pp. 104-122, 2019.

[90] M. H. Tahir, G. Çakman, J. L. Goldfarb, Y. Topcu, S. R. Naqvi and S. Ceylan, "Demonstrating the suitability of canola residue biomass to biofuel conversion via pyrolysis through reaction kinetics, thermodynamics and evolved gas analyses," Bioresource Technology, vol. 279, pp. 67-73, 2019.

[91] A. Oasmaa and D. Meier, "Characterisation, analysis, norms and standards," in Fast pyrolysis of biomass: A handbook, United Kingdom, 2005, pp. 19-60.

[92] A. Bridgwater and S. Bridge, "A Review of Biomass Pyrolysis and Pyrolysis Technologies," in Biomass Pyrolysis Liquids Upgrading and Utilization, A. Bridgwater and G. Grassi, Eds., The Netherlands, Springer, 1991, pp. 11-92.

[93] N. Abdullah, F. Sulaiman and H. Gerhauser, "Characterisation of Oil Palm Empty Fruit Bunches for Fuel Application," Journal of Physical Science, vol. 22, no. 1, pp. 1-24, 2011.

[94] D. Woulf, J. Lehmann, S. Joseph, C. Campbell, F. Christo and L. Angenent,

"An open-source biomass pyrolysis reactor," Biofuels, Bioprod. Bioref., vol. 11, p. 945–954, 2017.
[95] J. White, W. Catall and B. Legendre, "Biomass pyrolysis kinetics: a comparative critical review with relevant agricultural residue case studies.," Anal Appl Pyrol, 2011.
[96] N. Panwara, V. Richa Kotharib and V. Tyagic, "Thermo chemical conversion of biomass – Eco friendly energy routes," Renewable and Sustainable Energy Reviews , vol. 16 , p. 1801– 1816, 2012.
[97] N. Abdullah, H. Gerhauser and A. Bridgwater, "Bio-oil from fast pyrolysis of oil palm empty fruit bunches," Journal of Physical Science, vol. 18 , no. 1, pp. 57-74, 2007.
[98] M. Samolada, A. Papafotica and I. Vasalos, "Catalyst evaluation for catalytic biomass pyrolysis," Energy & Fuel, vol. 14 , p. 1161–1167, 2000.
[99] A. Lappas, M. Samolada, D. Iatridis and S. V. I. Voutetakis, " Biomass pyrolysts in a circulating fluid bed reactor for the production of fuel and chemicals," Fuel, vol. 81, no. 16, p. 2087–2095, 2002.
[100] J. Gaunt and J. Lehmann, "Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy," Environ, Sci. Technol, vol. 42, pp. 4152-4158, 2008.
[101] K. Roberts, B. Gloy, S. Joseph, Scott, NR and Lehmann J, " Life cycle assessment of biochar systems: estimating the energetic, Biomass Conv. Bioref. , vol. 2, pp. 21-39, 2012 .
[104] J. Lédé, "Biomass Fast Pyrolysis Reactors: A Review of a Few Scientific Challenges and of Related Recommended Research Topics," Oil & Gas Science and Technology – Rev. IFP Energies nouvelles, vol. 68, no. 5, pp. 801-814, 2013.
[105] A. Demirbaº, "Biomass resource facilities and biomass conversion processing for fuels and chemicals.," Energy Convers. Manage. , vol. 42, no. 11, pp. 1357-1378., 2001.
[106] A. Bridgwater, "Fast Pyrolysis of Biomass," in Thermal Biomass Conversion,, A. Bridgwater, H. Hofbauer and S. Van-Loo, Eds., London, Thermal Net, CPL Press, UK, 2009.
[107] A. Bhavanam and R. Sastry, "Biomass gasification processes in downdraft fixed bed reactors: a review.," International Journal of Chemical Engineering and Applications, vol. 2, pp. 425-433, 2011.
[108] S. Czernik and A. Bridgwater, "Overview of application of biomass fast pyrolysis oil.," Energy Fuels, vol. 18, pp. 590-598, 2004.
[109] T. Kan, V. Strezov and T. Evans, "Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters.," Renew Sustain Energy Rev , vol. 57, no. 11, pp. 26-40, 2016.

