Bio-oil production from pyrolysis of oil palm biomass and the upgrading technologies: A review

Liza Melia Terry [a], Claudia Li [a], Jiuan Jing Chew [a], Aqsha Aqsha [b], Bing Shen How [a], Adrian Chun Minh Loy [c], Bridgid Lai Fui Chin [d], Deni Shidqi Khaerudini [e], Nishar Hameed [f], Guoqing Guan [g], Jaka Sunarso [a,*]

[a] Research Centre for Sustainable Technologies, Faculty of Engineering, Computing and Science, Swinburne University of Technology, Jalan Simpang Tiga, 93350 Kuching, Sarawak, Malaysia
[b] Department of Bioenergy Engineering and Chemurgy, Faculty of Industrial Technology, Institut Teknologi Bandung, Bandung 40132, Jawa Barat, Indonesia
[c] Department of Chemical Engineering, Monash University, Victoria 3800, Australia
[d] Department of Chemical and Energy Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri Sarawak, Malaysia
[e] Research Centre for Physics, National Research and Innovation Agency (BRIN), Gd. 440-442 Kawasan Puspiptek Serpong, South Tangerang, 15314 Banten, Indonesia
[f] Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
[g] Energy Conversion Engineering Group, Institute of Regional Innovation (IRI), Hirosaki University, 2-1-3, Matsubara, Aomori 030-0813, Japan

ARTICLE INFO

ABSTRACT

Oil palm biomass (OPB) represents major portion of the lignocellulosic waste in Malaysia that can be converted into bio-oil. This review aims to provide important insights in OPB-derived bio-oil production by first discussing the chemical compositions of different OPB and their effects to the bio-oil yield and quality obtained from pyrolysis process, followed by discussing the addition of plastics and catalysts into the pyrolysis for bio-oil upgrading, and lastly summarizing the existing technoeconomic and environmental studies and the potential use of process integration and intensification in this topic. Polypropene (PP), low density polyethylene (LDPE), and high density polyethylene (HDPE) have been commonly used in co-pyrolysis of OPB, which can effectively increase the heating value of bio-oil up to 80 % that of diesel. Likewise, acidic, basic, and neutral catalysts have been applied to increase the amount of hydrocarbon and phenol in the bio-oil, further improving the heating value to be comparable to diesel. The bio-oil production from OPB is currently still limited to demonstration scale despite the favorable environmental compatibility and technoeconomic feasibility shown by studies focused on empty fruit bunch (EFB). Several promising advanced pyrolysis processes that integrate other processes such as anaerobic digestion, hydrogen production process, and heat and power generation units as well as the advanced reactor designs are also overviewed here as future innovation of the bio-oil production from OPB, which may play more significant role as the technology matures.

1. Introduction

Oil palm biomass, which is one of the most abundant lignocellulosic biomass in Malaysia, represents an alternative energy resource that can be exploited to reduce the dependency on fossil fuel whilst fulfilling the increasing energy demand [1]. The palm oil industry is currently one of the major contributors to the Malaysian economy, which generates more than 311 million tons of lignocellulosic biomass wastes annually from palm oil plantation and milling activities (Fig. 1). The oil palm biomass is nonetheless presently underutilized despite its potential to be converted to fuel and other value-added products [2]. The current applications of the oil palm biomass are listed in Table 1.

The conversion of oil palm biomass into valuable biofuels can be achieved through biochemical, chemical, and thermochemical processes. Compared to chemical and biochemical approaches, the thermochemical process provides higher flexibility in the feedstock
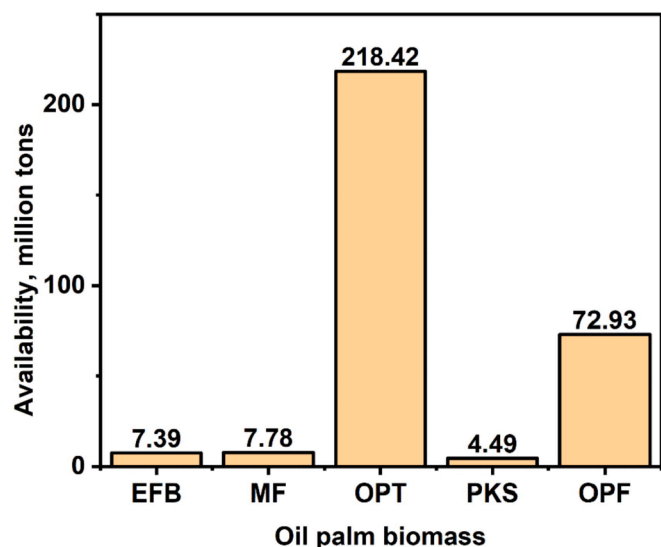
Fig. 1. Production of oil palm biomass in Malaysia in 2020. (The availability of oil palm biomass is calculated based on the standard biomass to fresh fruit bunch extraction rate, where data for oil palm planted area and the fresh fruit bunch processed by mills is obtained from the online reports of the Malaysian Palm Oil Board) [6–8].

Table 1
Current applications of oil palm biomass.

Oil palm biomass	Applications	Ref.
Empty Fruit Bunch (EFB)	Boiler fuel, ash as the fertilizer, carbon source for bioplastic production	[5,8–10]
Mesocarp Fiber (MF)	Boiler fuel, fillers in thermoplastics, board production	[1,5,8,10]
Oil Palm Trunk (OPT)	Plywood, particleboard panel, syngas production through gasification	[5,8,11–13]
Palm Kernel Shell (PKS)	Boiler fuel, adsorbents for wastewater treatment	[5,8,10]
Oil Palm Frond (OPF)	Particleboard panel, pulp, roof tiles, roughage source for ruminants	[1,8,10,12,14]

selection, operating condition, and product distribution [3]. For the production of bio-oil from oil palm biomass, pyrolysis would be the more promising option among the available thermochemical processes (gasification, liquefaction, and pyrolysis) given its high flexibility of feedstock selection (regardless of types, physical shape, and physicochemical properties), operability at broad temperature range and atmospheric pressure, and production of three different types of products (solid, liquid, and gas). The distribution of solid, liquid, and gaseous products is highly dependent on the operating condition applied during the pyrolysis process.

Bio-oil, the liquid product from the pyrolysis, is one of the most attractive biofuels (e.g., bio-diesel, bio-ethanol, and bio-oil) in the near future given its carbon–neutral property [4]. Lower sulfur dioxide and nitrogen dioxide emissions are generated from the use of bio-oil as compared to traditional fossil fuels. Storing and transporting bio-oil is easier relative to biochar and biogas given its compatibility with most of the existing equipment, pumping systems, and safety requirements [3,5].

To date, several reviews related to bio-oil production from pyrolysis and co-pyrolysis of biomass have been published. These reviews mainly present the available pyrolysis and bio-oil upgrading models [15–17], as well as parametric studies for bio-oil production during pyrolysis [18–19]. Abnisa et al. [20] and Zhang et al. [21] extended the parametric analysis to include catalytic and non-catalytic co-pyrolysis of biomass with polymers. Zhang et al. [22] analyzed the importance of catalysts in the pyrolysis and co-pyrolysis of biomass and the

optimization of product distribution. Although these reviews provide a holistic overview of the pyrolysis and co-pyrolysis of biomass to produce bio-oil, they do not focus on oil palm biomass and tend to lean towards biomass that is more abundantly available within their geographical regions. Aside from that, several reviews have focused solely on the pyrolysis of oil palm biomass without covering the main process parameters and operating conditions [23] or are limited to a single type of oil palm biomass, e.g., EFB [9,24] or PKS [25]. This review thus aims to provide a more concise overview on pyrolysis and co-pyrolysis of all types of oil palm biomass as well as a thorough analysis of the main process parameters that affect bio-oil production. The present and projected feasibility of the bio-oil production from oil palm biomass are also discussed. To provide an integrated picture on this topic, the following discussions are made on bio-oil production through pyrolysis, followed by the characterization of oil palm biomass and the available upgrading routes to enhance the fuel properties of the bio-oil from biomass material. Additionally, the existing challenges surrounding oil palm biomass pyrolysis are covered and promising directions for bio-oil production from oil palm biomass are also proposed and discussed.

