



## Review

# Bio-oil derived from palm empty fruit bunches: Fast pyrolysis, liquefaction and future prospects

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## ABSTRACT

Bio-oil is a potential biofuel for fossil fuel substitution due to its great versatility in feedstock and environmental benefits. In particular, bio-oil derived from palm empty fruit bunches (PEFB) has drawn considerable research attention in recent years owing to the abundant supply of PEFB and the emergence of motivation to turn waste into wealth for environmental sustainability. Therefore, this paper aims to provide a state-of-the-art review on the bio-oil derived from PEFB. A particular emphasis is placed on the optimum production conditions of PEFB-derived bio-oil by various fast pyrolysis and liquefaction processes, as well as on the characteristics of PEFB-derived bio-oil in terms of their physicochemical properties, major chemical components and their compositions. A comparison of physicochemical properties of PEFB-derived bio-oil with those of other biomass-derived bio-oil and petroleum fuel oil is also outlined. Upgrading of PEFB-derived bio-oil by different methods along with its fuel applications and future prospects are also discussed.

## 1. Introduction

Energy is essential for life on Earth and plays a crucial role as a cornerstone in driving the global socio-economic development. It is primarily derived from fossil fuels such as crude oil, coal, and natural gas, which account for the lion's share of the total world energy consumption of over 80% [1], due to their relatively simple and low-cost conversion processes. However, fossil fuel reserves are finite, and with the escalating world population and rapid industrialization in developing countries, it is only a matter of time before they are diminished. Some projections say that there may only be as few as 35, 107 and 37 years of crude oil, coal and natural gas [2], respectively, left in the world, while others estimate them to be last in 40, 200 and 70 years [3], respectively. Meanwhile, the excessive burning of fossil fuels from various anthropogenic activities also contributes to global warming due to the emissions of noxious greenhouse gases which may lead to potentially catastrophic changes in climate, environment, biodiversity and public health [4]. Therefore, environmentally benign and sustainable renewable energy sources such as wind, sunlight, waves, and biomass become vital and have been proactively sought after by numerous researchers over the past few decades [5,6].

Of all the renewable energy sources, biomass has been a subject of intense interest among researchers owing to its abundant supply, low cost, biodegradability and carbon neutrality [7]. In general, biomass is any inedible organic matter or waste derived from flora and fauna that

contains solar energy such as wood waste, agro-industrial waste, animal waste, food waste and a whole host of other materials [8]. It can be used directly as a solid fuel or converted into a liquid or gaseous fuel by means of thermochemical or biochemical processes. The thermochemical conversion processes include pyrolysis, liquefaction, and gasification, where the former two convert biomass into bio-oil (also known as biocrude, pyrolysis or pyrolytic oil) as the main product [9] while the latter generates predominantly syngas (a mixture of carbon monoxide, carbon dioxide, hydrogen, and methane) [10]. The biochemical conversion processes, on the other hand, convert biomass into bioethanol [11] and biogas [12] by fermentation and anaerobic digestion, respectively. Among these biofuels, bio-oil, a complex liquid mixture resulting from the thermal degradation of biomass building blocks (cellulose, hemicellulose and lignin), is one of the most technically promising alternatives to fossil fuels. A diverse range of biomass, for example birch sawdust [13], rice straw [14], soap stock [15], waste tire [16], sewage sludge [17], swine manure [18], waste potato starch [19] and algae [20], have been utilized to produce bio-oil, mainly by fast pyrolysis or liquefaction [8]. By converting a huge amount of biomass into bio-oil, a clean and safe environment, good public health and wellbeing, as well as energy independence and economic growth could be accomplished when waste is managed effectively. These advantages, coupled with the environmental benefits of bio-oil of being renewable, biodegradable and significantly low in greenhouse gas emission, have rendered bio-oil substantially cleaner than fossil fuels.

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**List of abbreviations**

BO <sub>aq</sub>	Aqueous-phase bio-oil
BO <sub>mix</sub>	Mixture of BO <sub>org</sub> and BO <sub>aq</sub>
BO <sub>org</sub>	Organic-phase bio-oil
CFP	Catalytic fast pyrolysis
CSL	Catalytic subcritical liquefaction
CSPL	Catalytic supercritical liquefaction
FAME	Fatty acid methyl esters
H:C	Hydrogen to carbon

HHV	Higher heating value
HSHFO	High sulfur heavy fuel oil
LFO	Light fuel oil
LSHFO	Low sulfur heavy fuel oil vc
NCFP	Non-catalytic fast pyrolysis
NCSL	Non-catalytic subcritical liquefaction
NCSPL	Non-catalytic supercritical liquefaction
O:C	Oxygen to carbon
PEFB	Palm empty fruit bunches
TAN	Total acid number

Nevertheless, bio-oil is a low-quality fuel due to some of its deleterious physicochemical properties such as high viscosity, high water content, high oxygen content, high acidity, high instability and low heating value which have hindered its direct application as a fuel [8]. To increase the quality of bio-oil, several upgrading methods such as hydrotreating, hydrocracking, solvent addition, fuel blending or emulsification, esterification, supercritical fluid treatment and steam reforming have been employed [8,21]. In spite of their efficiencies in laboratory-scale studies, none of these upgrading methods have been utilized in large-scale applications due to some of their unresolved technological challenges which have led to their low energy and cost efficiencies [8]. As yet, the application of bio-oil has been restricted largely to substitute petroleum fuel oil, either partially or completely, in stationary devices such as boilers [22], turbines [23], furnaces [24] and diesel engines [25], which are known for their fuel flexibility and high tolerance to low-grade fuels, for electricity generation at power plants. Although relatively rare and still in their infancy, conversion of bio-oil into biochemicals such as olefins [26–28], aromatics [27] and fatty acids [29], as well as into transportation biofuels such as biodiesel [17], green diesel [30], bio-gasoline [31] and bio-jet fuel [32,33], have also been reported.