[110] A. Zheng, Z. Zengli, H. Zhen, K. Zhao, W. Guoqiang, W. Xiaobo, H. Fang and L. Haibin, "Catalytic fast pyrolysis of biomass pretreated by torrefaction with varying severity," . Energy & Fuels, vol. 28, no. 9, pp. 5804-5811, 2014.
[111] B. Zhang, Z. Zhaoping, C. Paul and R. Roger, Bioresource technology, vol. 197 , pp. 79-84., 2015.
[112] A. Demirbas, "Hydrocarbons from pyrolysis and hydrolysis processes of biomass.," Energy Source Part A, vol. 25, p. 67–75, 2003.
[113] A. Demirbas, "Yields and heating values of liquids and chars from spruce trunkbark pyrolysis," .Energy Source Part A, vol. 27, no. 35, pp. 1367-1373, 2005.
[114] A. Bridgwater, "Biomass fast pyrolysis.," Therm Sci., vol. 8, pp. 21-49, 2004.
[115] K. Sembiring, N. Rinaldi and S. Simanungkalit, "Bio-oil from Fast Pyrolysis of Empty Fruit Bunch at Various Temperature," Energy Procedia, vol. 65, p. 162 – 169, 2015.
[116] A. Demirbas, "Recent advances in biomass conversion technologies.," Energy Educ. Sci. Technol., vol. 6, p. 77–83, 2000.
[117] T. Cornelissen, Y. Yperman, G. Reggers, S. Schreurs and R. Carleer, ". Flash co-pyrolysis of biomass with polylactic acid. Part 1: Influence on bio-oil yield and heating value," Fuel, vol. 87, p. 1031–1041, 2008.
[118] K. G. Vamshi and L. Qi, "Fast Pyrolysis of Biomass," in Recent Advances in Thermo-Chemical Conversion of Biomass, Elsevier, 2015, pp. 479-491.
[119] J. Garcia-Nunez, M. Pelaez-Samaniego, M. Garcia-Perez, I. Fonts, J. Abrego, R. . Westerhof and M. Garcia-Perez, "Historical Developments of Pyrolysis Reactors: A Review," Energy & Fuels, vol. 31, pp. 5751-5775, 2017.
[120] D. C. Scott, J. Piskorz and D. Radlein, "Liquid product from continous fast pyrolysis of biomass," Ind. Eng. Chem., Process DesDeV., vol. 24, p. 581, 1985.
[121] R. G. Graham, B. A. Freel and M. A. Bergougnou, "The production of pyrolysis Liquids, Gas and char from wood and cellulose by fast pyrolysis.," in Research in Thermodynamical Biomass Conversion, London, Elsevier Applied Science, 1988, pp. 31-40.
[122] B. M. Wagenaar, R. H. Vanderbosh, J. Carrasco, R. Strenziok and B. van der Aa, "Scalling up of the rotating cone technology for biomass fast pyrolysis.," in 1st World Conference and Exhibition on Biomass for Energyand Industry, Seville, Spain,, 2000.
[123] J. Diebold and J. Scahill, "Production of Primary Pyrolysis Oils in a Vortex Reactor.," in Pyrolysis Oils from Biomass: Producing, Analyzing,and Upgrading, Washington, DC, American Chemical Society, 1988, pp. 629-641.
[124] D. S. Scott.Canada Patent . 1,241,541, 1988.
[125] H. Yun, S. Ramirez-Solis and V. Dupont, "Bio-CH4 from empty fruit bunch

via pyrolysis - direct methanation: Full plant model and experiments with bio-oil surrogate," Journal of cleaner production, vol. 244, p. 118737, 2020.

[126] K. Azduwin, M. Ridzuan, A. Mohamed and S. Hafis, "Pyrolysis of Empty Fruit Bunch (EFB) in a vertical fixed bed reactor," Applied Mechanics and Materials, vol. 695 , pp. 228-231, 2015.

[127] A. Bridgwater, "Review of fast pyrolysis of biomass and product upgrading," Biomass and Bioenergy, vol. 38, pp. 68-94, 2012.

[128] R. Graham and M. F. B. Bergougnou, "The kinetics of vapor phase cellulose fast pyrolysis reactions.," Biomass and Bioenergy, vol. 7, no. 16, pp. 33-47, 1994.

[129] N. Dong, K. Luo and Q. Wang, "Modelling biomass pyrolysis in a bubbling fluidized bed reactor: impact of intra-particle heat conduction," Fuel Processing Tech., vol. 161, pp. 199-203, 2017.