2. Lignocellulosic properties of oil palm biomass

Oil palm biomass is rendered favorable as the feedstock for bio-oil production through pyrolysis given its abundant availability and the presence of numerous research studies on this topic. The types of oil palm biomass that can be converted into bio-oil include EFB, PKS, MF, OPT, OPF, and oil palm leaf (Fig. 2) [23].

Oil palm biomass consists of 20 to 59 wt.% of cellulose, 20 to 40 wt.% of hemicellulose, and 18 to 50 wt.% lignin (Table 2). Compared to fossil fuels, oil palm biomass tends to have lower nitrogen content (<1 wt.%), sulfur content (<0.2 wt.%), and higher oxygen content (40–50 wt.%) (Table 3). The variation in the biomass physicochemical properties will
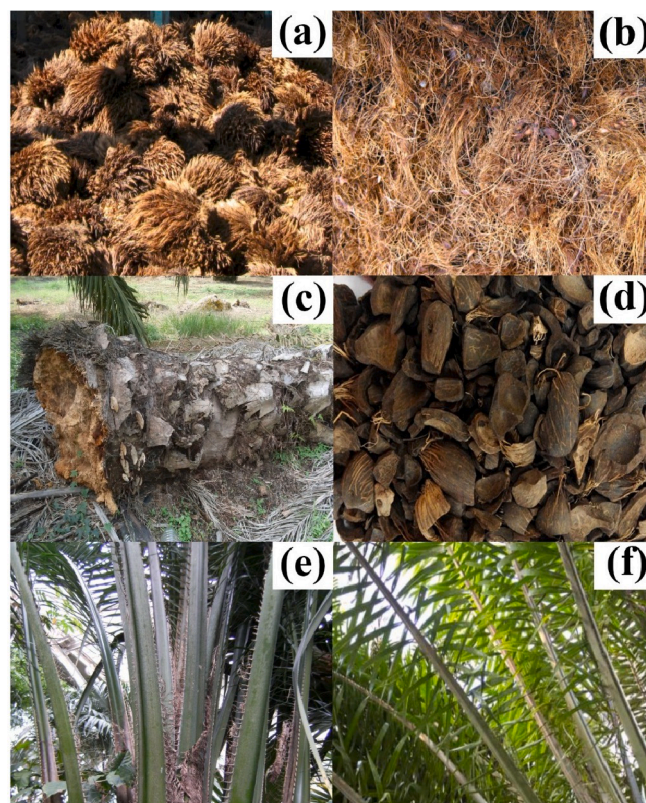

Fig. 2. Oil palm biomass from palm oil mills and plantations. (a) Empty fruit bunch [37], (b) mesocarp fiber [38], (c) oil palm trunk [39], (d) palm kernel shell [40], (e) oil palm frond [41], and (f) oil palm leaf [42].

Table 2

Chemical composition of oil palm biomass.

Oil palm biomass	Cellulose, wt.%	Hemicellulose, wt.%	Lignin, wt.%	Extractives, wt.%	Ash, wt.%	Ref.
EFB	59.70	22.10	18.20	-	-	[26]
MF	40.00	20.00	30.00	9.00	-	[27]
OPT	34.50	31.80	25.70	3.70	4.30	[28]
PKS	20.80	22.70	50.70	4.80	1.00	[28]
OPF	30.40	40.40	21.70	1.70	5.80	[29]

Table 3

Ultimate and proximate analyses of oil palm biomass and plastics.

Feedstocks	Ultimate analysis, wt.%						Proximate analysis, wt.%				HHV, MJ kg^{-1}	Ref.
	C	H	O	N	S	Cl	Moisture content	Volatile content	Fixed carbon	Ash		
EFB	51.77	7.04	40.31	0.72	0.16	-	7.38	76.41	11.57	4.64	18.74	[26]
MF	45.02	6.15	47.89	0.94	-	-	8.60	78.00	7.60	5.80	17.00	[30]
OPT	43.68[a]	6.07[a]	49.84[a]	0.40[a]	0.0[a]	-	7.60[b]	74.06[a]	14.92[a]	3.42[a]	16.11	[29]
PKS	44.56[c]	5.22[c]	49.77[c]	0.40[c]	0.05[c]	-	9.40[b]	82.50[b]	1.40[b]	6.70[b]	15.60	[31]
OPF	43.44[a]	6.08[a]	50.28[a]	0.19[a]	0.01[a]	-	7.50[b]	73.06[a]	16.55[a]	2.89[a]	15.81	[29]
HDPE	85.50[c]	14.20[c]	0.00[c]	0.00[c]	0.30[c]	0.00[c]	0.00[a]	99.40[a]	0.00[a]	0.60[a]	-	[32]
LDPE	85.50[c]	14.30[c]	0.00[c]	0.00[c]	0.20[c]	0.00[c]	0.00[d]	99.70[d]	0.00[d]	0.30[d]	46.60	[32–33]
PP	85.80[d]	14.20[d]	0.00[d]	0.00[d]	0.00[d]	0.00[d]	0.00[d]	80.00[d]	20.00[d]	0.00[d]	46.40	[33–34]
PS	92.20[d]	7.80[d]	0.00[d]	0.00[d]	0.00[d]	0.00[d]	0.00[d]	99.50[d]	0.50[d]	0.00[d]	42.10	[33–34]
PET	64.22	4.65	30.53	0.05	0.55	0.00	0.00	88.61	11.39	0.00	-	[35]
PVC	31.67	4.32	0.00	0.00	1.89	62.12	0.00	98.50	0.00	1.50	-	[36]

Note: [a]dry basis; [b]wet basis; [c]ash free basis; [d]air-dried basis.

affect the quality of the bio-oil during pyrolysis.

To achieve a high bio-oil production efficiency, higher cellulose content of oil palm biomass is desirable since their decomposition produces higher volatiles, which can be condensed into bio-oil during pyrolysis [19]. Among the oil palm biomass, the cellulose content of EFB is the highest (59.70 wt.%), followed by MF (40 wt.%), OPT (34.50 wt.%), OPF (30.40 wt.%), and PKS being the lowest (20.80 wt.%). Palamanit et al. [29] stated that OPF contributes to higher bio-oil yield (45.99 wt. %) than PKS (36 wt.%) during the pyrolysis at 500 °C given its higher cellulose content.

Kim et al. [26] and Bensidhom et al. [43] compared the thermal decomposition behavior oil palm biomass and other types of lignocellulosic biomass in the studies. Kim et al. [26] revealed that the pyrolysis of EFB can produce higher bio-oil yield (53.97 wt.%) as compared to PKS (51.96 wt.%) and Jatropha seedshell cake (47.78 wt.%) at a pyrolysis temperature of 478 °C. Similar results were obtained from another study conducted by Bensidhom et al. [43] as higher bio-oil yield was obtained from the pyrolysis of EFB (26 wt.%) and Date Palm Rachis (26 wt.%) with higher cellulose content as compared to Date Palm Glaich (25 wt. %) and Date Palm Leaflets (17.03 wt.%).