Palm empty fruit bunches (PEFB), a type of palm biomass generated abundantly from the rapidly growing oil palm industry in Southeast Asia, particularly Malaysia and Indonesia, has drawn a great deal of research attention in recent years following the emergence of motivation to turn waste into wealth for environmental sustainability [34–37]. In Malaysia, for instance, the total PEFB generated in 2017 was approximated to 19.92 million tonnes [38] based on a conservative estimate of the one-to-one ratio of the amount of crude palm oil produced to that of PEFB generated in that year [39]. This prodigious amount of PEFB poses a dire environmental hazard to wildlife and human health if it is not handled appropriately. One of the lucrative methods to mitigate the immense amount of PEFB is utilizing it as a renewable energy feedstock to produce biofuels like bio-oil [9]. In fact, a review of PEFB as bio-oil feedstock centering around such topics as the fundamental characteristics of PEFB, conversion processes of PEFB into bio-oil, and the properties of PEFB-derived bio-oil in comparison with those of petroleum fuel oil had been documented [9]. Nevertheless, detailed discussions on the production conditions, characteristics, upgrading, and fuel applications of PEFB-derived bio-oil were lacking or insufficient. In light of the aforementioned, the present work aims to provide a state-of-the-art review on the bio-oil derived from PEFB. A particular emphasis is placed on the optimum production conditions of PEFB-derived bio-oil by various fast pyrolysis and liquefaction processes, as well as on the characteristics of PEFB-derived bio-oil in terms of their physicochemical properties, major chemical components and their compositions. A comparison of physicochemical properties of PEFB-derived bio-oil with those of other biomass-derived bio-oil and petroleum fuel oil is also outlined. Upgrading of PEFB-derived bio-oil by different methods along with its fuel applications and future prospects are also discussed.

## 2. Optimum production conditions of bio-oil derived from PEFB

The bio-oil derived from PEFB is mostly produced by fast pyrolysis and liquefaction processes [9]. In general, fast pyrolysis is characterized by relatively higher temperature but lower pressure and shorter residence time than liquefaction. It requires drying of feedstock down to approximately 10 wt% moisture content or less [40] which is, however, not needed in liquefaction. Fast pyrolysis undergoes a gas-phase reaction while liquefaction occurs in a liquid medium or solvent under either subcritical or supercritical condition [8]. The solvent used in liquefaction could be water (popularly known as hydrothermal liquefaction), a pure or a mixture of organic solvents, or a mixture of water and organic solvents [41,42]. Both fast pyrolysis and liquefaction are carried out with or without a catalyst, usually under an inert gas (N<sub>2</sub>, He or Ar) atmosphere [43,44], but sometimes under a CO<sub>2</sub> [45], steam [46] or vacuum [47] atmosphere for fast pyrolysis and a H<sub>2</sub> or CO atmosphere for liquefaction [43]. Although bio-oil can be produced by both fast pyrolysis and liquefaction as the main product along with biochar and syngas as side products, its optimum production conditions are totally different between these processes and, in most cases, vary from one biomass feedstock to another in both processes [48,49].

Table 1 summarizes the optimum production conditions of bio-oil derived from PEFB via fast pyrolysis and liquefaction obtained from the literature. All of the PEFB used were unwashed with water prior to their use unless stated otherwise. It was found that fast pyrolysis of PEFB was largely carried out in either a fluidized- or fixed-bed reactor while liquefaction of PEFB in an autoclave reactor regardless of whether the process was catalytic or not. On the whole, the non-catalytic process was more widely used than the catalytic counterpart in either fast pyrolysis or liquefaction of PEFB and a majority of them produced bio-oil as the main product. As shown in Table 1, the highest bio-oil yields of non-catalytic fast pyrolysis (NCFP) and non-catalytic subcritical or supercritical liquefaction (NCSL or NCSPL) of PEFB were attained at 61.34% and 56.20%, respectively, while those of their catalytic counterparts, namely, catalytic fast pyrolysis (CFP) and catalytic subcritical or supercritical liquefaction (CSL or CSPL), were achieved at 44.10% and 68.00%, respectively. Both of the former non-catalytic processes utilized water-washed PEFB as feedstock but produced bio-oil at totally different conditions: temperature of 500 °C vs. 350 °C, pressure of 1 bar vs. 291 bar and residence time of ~1 s vs. 3600 s (Table 1). The upside of washed PEFB over the unwashed PEFB was that the former had much lower ash content, particularly potassium content, than the latter, which in turn suppressed the unfavorable secondary reactions for water, syngas and biochar yields and increased the bio-oil yield [50].

Table 1 also reveals that the bio-oil yields achieved by NCFP of PEFB were often higher than those by CFP of PEFB but those accomplished by NCSL or NCSPL of PEFB were lower than those by CSL or CSPL of PEFB (Table 1). The former could be deduced from the catalytic cracking of bio-oil into water and syngas that led to the diminution of bio-oil yield in CFP of PEFB [51,52], while the latter was due to the enhanced degradation of PEFB by catalysts in CSL or CSPL of PEFB [53].

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