[130] P. Shusheng, "fuel - flexible energy generation," in Fuel- flexible energy generation: solid, liquid and gasseous fuel, Elsevier ltd, 2016, pp. 305-316.

[131] A. Bridgwater, " Review of fast Pyrolysis of Biomass and Product Upgrading,," Biomass Bioenergy , vol. 38, pp. 1-27, 2011.

[132] F. Motaseni and M. Afzal, "A review on the Microwave assisted pyrolysis technique," Renewable & Sustainable Energy Review, vol. 28, pp. 317-330, 2013.

[133] M. Miura, H. Kaga, A. Sakurai and T. K. Kakuchi, "Rapid pyrolysis of wood block by microwave heating.," Journal of Analytical and Applied Pyrolysis,, vol. 71 , pp. 187-199, 2004.

[134] H. Lei, S. Ren and J. Julson, "The effects of reaction temperature and time and particle size of corn stover on microwave pyrolysis.," Energy & Fuels,, vol. 23 , pp. 3254-3261, 2009.

[135] Y. Huang, W. Kuan, S. Lo and C. Lin, "Hydrogen-rich fuel gas from rice straw via microwave-induced pyrolysis.," Bioresour Technol,, vol. 101 , pp. 1968-1973, 2010.

[136] A. Salema and F. Ani, "Microwave induced pyrolysis of oil palm biomass.," Bioresour. Technol., vol. 102, no. 3, pp. 3388-3395, 2011.

[137] A. Salema and F. Ani, "Microwave-assisted pyrolysis of oil palm shell biomass using an overhead stirrer.," Journal of Analytical and Applied Pyrolysis, vol. 96 , pp. 162-172, 2012a.

[138] R. Omar, A. Idris, R. Yunus, K. Khalid and M. Isma, "Characterization of empty fruit bunch for microwave-assisted pyrolysis.," Fuel, vol. 90, pp. 1536-1544, 2011.

[139] A. Salema and F. Ani, "The Performances of Fixed and Stirred Bed in Microwave Pyrolysis of Biomass.," APCBEE Procedia, vol. 3, pp. 188-193, 2012b.

[140] A. Salema and F. Ani, "Pyrolysis of oil palm empty fruit bunch biomass pellets

using multimode microwave irradiation.," Bioresource technology, vol. 125 , pp. 102-107, 2012c.

[141] D. Meier, B. Beld, A. Bridgwater, D. Elliott, A. Oasmaa and F. Preto, "State-of-the-art of fast pyrolysis in IEA bioenergy member countries," Renewable and Sustainable Energy Reviews, vol. 20, pp. 619-641, 2013.

[142] S. Thangalazhy-Gopakumar, S. Adhikari, H. Ravindran, R. Guptam, O. Fasina, M. Tu and S. Fernando, "Physiochemical properties of bio oil produced at various temperature from pine wood using an auger reactor,," Bioresource Technolog, , vol. 101, pp. 8389-8395., 2010.

[143] D. Kirenraj, Y. Suzana, K. Cheah, M. Nur.Suriawanie, K. Haswin and S. Gurdeep, "Optimization Studies on Catalytic Pyrolysis of Empty Fruit Bunch (EFB) Using L9 Taguchi Orthogonal array," International Journal of Biomass & Renewables, vol. 5, no. 3, pp. 27 - 32, , 2016 .

[144] M. Balat, " Production of bioethanol from lignocellulosic materials via the biochemical pathway: a review.," Energy Convers Manage, vol. 52, pp. 858-875, 2011.

[145] A. Putun, A. Ozcan and E. Putun, "Pyrolysis of hazelnut shells in a fixed-bed tubular reactor: yields and structural analysis of bio-oil.," J Anal Appl Pyrol , vol. 52, pp. 33-49, 1999.

[146] X. Lim, A. Sanna and J. Andrésen, "Influence of red mud impregnation on the pyrolysis of oil palm biomass-EFB.," Fuel. , vol. 119, pp. 259-265, 2014.

[147] M. Asadieraghi and W. Daud, "In-depth investigation on thermochemical characteristics of palm oil biomasses as potential biofuel sources.," J. Anal. Appl. Pyrol. , vol. 115, pp. 379-391 , 2015.