Excessive moisture content in feedstock prior to pyrolysis can result in energy penalty as more heat is required to evaporate water from the biomass during processing. According to literature, the moisture content of the biomass feedstock should be maintained at 10 wt.% or below [15,20]. For oil palm biomass, the moisture content generally lies within the recommended limit of 10 wt.% (Table 3). High moisture content in biomass can also lead to high water content in bio-oil that dampens its energy content (i.e., heating value).

Ash content (i.e., mineral) in oil palm biomass comes from natural life cycle of the plant (i.e., from the soil and fertilizer that forms the essential plant nutrients) (Table 3). In the production of bio-oil, high ash content is undesirable. Patwardhan [44] reported that the presence of NaCl and KCl in the biomass enhanced the formation of glycolaldehyde from cellulose decomposition but reduced the production of levoglucosan. In contrast, $MgCl_2$ and $CaCl_2$ performed well in dehydration reactions during biomass decomposition to enhance the formation of furans and levoglucosan. Lignin decomposition, on the other hand, is not significantly affected by the minerals.

According to Mohammed et al. [45], higher bio-oil yield of 34.23 wt.

% was obtained from the pyrolysis of OPF at 600 °C as compared to EFB (30.23 wt.%) and OPT (29.56 wt.%). This is due to the lower ash content of OPF (3.61 wt.%) as compared to EFB (4.76 wt.%) and OPT (6.51 wt. %). Additionally, they compared the ash content of OPT samples collected from various elevations and they similarly concluded that samples with lower ash content result in a higher bio-oil yield. Fukuda [46] investigated the pyrolysis of EFB (2.1 wt.%), rice husk (31.2 wt.%), rice straw (14.9 wt.%), rubber wood (6.1 wt.%), eucalyptus wood (2.4 wt.%), and Teng wood (<0.1 wt.%) with different ash content at 450 to 550 °C. It has been concluded that higher bio-oil yield obtained from EFB (55.2 wt.%), eucalyptus wood (61.2 wt.%), and Teng wood (58.2 wt.%) as compared to rubber wood (51.6 wt.%), rice husk (49.4 wt.%), and rice straw (49.1 wt.%) given their lower ash content [46].

Besides, the effects of pre-treatment on the properties of oil palm biomass had been studied. The treated EFB with 10 and 20 wt.% HNO_3 contain lower ash content (1.27 and 1.17 wt.%) as compared to the untreated EFB (8.24 wt.%). The bio-oil yield increased from 43.25 to 69.01 wt.% and 66.46 wt.%, respectively when acid-treated EFB with 10 and 20 wt.% HNO_3 were used in the pyrolysis at 500 °C [47]. This is due to the reduction of inorganic materials such as potassium, sodium, and magnesium, which promotes the production of biochar and biogas instead of bio-oil [47–48]. Besides, deionized water washing pretreatment was used to reduce the ash content of EFB from 5.19 to 2.48 wt.% [48]. The bio-oil yield increased when EFB was pre-treated with distilled water and H_2SO_4 [49]. Lim et al. [50] modified EFB by impregnating it with red mud, red mud extract, acidified washed red mud, acidified washed red mud extract, and $FeSO_4$ and pre-treated EFB with acid water and deionized water. They observed that the ash content of EFB was reduced from 7 wt.% to the lowest value of 1.5 wt.% after the modification and pre-treatment.

Torrefaction is one of the pre-treatment methods that can be considered to improve the properties of raw oil palm biomass (i.e., increase energy content and reduce oxygen content and moisture content), which eventually enhances the bio-oil production. Dai et al. [51] reported that bio-oil quality has been improved when torrefied biomass was used during the pyrolysis (based on the review on several studies with different biomass feedstock). The increase in heating value, reductions in acidity, O/C ratio, and water content of the bio-oil produced from the torrefied biomass were observed. However, bio-oil yield

reduces as the torrefaction enhances the cross-linking reactions of biomass during pyrolysis, which increases the solid biochar formation. Dai et al. [51] also pointed out that the integration of torrefaction and pyrolysis can potentially improve the energy efficiency of the whole system.

Sukiran et al. [52] reported that the energy content (calorie value) of oil palm biomass (i.e., EFB, OPF, and OPT) can be increased by 12.21–22.20 % and the oxygen content can be reduced by 31.52–36.66 % after the torrefaction at 200–300 °C. Given the limited studies on the torrefied oil palm biomass for bio-oil production, intensive research studies should be conducted to confirm the potential of applying torrefaction as the pre-treatment method for bio-oil production.

Due to the inherent poor heat conductivity of biomass, particle size reduction can increase the heat transfer efficiency and thus enhance the biomass decomposition during pyrolysis [19–20]. However, excessive heat transfer promotes further cracking of primary volatiles into gaseous products (i.e., lowering bio-oil yield) [19,31]. Thus, the optimum particle size range of the biomass for high bio-oil yield is closely related to the natural structure of the feedstock and reactor designs. For the laboratory scale studies of pyrolysis, the oil palm biomass was prepared in the particle size of less than 2 mm [31,53–55]. Several works have demonstrated that the bio-oil yield from the pyrolysis of EFB and PKS was maximized when an appropriate small particle size range (<0.50 mm for EFB and 0.45 mm to 0.85 mm for PKS) was applied for uniform and higher heat transfer in fluid bed reactor [31,53,56], except in the work of Ogunkami et al. [57]. In the study of PKS pyrolysis using a fixed bed reactor, the bio-oil yield obtained was 15 wt.% when PKS with 5 mm particle size was used, which was lower as compared to bio-oil yield obtained (28 wt.%) when PKS with 1.18 mm particle size was used. The appropriate particle size is closely associated with the types of reactor used. According to Bridgwater [15], fluidized bed reactor is mostly used in larger scale bio-oil production from biomass, whereby less than 2–3 mm is the optimum particle size for the pyrolysis process.

3. Pyrolysis of oil palm biomass

Based on the pyrolysis studies on different oil palm biomass, bio-oil yield increases with temperature increment until a peak temperature where the maximum yield is attained. Beyond this maximum temperature, which differs for different biomass, the bio-oil yield gradually decreases with further temperature increase as illustrated in Fig. 3. This is attributed to the promotion of secondary reactions of the primary
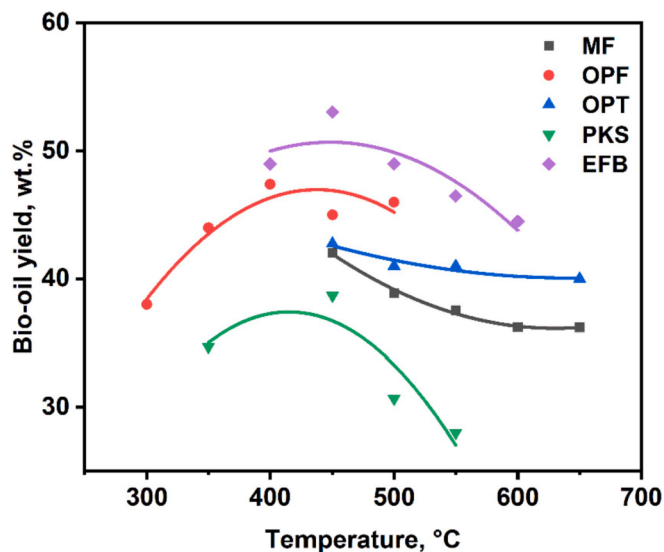

Fig. 3. Bio-oil yield as a function of temperature for the pyrolysis of MF [64], OPF [65], OPT [63], PKS [57], and EFB [60].

volatiles (e.g., acids, alcohols, levoglucosan, and furans) into incondensable gases (e.g., methane, carbon dioxide, and carbon monoxide) with the additional energy input [58,59].