[148] F. Abnisa, W. Daud, W. Husin and J. Sahu, "Utilization possibilities of palm shell as a source of biomass energy in Malaysia by producing bio-oil in pyrolysis process.," Biomass Bioenergy, vol. 35, pp. 1863-1872, 2011.

[149] M. Islam, R. Zailani and F. Ani, "Pyrolytic oil from fluidised bed pyrolysis of oil palm shell and itscharacterisation.," Renew. Energ., vol. 17, no. 1, pp. 73-84, 1999.

[150] T. Bidgewater, "Biomass pyrolysis," in IEA Bioenergy annual Report, 2007, pp. 4-19.

[151] M. Blanco Lopez, C. Blanco, A. Martinez-Alonso and J. Toscon, "Composition of gases released during olive stones pyrolysis.," J. Anal. Appl. Pyrolysis, vol. 65, p. 313–322, 2002.

[152] P. McKendry, "Energy production from biomass (part 1): Overview of biomass.," Bioresour.Technol., vol. 83, p. 37–46, 2002.

[153] E. Kantarelis and A. Zabaniotou, "Valorization of cotton stalks by fast pyrolysis and fixed bed air gasification for syngas production as precursor of second

generation biofuels and sustainable agriculture.," Bioresour. Technol., vol. 100, p. 942–947, 2009.

[154] X. Lee, L. Lee, S. Gan, S. Thangalazhy-Gopakumar and H. Ng, "Biochar potential evaluation of palm oil wastes through slow pyrolysis: Thermochemical characterization and pyrolytic kinetic studies.," Bioresource Technology, vol. 236 , no. 863, pp. 155-163, 2017.

[155] X. Xu, Y. Zhao, J. Sima, L. Zhao, O. Mašek and X. Cao, "Indispensable role of biochar-inherent mineral constituents in its environmental applications: A review," Bioresource Technology,, vol. 241, pp. 887-899, 2017.

[156] M. Küçük and A. Demirbas, "Biomass conversion processes.," Energy Convers Manage, vol. 38, pp. 151-165, 1997.

[157] G. Maschio, C. Koufopanos and A. Lucchesi, "Pyrolysis, a promising route for biomass utilisation.," Bioresour Technol, vol. 42, pp. 219-231, 1992.

[158] J. Encinar, F. Beltran, A. Ramiro and J. Gonzalez, "Pyrolysis/gasification of agricultural residues by carbon dioxide in the presence of different Additives: influence of variables.," Fuel Process Technol, vol. 55, pp. 219-233, 1998.

[159] T. Fisher, M. Hajaligol, B. Waymack and D. Kellogg, "Pyrolysis behaviour and kinetics of biomass derived materials.," J. Appl. Pyrolysis, vol. 62, p. 331–349., 2002.

[160] International Energy Agency. Annual Report, "IEA Bioenergy: Task 34, Pyrolysis of Biomass," International Energy Agency, Paris, France, 2006.

[161] D. Elliott, "Historical developments in hydroprocessing bio-oils.," Energy & Fuels, vol. 21, pp. 1792-1815, 2007.

[162] S. Kumar, J.-P. Lange, G. VanRossum and S. Kersten, "Bio-oil fractionation by temperatureswing extraction: Principle and Application.," Biomass and Bioenergy, vol. 83, pp. 96-104, 2015.

[163] X. Li, S. Kersten and B. Schuur, "Extraction of acetic acid, glycolaldehyde and acetol from aqueous solutions mimicking pyrolysis oil cuts using ionic liquid.," Separation and Purification technology, vol. 175, no. 24, pp. 498-505, 2017.

[164] A. Javaid, T. B. G. Ryan, X. Pan, T. Vispute and S. Bhatia, "Removal of char particles from fast pyrolysis bio-oil by microfiltration.," Journal of Membrane Sience, vol. 363, pp. 120-127, 2010.

[165] T. Vispute, H. Zhang, A. Sanna, R. Xiao and G. Huber, "Renewable chemical commodity feedstocks from integrated catalytic processing of pyrolysis oils.," Science, vol. 330, pp. 1222 - 1227, 2010.

[166] J. Li, L. Xiangyu, Z. Guoqiang, W. Wei, W. Chengwen, K. Sridhar and Y. W. solutions., "Catalytic fast pyrolysis of biomass with mesoporous ZSM-5 zeolites prepared by desilication with NaOH," Applied Catalysis A: General, vol. 470, pp. 115-122, 2014.