Several works have reported that between 450 and 600 °C, a maximum bio-oil yield ranging from 35 to 55.20 wt.% can be achieved in EFB pyrolysis [46,55,58,60]. Bio-oil yield for PKS can reach up to 30.90–58 wt.% when pyrolysis is performed between 320 and 600 °C [57,61,62]. Unlike EFB and PKS, the pyrolysis of OPT, MF, and OPF have received limited attention from researchers. The bio-oil yield achieved between 400 and 600 °C, for OPT, MF, and OPF are about 39–43.50 wt. %, 37.98–42.03 wt.%, and 46–47.41 wt.%, respectively [29,58,63,27,64–66]. In this temperature range, the formation of valuable compounds such as phenols from lignin and levoglucosan and furans from cellulose are enhanced at 450–600 °C and 400 °C, respectively [67,68]. Beyond 600 °C, secondary reactions will trigger the formation of the secondary chars and incondensable gases and thus reducing the yield of bio-oil.

Heating rate can also affect the biomass decomposition during pyrolysis. Higher heating rate allows higher rate of decomposition for oil palm biomass and increases the yield of bio-oil [18,19]. Sukiran et al. [53] reported that bio-oil yield from the pyrolysis of EFB increases by 40 % with the increase in heating rate from 10 to 100 °C min^{-1} in a fluidized bed reactor at 500 °C. However, Mohamed et al. [69] observed that bio-oil yield increased by 7.45 % when the heating rate increased from 10 to 20 °C min^{-1} and decreased by 17.89 % when the heating rate increased further to 60 °C min^{-1} during the pyrolysis of EFB in a fixed bed reactor at 500 °C. The different trends manifest as the effect of heating rate towards bio-oil production depends on the other process parameters such as types of reactor, feedstock, and process temperature [19].

Bio-oil produced from oil palm biomass contains higher oxygen content (16–46 wt.%), higher water content (1.2–18 wt.%), lower pH (about 3), and lower heating value (18–30 MJ kg^{-1}) (Table 4), which render it unattractive for commercial applications. High oxygen content in bio-oil is mainly attributed to the presence of oxygenated compounds. As cellulose and hemicellulose are the main constituents of EFB, OPF, and MF, the derived bio-oil mainly contains acids and ketones. OPT has relatively high cellulose and lignin content, which contribute to the formation of acids and phenols as the major compounds in the bio-oil. PKS contains higher lignin content and thus contributes to the formation of phenolic compounds as the major compounds in the bio-oil produced (Table 5).

The heating values of bio-oil from EFB, OPT, and OPF range between 18–28 MJ kg^{-1}, which is only around 40–50 % of the heating value of petrodiesel (42–46 MJ kg^{-1}) [75]. When comparing with other oil palm biomass, the heating value of bio-oil derived from PKS is higher (30 MJ kg^{-1}) given its higher lignin content. However, the high lignin content in PKS also favors the formation of biochar and thus, reduces the desirable bio-oil yield. Besides, two studies reported that the effect of temperature towards the increment of heating rate of EFB derived oil from 400 to 600 °C is insignificant, whereby the heating value is improved by 6 % or less [55,59]. Therefore, it is recommended to add the plastics or/and catalysts into the pyrolysis of oil palm biomass to provide significant improvement in the properties of bio-oil produced.

4. Bio-oil upgrading

Bio-oil upgrading involves the reduction of oxygenated compounds in bio-oil through deoxygenation reactions, includes dehydration, decarboxylation, and decarbonylation by adding plastics or/and catalysts into the pyrolysis of lignocellulosic biomass [20–22]. Consequently, desirable hydrocarbons are produced as the main products while water, carbon dioxide, and carbon monoxide are released as byproducts.

Plastics are promising co-feeding materials in co-pyrolysis of oil palm biomass as they are rich in carbon and hydrogen (e.g., high hydrogen-to-

Table 4
Characteristics of bio-oil from oil palm biomass.

Characteristics	EFB derived oil	OPT derived oil	MF derived oil	PKS derived oil	OPF derived oil	Heavy fuel oil
Caloric value, MJ kg^{-1}	21.41	28.04	-	30.90	18.20	44.17
Water content, %	18.74	5.04	-	1.20	-	0.10
pH	3.0	3.0	-	-	3.0	-
Carbon, wt.%	49.80	45.21	58.31	71.50	66.20	85.60–86.68
Hydrogen, wt.%	7.98	6.54	7.05	10.30	9.40	10.30–12.04
Oxygen, wt.%	40.29	46.45	32.47	15.90	23.80	0.60–0.65
Nitrogen, wt.%	1.93	1.78	1.72	2.82	0.05	0.60
Sulphur, wt.%	0.00	0.02	0.45	0.12	0.00	2.50
Ref.	[59]	[63]	[64]	[31]	[70]	[71]

Table 5
Major compounds in bio-oil from oil palm biomass.

Oil palm biomass	Major compounds in bio-oil	Ref.
EFB	• Acids (acetic acid, oleic acid) • Ketones (cyclopentenones) • Phenolic compounds (phenols, 2,6-dimethoxy-phenol) • Furan compounds (furfural, 5-hydroxymethylfurfural) • Sugars (levoglucosan, levoglucosenone)	[46,50,72–73]
OPT	• Acids (acetic acid) • Phenolic compounds (phenols, 2,6-dimethoxy-phenol) • Ketones (1-hydroxy-2-propanone)	[29,66]
PKS	• Phenolic compounds (phenols, 2,6-dimethoxy-phenol) • Aldehydes (2-furan-carboxaldehyde) • Furan compounds (furfural) • Acids (Acetic acid)	[29,61]
OPF	• Acids (acetic acid) • Phenolic compounds (phenols, 2-methoxy-phenol) • Aldehydes (2-furan-carboxaldehyde) • Ketones (1-hydroxy-2-propanone)	[29,74]

carbon ratio of about 2) to provide sufficient hydrocarbon pool for the reactions with oxygenated compounds in bio-oil [20,76,77]. The most widely used types of plastics as the co-feeding material include high density polyethylene (HDPE), low density polyethylene (LDPE), polypropene (PP), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) [77]. The ultimate and proximate analyses of the plastics are shown in Table 3. PP, LDPE, and HDPE are more promising feedstock for co-pyrolysis with oil palm biomass as they contain high hydrogen content (about 14 wt.%).

In the co-pyrolysis of EFB with PP and HDPE, a contradicting trend was reported whereby bio-oil yield reduces with the increase in biochar yield [78,79]. As compared to previous studies, the larger particle size of 1 to 5 cm used in co-pyrolysis of EFB with PP and HDPE might have reduced the decomposition efficiency. Another study reported that higher bio-oil yield obtained from co-pyrolysis of EFB and OPF with LDPE as compared with PP [80]. It was explained that hydrogen from the LDPE prohibits the polymerization of biomass to form biochar, and thus increasing the weight loss of the feedstock to be converted into bio-oil. More studies need to be considered for the effects of operating parameters, particularly for plastic feedstocks, as limited publications are available for co-pyrolysis of oil palm biomass [78,79,81].

The presence of plastics in the co-pyrolysis with oil palm biomass typically improved the properties of bio-oil produced, i.e., increase the carbon content, heating value, and reduce oxygen content. The relevant studies showed that the carbon content of bio-oil increased by 6.4 to 16 % while the oxygen content of bio-oil decreased by 13 to 54 % [31,81–83]. The increase in carbon content contributed to the increase in heating value by 9–54 %, depending on the types of plastics added into the co-pyrolysis of oil palm biomass [81,83]. The heating value of

the upgraded bio-oil is in the range of 30 to 40 MJ kg^{-1}, and is relatively close to that of petrodiesel (42–46 MJ kg^{-1}) [79]. The detailed characteristics of bio-oil produced from co-pyrolysis of oil palm biomass with plastics are listed in Table 6.

Compared to commercial liquid fuels (i.e., heavy fuel oil, diesel, and gasoline), bio-oils from the pyrolysis of oil palm biomass have higher O/C ratios as revealed by their location on the right spectrum of the van Krevelen diagram shown in Fig. 4. Lower O/C ratio (towards the left hand side of the diagram) is desirable for liquid fuels since it provides higher heating value for applications. The addition of plastics into the co-pyrolysis of oil palm biomass clearly improves bio-oil's fuel properties.

On the other hand, the deoxygenation reactions can also be facilitated by the addition of catalysts to increase the selectivity of the desired compounds (e.g., hydrocarbons and phenols) in the bio-oil produced [21,76,86]. Various types of catalysts have been utilized in the pyrolysis of oil palm biomass, which can be categorized into three main categories and are listed in Table 7. The difference in the characteristics of the catalysts contributes to the variation in the formation of the desired products.

Acidic catalyst such as HZSM-5 with high acidity shows excellent catalytic performance for the aromatization. The Lewis and Brønsted acid sites in HZSM-5 promote the cracking and scission of C–O and C–C bonds of oxygenated compounds *via* acid catalysis, deoxygenation, dehydrogenation, dealkylation, and oligomerization. Cheah et al. [74] showed the use of HZSM-5 in the pyrolysis of OPF produced higher aromatics (3.02 GC/MS area%) than graphite nanofiber (0 GC/MS area%) at 500 °C. As acid site was absent on the graphite nanofiber, desirable cracking reactions cannot be conducted to promote the formation of aromatics.

Besides, HZSM-5 also promotes the aromatics formation from the conversion of phenols through cracking and H-transfer reactions [87]. Ro et al. [87] observed the decrease in phenols from 60.9 to 37.2 GC/MS area% and the increase in aromatics from 1.0 to 40.4 GC/MS area%. HZSM-5 nonetheless are microporous catalysts. Their small pore size may restrict the mass transfer of larger compounds in and out of the pores and thus lead to the coke formation. Shafaghat et al. [86] reported that MesoMFI, one of the mesoporous catalysts improves the selectivity of the aromatic hydrocarbons (i.e., benzene, toluene, xylenes, benzene-C$_3$, benzene-C$_4$, and benzene-C$_5$) by increasing aromatic hydrocarbons from 0.14 to 15.14 wt.%. For targeted deoxygenation reactions involving lignin-derived compounds (i.e., larger molecules), the use of MesoMFI can minimize coke formation.

Compared to HZSM-5, spent FCC with lower acidity is more promising to promote phenol production. Ro et al. [87] stated that spent FCC increases the selectivity of phenols from 60.9 GC/MS area% to 70.2 GC/MS area% through the dealkoxylation of guaiacols and syringols during the catalytic pyrolysis of EFB.

Basic catalysts such as bentonite, dolomite, and olivine show less or no efficiency in the aromatization reactions [87]. This is due to different structure of the catalysts that have no acid site to promote the cracking reactions of EFB. On the other hand, alkali earth metal catalyst such as Ca(OH)$_2$ shows promising results in the enhancement of phenol

Table 6

Characteristics of bio-oil produced from co-pyrolysis of oil palm biomass with plastics.

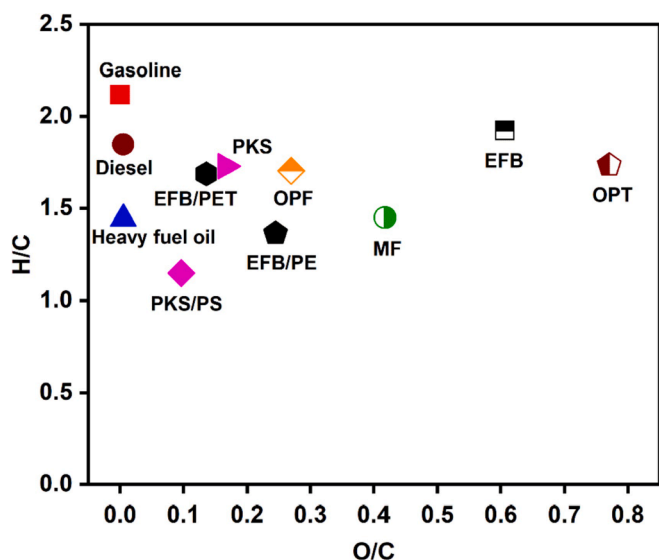| Feedstocks	EFB	EFB/PET	EFB/PE	PKS	PKS/PS	PKS [20 wt.% CaO]	PKS/LDPE [20 wt.% CaO]
Temperature, °C	500	500	500	490	600	500	500
Mass ratio	100	50:50	50:50	100	60:40	100	50:50
C, wt.%	64.61	74.98	68.71	71.50	81.34	-	-
H, wt.%	7.38	10.54	7.82	10.30	7.79	-	-
O, wt.%	25.84	13.634	22.44	15.90	10.50	-	-
HHV, MJ kg^{-1}	27.75	37.93	30.37	30.90	40.34	18.00	39.00
Ref.	[81]	[81]	[81]	[31]	[82]	[83]	[83]

Fig. 4. H/C and O/C ratios for bio-oils from pyrolysis of oil palm biomass, co-pyrolysis of oil palm biomass and plastic (calculated based on C, H, and O from Table 4 and Table 6), and commercial liquid fuels (calculated based on C, H, and O from [84,71], and [85].

Table 7

Catalyst types used in the pyrolysis of oil palm biomass.

Main category	Catalysts	Ref.
Acidic catalyst	• Microporous (HZSM-5 & Fluid catalytic cracking (FCC) catalysts) • Mesoporous (MesoMFI, Al-SBA-15, Al-MSU-F)	[74,86–87]
Basic catalyst	• Alkali & alkali earth metal (CaO, MgO, ZnO, K$_2$CO$_3$, Ca(OH)$_2$) • Other alkaline catalyst (Bentonite, Dolomite, Olivine)	[72–73,87]
Neutral catalyst	• Graphite nanofiber	[74]

formation from 7.585 to 14.601 GC/MS area% during EFB pyrolysis through demethylation and demethoxylation [72]. However, Chong et al. [73] reported the reduction of phenols production when metal oxide catalysts (i.e., CaO, MgO, and ZnO) were used in the pyrolysis of EFB. Metal oxide catalysts appear to enhance the decomposition of phenols into carbon monoxide.

Both acidic and basic catalysts enhance deacidification of bio-oil as the reduction of acids can be observed in several studies [72–74,86,87]. The deacidification of bio-oil by the acidic catalyst takes place by the deoxygenation reactions. On the other hand, metal oxide catalysts perform neutralization to reduce the acids from the bio-oil.

Still, challenges such as coke formation and catalyst deactivation are present during the catalytic process [20]. Coke formation can cause rapid catalyst deactivation, the blockage of catalyst pores, and catalyst poisoning; all of which negatively affect the performance of the

catalysts. As mentioned above, one of the factors that causes coke formation is the small pore size of the catalyst such as HZSM-5, which restricts the mass transfer of larger compounds. This can be improved through the application of mesoporous catalyst, which has high acidity but larger pore size [86]. The modification of HZSM-5 through the doping of metals such as nickel-cerium [88] and application of dual catalysts bed such as HZSM-5 and MgO [89] can increase the selectivity of hydrocarbon yield as well as minimize the coke formation. Alternatively, the addition of plastics that are rich in hydrogen (high hydrogen-to-carbon effective ratio of 2) can improve the biomass conversion efficiency and reduces coke formation [76,86].