[167] D. Ro, K. Young-Min, L. In-Gu, J. Jungho, J. Sang-Chul, C. K. Sang and P. Young-Kwon, “.Bench scale catalytic fast pyrolysis of empty fruit bunches over low cost catalysts and HZSM-5 using a fixed bed reactor,” Journal of Cleaner Production, vol. 176, pp. 298-303, 2018.

[168] X. Wang, S. Kersten, W. Prins and W. van Swaaij, “Biomass Pyrolysis in a Fluidized bed reactor. Part 2: Experimental Validation of Model results.,” Ind. Eng. Chem. Res., vol. 44, pp. 8786-8795, 2005.

[169] O. Beaumont and Y. Schwob, “Influence of physical and chemical parameters on wood pyrolysis.,” Ind. Eng. Chem. Res., vol. 23, p. 637., 1984.

[170] R. Westerhof, H. Nygard, W. van Swaaij, S. Kersten and D. Brilman, “Effect of Particle Geometry and Microstructure on Fast Pyrolysis of Beech Wood.,” Energy & Fuels,, vol. 26 , no. 4, p. 2274, 2012.

[171] E. Hoekstra, W. Van Swaaij, S. Kersten and K. Hogendoorn, “Fast Pyrolysis in a novel wire-mesh reactor: Decomposition of pine wood and model compounds.,” Chemical Engineering Journal, vol. 187, pp. 172-184, 2012.

[172] J. Montoya, B. Pecha, D. Roman, F. Chejna-Janna and M. Garcia-Perez, “Effect of temperature and heating rate on product distribution from the pyrolysis of sugarcane bagasse in a hot plate reactor.,” J. Anal. Appl. Pyrolysis, vol. 123 , pp. 347-362, 2017.

[173] D. Shen, W. Jin and J. Hu, “An overview on fast pyrolysis of the main constituents in lignocellulosic biomass to valued-added chemicals: Structures, pathways and interactions.,” Renew Sustain Energy Rev., vol. 51 , pp. 761-774, 2015.

[174] J. Onwudili, N. Insura and P. Williams, “Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: effects of temperature and residence time.,” J. Anal. Appl. Pyrol. , vol. 86, pp. 293-303, 2009.

[175] L. Zhao, D. Chen, Z. Wang, X. Ma and G. Zhou, “Pyrolysis of waste plastics and whole combustible components separated from municipal solid wastes: comparison of products and emissions.,” in Proceedings of the Thirteen International Waste Management and landfill sympossium, Sardinia, 2011.

[176] N. Abdullah and H. Gerhause, “Bio-oil derived from empty fruit bunches,” Fuel, vol. 87, p. 2606–2613, 2008.

[177] R. Pogaku, B. Hardinge, H. Vuthaluru and A. Amir, “Production of bio-oil from oil palm empty fruit bunch by catalytic fast pyrolysis: a review,” Biofuels, vol. 7, no. 6, pp. 647-660, 2016.

[178] A. Sharma, V. Pareek and D. Zhang, “Biomass pyrolysis—A review of modelling, process parameters and catalytic studies.,” Renew Sustain Energy Rev., vol. 50, p. 10811096, 2015.

[179] H.,. A. F. ,. Lund, F. Hvelplund, D. Connolly, B. Mathiesen and P. **Karnøe,**

"Modelling, Simulation versus Optimisation: Theoretical Positions in Energy System," Energies, vol. 840 , p. 10, 2017.

[180] D. Connolly, H. Lund, B. Mathiesen and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems.," Appl. Energy, vol. 87, p. 1059–1082, 2010.

[181] A. Grunwald, "Energy futures: Diversity and the need for assessment," Futures, vol. 43, pp. 820-830, 2011.

[182] Y. H. Chan, V. D. Khanh, Y. Suzana, L. Mook Tzeng, M. Z. Asna and U. Yoshimitsu, "Studies on catalytic pyrolysis of empty fruit bunch (EFB) using Taguchi's L9 Orthogonal Array.," Journal of the Energy Institute, vol. 87 , no. 3 , pp. 227-234, 2014.