To date, there is still lack of study on the modification of HZSM-5, application of dual bed catalysts, and addition of plastics in the pyrolysis of oil palm biomass towards the improvement of coke formation issue and desirable compounds selectivity in bio-oil. Therefore, more studies should be conducted to address this knowledge gap.

5. Techno-economic and environmental performance

The present status of the oil palm biomass pyrolysis system is overviewed based on techno-economic and environmental performances. As illustrated in Fig. 5, most of the current pyrolysis systems are in commercial state throughput standpoint. The niche researches on oil palm-based pyrolysis are concentrated in the Asia continent, mainly from Malaysia and Indonesia. Based on the Web of Science (WOS) database [90], a majority of the literature reported on oil palm-based feedstock pyrolysis come from institutions such as Universiti Teknologi PETRONAS, Universiti Kebangsaan Malaysia, Universiti Putra Malaysia, Tenaga Nasional Berhad, PETRONAS Research Group, Malaysian Palm Oil Berhad (Malaysia); Hankyong National University and Keimyung University (Korea); Kumamoto University and Nagoya University (Japan); and Resilience Development Initiative, Institut Teknologi Sepuluh Nopember, Universitas Gadjah Mada, and Universitas Sebelas Maret (Indonesia). Fig. 5 shows that circulating bed, fluidized bed, and rotating cone are mostly used as the pyrolyzers in the commercial system due to simple operation, good temperature control, and high efficiency of heat transfer [15]. Other types of pyrolyzers such as ablative and gas solid vortex reactor are also used as pyrolyzers in demonstration and commercial scale [91,92].

However, when the search boundary is constrained for only techno-economic and environmental assessment on oil palm based pyrolysis refinery related studies, only about seven works [101–107] were shown despite numerous works on the general process of oil palm based pyrolysis to value-added products from laboratory to demonstration scale. This observation indicates that the commercialization of oil palm-based pyrolysis refinery still remains at its infancy stage, whereby many uncertainties such as catalyst characteristics, reaction conditions, and downstream processes should be thoroughly analyzed to improve the technology readiness level of this process.

From the techno-economic standpoint, the scale of the co-pyrolysis needs to be investigated in detail for the purpose of scale-up and upgrading products performance. Most of the research related to co-pyrolysis of biomass and plastic waste mixtures are on laboratory and pilot scale [108–111]. This is attributed to some challenges pertaining to economic and production aspects due to lack of awareness on the
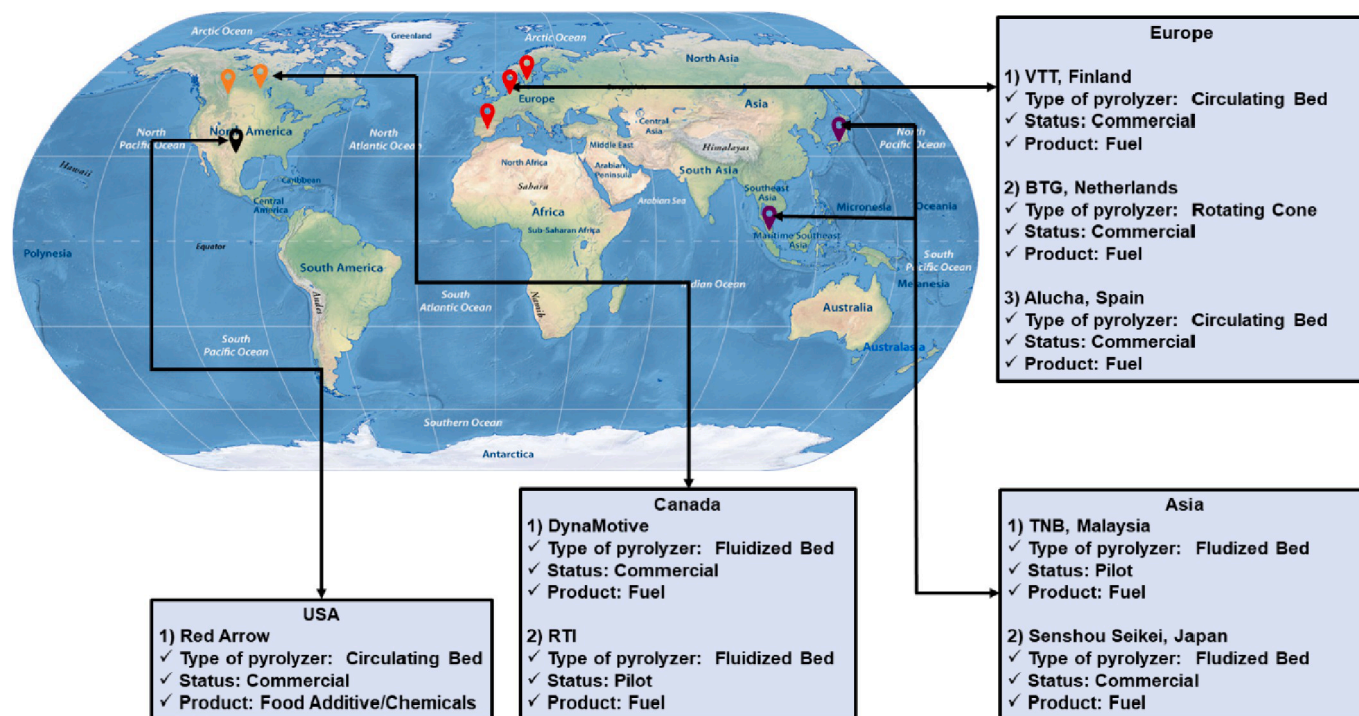
Fig. 5. Worldwide biomass pyrolyzer plants [93–100].

application of the co-pyrolysis products, i.e., bio-oil [94]. Hence, the upscaling study for the co-pyrolysis of biomass and plastic waste mixtures is essential to accomplish the goal for industrial production and market application as an alternative fuel from fossil fuel. This can be achieved through technology improvement with minimal capital cost and through delivering major progress in coping and utilizing all products produced from co-pyrolysis technology. According to Chan et al. [112], these existing markets are highly competitive and offer a

Table 8
Techno-economic and environmental performance of oil palm based pyrolysis.

Biorefinery feedstock	Techno-economic analysis	Environmental analysis	Functional unit	Remarks	Ref.
Palm bagasse	X	X	7,700 kg hr^{-1} of palm oil	• Palm oil exhibits a higher value for acidic potential and aquatic toxicity potential categories as compared to Jatropha curcas oil, which can be assigned to the sulfur content in palm bagasse. • Blending with other oil is a better option to lower the environmental impacts. • The net present value and internal rate of return of the biorefinery plant are calculated to be 8,455,147.29 USD and 33.18 %, respectively.	[103]
PKS and EFB		X	1 MJ of biodiesel	• Fast pyrolysis process to obtain bio-oil and biochar proved to be an environmentally friendly and a carbon credit process, where the air emissions are greatly reduced with an increase in thermal energy recovery capacity. • The Net Energy Ratio is calculated to be 21.17, which is comparable to other thermal technologies.	[102]
EFB		X	1 kg of bio-oil	• A net 4.46 kg CO_2 equivalent is generated per kg of bio-oil produced *via* fast pyrolysis of EFB. • The pretreatment of EFB is the main factor that contributed the most CO_2 emission.	[101]
EFB	X	X	100 kW power plant	• The net present value of microwave assisted pyrolysis is calculated to be 1,073,772 USD. • Microwave assisted pyrolysis provides a better climate change performance by emitting a lower CO_2 composition of 22 tCO_2 yr^{-1}. as compared to the conventional plant.	[104]
EFB	X		1 kton-dry EFB yr^{-1}	• Bio-oil from EFB can be attained at 0.27 USD kg^{-1} via fast pyrolysis. • The least profitable plant size is found to be 20 kton-dry EFB yr^{-1} at a rate of 0.47 USD kg^{-1} bio-oil production.	[105]
EFB		X	1 kg hr^{-1} of EFB	• A net 586 kg of CO_2 eq hr^{-1} EFB processed. • Some other potential environmental impacts such as 0.02149 kg SO_2 equivalent as the cause of acidification and 0.00399 kg PO_4 equivalent as the cause of Eutrophication are observed.	[106]
EFB	X		6 metric ton hr^{-1} of EFB	• The feedstock price drives the production cost. • Best option is to have the bio-oil plant integrated with the palm oil, hence no cost for EFB feedstock, and also off the market influence. • With the feedstock requirement of 43,200,000 kg yr^{-1}, a total of 12,772,800 kg yr^{-1} bio-oil is produced.	[107]

Note: X represents the applicable works that have been carried out in the relevant area.

very slim margin for emerging pyrolysis industry. Bio-oil is an inherent greenhouse gas (carbon) neutral energy product, which is the key highlight benefit. However, the development of a pyrolysis industry depends solely on government policy [112]. Currently, there are still very limited studies that focus on the utilization of gasoline and boiler fuels derived from co-pyrolysis oil [113]. Therefore, studies from the aspects of techno-economic feasibility and process optimization in the plant operation from the co-pyrolysis process are a necessity to fulfil the market demand on the energy supply and demand, pollution reduction attributed from the biomass and plastic waste disposal, and substitution of the conventional fossil fuel combustion process. Besides, the global massive amount of plastic and biomass waste generated would not be the limiting factor in achieving the co-pyrolysis process in the commercialization stage. According to Wang et al. [113], the consideration to explore in detail the downstream processes such as the feedstock's collection, transportation, and storage involving co-pyrolysis technology is an important aspect for the techno-economic analysis for the recovery of the co-pyrolysis value-added products.

From the environmental standpoint, bio-oil production from oil palm-based pyrolysis process is reported to be more environmentally friendly as compared to the conventional thermal process (Table 8). In 2016, Yusup and co-workers [101] studied the environmental impact of fast pyrolysis process for the conversion of EFB into bio-oil using GREET software. The most severe environmental impacts come from the CO_2 and SO_2 emissions, mainly attributed by the consumption of electricity at pre-treatment stage whereas the least severe impact is found to come from eutrophication. The estimated emission is around 8.27 kg of CO_2 equivalent of GWP (Global Warming Potential) in fast pyrolysis process due to the emission of greenhouse gases. Similar observation is reported by Ocampo Batlle et al. [102], where the bio-oil production from fast pyrolysis of EFB is proven to be environmentally benign. The environmental impacts of bio-oil production are 32.5 % lower than the conventional electricity process (climate change category), indicating that the production of bio-oil using fast pyrolysis biorefinery is more environmentally friendly. Net energy ratio index is defined as the ratio of the energy outputs to the energy inputs, where net energy ratio index from non-renewable energy is less than 1. Thus, the net energy ratio value of 21.17 obtained from the system supports the standpoint from an environmental and energy perspective.

6. Future perspective

The potential of oil palm biomass pyrolysis system is analyzed in terms of their future application in these research areas of interest, i.e., process integration and process intensification. Prospective works in these areas serve to enhance the overall biomass pyrolysis process and guide the development of future technologies to benefit pyrolysis process performance.

6.1. Process integration

Process integration (PI), which is commonly defined as "*a holistic approach to design and operation that emphasizes the unity of the process,*" [114] can be applied (i) to generate new advantages (such as minimizing the raw material requirement *via* resources conservation network [115] and maximizing the heat recovery *via* heat integration technique [116], and (ii) to resolve bottlenecks encountered by individual pyrolysis process (such as maximizing the process efficiency and sustainability performance) [117].

One of the notable applications of PI in pyrolysis process is the integration of pyrolysis with anaerobic digestion. In the integrated system of anaerobic digestion followed by the pyrolysis, the quality of bio-oil produced from the pyrolysis of anaerobic digestate (animal and plant wastes) was improved, as its heating value (35.2 MJ kg^{-1}) becomes comparable to that of biodiesel (39.3 MJ kg^{-1}) [118]. Such process simultaneously helps to reduce the management cost of

anaerobic digestate. Deng et al. [119] proposed a cascading circular bioenergy system, which integrates the use of anaerobic digestion (*L. digitata*) and pyrolysis (forest residue) (Fig. 6(a)). In this integrated system, the biochar from pyrolysis is applied in the anaerobic digestion, which enhanced the biomethane production by 17 % while the addition of anaerobic digestate into the pyrolysis increased the bio-oil yield by 10 %. However, some aspects need to be considered if oil palm biomass is to be used in this integrated system. As the type of feedstock used can affect the microorganism activity during anaerobic digestion, it is essential to study the use of oil palm biomass on the microorganism activity to ensure the stability of the process. Also, the addition of substrates such as food waste and animal slurry can facilitate the degradation activity of microorganisms during anaerobic digestion. However, there is still uncertainty on the composition of bio-oil from the pyrolysis of anaerobic digestate. More research studies need to be conducted to investigate the feasibility of the oil palm biomass in this integrated system for bio-oil production.

Taking the study from Sharifzadeh et al. [120] as an example, the integration of two upgrading technologies, i.e., hydrothermal upgrading (lower bio-oil yield but with less hydrogen requirement) and liquid phase hydrodeoxygenation (higher bio-oil yield but with higher hydrogen requirements) are investigated (Fig. 6(b)). To maximize the overall benefit i.e., maximizing the bio-oil yield while minimizing the need of external hydrogen source, the bio-oil derived from pyrolysis of Norwegian Spruce is sent to hydrodeoxygenation and hydrothermal upgrading units with a split ratio of 31.85:68.15 [120]. Regardless of the feedstock requirement, various types of biomass, including oil palm biomass can be applied into this integrated system for bio-oil upgrading. Hence, it is encouraged to conduct the study related to such integration schemes using oil palm biomass as feedstock in the pyrolysis.

Another significant body of literature on integrating pyrolysis in poly-generation system is available. Generally, the pyrolysis products can be used to generate heat and power which can be consumed within the system (Fig. 6(c)). For instance, (i) biochar can be burnt in char burner to supply heat energy for the biomass dryer during the pyrolysis of EFB [121] and pyrolyzer when wood chips and forest residues used as feedstock [122]; (ii) bio-oil from pyrolysis of wood can be used as boiler fuel to generate thermal and electricity energy [123]. In fact, the integration of pyrolysis in poly-generation system can lead to preferable economic and environmental benefits. For example, by integrating biomass pyrolysis into the conventional combined and heat power plant, a 57 % increment in annual operating hours can be achieved [123]. Besides, high-heating value biochar can be used to substitute the existing boiler (or furnace) fuel which is not environmental-friendly [121]. Although the aforementioned works are insightful, most of the works are merely simulation studies. Based on the use of wood and forest residue as the feedstock in simulation studies, OPT is the most comparable one
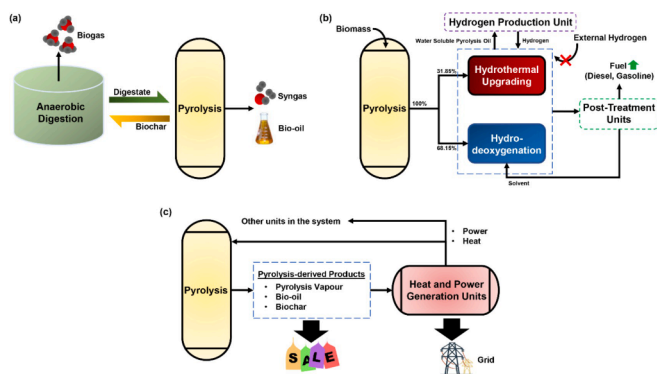

Fig. 6. Schematic diagram of (a) integrated AD-pyrolysis system; (b) integrated bio-oil upgrading process (Modified with permission from Sharifzadeh et al. [120] Copyright 2015 Elsevier); (c) poly-generation system incorporating pyrolysis process.

among oil palm biomass, which may be suitable as feedstock in the stimulated studies related to the poly-generation system. Also, pilot study on palm-biomass based poly-generation system that incorporates pyrolysis technology is recommended to evaluate and validate the feasibility of this integration scheme.