[183] W. Charusiri and T. Vitidsant., "Response Surface Methodology Optimization of Biofuels Produced by Catalytic Pyrolysis of Residual Palm Oil from Empty Fruit Bunch over Magnesium Oxide.," Journal of Chemical Engineering of Japan, vol. 50 , no. 9, pp. 727-736, 2017.

[184] K. Khor and K. Lim, "Slow pyrolysis of palm empty fruit bunches," Inter. Energy Jour., vol. 9, pp. 181-188, 2008.

[185] A. Mohamed, H. Zainab and M. Daud, "Optimization of the Pyrolysis Process of Empty Fruit Bunch (EFB) in a Fixed-Bed Reactor Through a Central Composite Design (CCD)," in 21st National Symposium on Mathematical Sciences (SKSM21), 2014.

[186] H. Mahmood, N. Ramzan, A. Shakeel, M. Moniruzzaman, Iqbal.T, A. Kazmi and M. Sulaimam, "Kinetic pyrolysis and optimizationof parameters for pyrolysis: a comparism of different lignocellulosic biomass," Energy Sources: Part A: Recovery, Utilization and Environmental Effects, vol. 41, no. 14, pp. 1690-1700, 2019.

[187] S. Shahlan, K. Kidam, L. Medic-Pejic, T. Abdullah, M. Mohamad Wijayanuddin Ali and Y. Zakaria, "Process Development of Oil Palm Empty Fruit Bunch Gasification by using Fluidised Bed Reactor for Hydrogen Gas Production," Chemical Engineering Transactions, vol. 63, pp. 559-564, 2018.

[188] P. Widiatmoko, I. F. Sukmana, I. Nurdin, T. Prakoso and H. Devianto, "Increasing yield of graphene synthesis from oil palm empty fruit bunch via two-stages pyrolysis," in 1st International Symposium of Indonesian Chemical Engineering (ISIChem), 2019.

[189] S. Thangalazhy-Gopakumar, S. Adhikari and R. Gupta, "Catalytic pyrolysis of biomass over H+ZSM 5 under hydrogen pressure.," Energy & Fuels., vol. 26, no. 8, pp. 5300-5306, 2012.

[190] M. Zabeti, T. Nguyen, H. Heeres and K. Seshan, " In situ catalytic pyrolysis of lignocellulose using alkali-modified amorphous silica alumina.," Bioresource Technology., vol. 118, pp. 374-381, 2012.

[191] D. Mansur, T. Yoshikawa, K. Norinaga, J. Hayashi, T. Tago and T. Masuda, “Production of ketones from pyroligneous acid of woody biomass pyrolysis over an iron-oxide catalyst.,” Fuel, vol. 103, pp. 130-134, 2013.

[192] G. Chen, J. Andries and H. Spliethoff, “Catalytic pyrolysis of biomass for hydrogen rich fuel gas production,” Energy Convers. Manage., vol. 44 , no. 14, pp. 2289-2296, 2003.

[193] D. Bulushev and J. Ross, “Catalysis for conversion of biomass via pyrolysis and gasification: A review.,” Catalysis Today, vol. 171, pp. 1-13, 2011.

[194] Q. Bu, H. Lei, S. Ren, W. L., Q. Zhang, J. Tang and R. Ruan, “Production of phenols and biofuels by catalytic microwave pyrolysis of lignocellulosic biomass.,” Bioresource Technology, vol. 108, pp. 274-279, 2012.

[195] R. French and S. Czernik, “Catalytic pyrolysis of biomass for biofuels production.,” Fuel Processing Technology., vol. 91, no. 1, pp. 25-32, 2010.

[196] Y. Elkasabi, C. Mullen and A. Boateng, “ Distillation and Isolation of Commodity Chemicals from Bio-Oil Made by Tail-Gas Reactive Pyrolysis.,” ACS Sustain. Chem. Eng. , vol. 2, pp. 2042-2052, 2014.

[197] S. Zhang, Y. Yan, T. Li and Z. Ren, “Upgrading of liquid fuel from the pyrolysis of biomass.,” Bioresour. Technol. , vol. 96 , p. 545–550, 2005.

[198] S. Wang, Q. Wang, X. Jiang, X. Han and H. Ji, “Compositional analysis of bio-oil derived from pyrolysis of seaweed.,” Energy Conv. Manag. , vol. 68, pp. 273-280, 2013.