6.2. Process intensification

Process intensification, which is defined as "*any chemical engineering development that leads to a substantially smaller, cleaner, and more energy efficient technology,*" can be applied to enhance the feasibility of biomass pyrolysis process [124]. In general, this can be achieved by applying necessary innovative changes in one or more of the four domains, i.e., "spatial" (focuses on structural measures for mass transfer performance), "thermodynamic" (focuses on heat transfer performance), "functional" (involves integration of multiple functional units into a single unit), and "temporal" (involves change in time scale or introduces periodicity to the system) [125,126].

Hot gas filtration is commonly known as a promising technique for solid residue (char and ash) removal from pyrolysis vapor as char and ash can cause the bio-oil instability during storage and limits the direct application of bio-oil as boilers fuel which can lead to fouling, corrosion, and erosion. Hoekstra et al. [127] proposed a novel *in situ* filtration design, which is capable to remove the solid residue from the pyrolysis vapor of bench wood and Lignocel 9 (pine soft wood) before they are channeled out from the reactor. In other words, both "reaction" and "separation" processes are held within the same equipment (under "functional" domain). In addition, the incorporation of *in situ* filtration system in the reactor was found capable of reducing the residence time of the pyrolysis vapor (under "temporal" domain), which is deemed preferable to mitigate the undesired secondary cracking of pyrolysis products [127]. As a result, the overall yield and quality of the synthetic oil are significantly enhanced. This technology has high potential in the ash reduction for bio-oil quality enhancement especially for oil palm biomass with high ash content such as PKS, MF, and EFB. Despite these promising results, the technique is yet to be widely applied by the research and industry communities, including the palm oil industry, and thus more research studies related to the hot gas filtration are warranted.

With regards to oil quality, Peterson et al. [128] took another approach, i.e., catalytic hot gas filtration to further enhance the pyrolysis vapor quality. On top of physically removing the solid particles (separation), catalytic hot gas filtration also involves catalytic conversion (partial deoxygenation reaction) of acid carbonyl into species that are not harmful to the catalysts used in downstream bio-oil upgrading processes [129]. Their work shows that the use of catalytic hot gas filtration can reduce carboxylic acid (include acetic acid, which is the key component that causes oil instability) by 65 %. This is advantageous for palm oil biomass-based pyrolysis since numerous studies had reported that the palm oil biomass-derived bio-oil is usually rich in acetic acid [130–132]. To date, the feasibility of catalytic hot gas filtration was merely studied using two catalysts, namely titania-supported molybdenum heteropolyacid (Mo-HPA/TiO$_2$) catalyst and metal-doped molybdenum carbide (Ni-doped and Ca-doped) supported catalysts [128,129]. The study can also be extended to other potential catalysts, including but not limited to ZSM-5, MgO-based catalysts, CeO$_2$/SiO$_2$, Co–Mo/Al$_2$O$_3$, and Ru/TiO$_2$ catalysts [133–136].

Besides, the change in reactor structure can aid the process intensification. Notably, gas–solid vortex reactor is proposed. In such configuration, fluidizing gas is injected tangentially into the reactor through multiple gas inlet slots (Fig. 7(a)). The generated centrifugal forces enable better heat and mass transfer between the phases (under the domains of "thermodynamic" and "spatial") [137,138]. Compared to conventional pyrolyzer, gas solid vortex reactor allows the feedstocks can reach reactor temperature more rapid and thus increase the bio-oil production with higher selectivity [137]. The effectiveness of gas solid
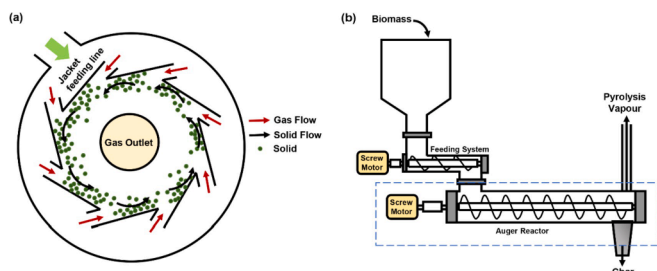

Fig. 7. Schematic diagram of (a) gas solid vortex reactor (GSVR) - top view (Modified with permission from Gonzalez-Quiroga et al. [92] Copyright 2017 Elsevier); and (b) auger reactor (Modified with permission from Campuzano et al. [91] Copyright 2019 Elsevier).

vortex reactor in the segregation of pine wood biomass and char particles during the pyrolysis which reduces the secondary cracking reactions of pyrolytic vapors, and thus results in a higher bio-oil yield (>70 wt.%) [138]. To date, the application of this technology remains limited to the palm oil industry and it is thus encouraged to extend the study to bio-oil production from oil palm biomass.

On the other hand, auger reactor is another promising technology to intensify the biomass pyrolysis process [91]. In general, a screw (or multiple screws) is used to convey the biomass (or a mixture, which contains biomass and heat carriers) down a horizontal reactor (Fig. 7 (b)). The continual mixing actions pose a positive impact in enhancing both heat and mass transfers [139,140] (under the domains of "thermodynamic" and "spatial"). Besides, auger reactor can be used for the bio-oil production from the wide range of feedstocks and with high higher yield due to the effective heat and mass transfer in the reactor. As the physicochemical properties of the oil palm biomass vary with the type, the higher flexibility of auger reactor in the feedstock selection shows high potential in the bio-oil production from the oil palm biomass.

Nevertheless, some works have pointed out that possible heat transfer difficulties may be experienced at large scale [91,141]. Thus, further studies on process upscaling, particularly for those using oil palm biomass as the pyrolyzer feed, are recommended.

7. Conclusion

Most of the pyrolysis of oil palm biomass are conducted between 450 and 600 °C to enhance the bio-oil yield and to promote the formation of valuable compounds such as phenols, levoglucosan, and furans. However, bio-oil from oil palm biomass tends to contain several undesirable properties, i.e., high oxygen content (16–46 wt.%), high moisture content (1.2–18 wt.%), low pH (about 3), and low heating value (18–30 MJ kg^{-1}). With the addition of plastics during co-pyrolysis, the oxygen content of oil palm derived bio-oil can be reduced by 13–54 % while the heating value can be increased by 9–54 %. Microporous catalyst such as HZSM-5 with high acidity exhibits excellent catalytic performance in the aromatization and reduction of oxygenated compounds in catalytic co-pyrolysis with oil palm biomass. Mesoporous catalysts such as MesoFI serve as an attractive alternative to HZSM-5 for deoxygenation reactions involving larger molecules. Basic catalysts, on the other hand, show lower efficiency in the aromatization reactions, but are excellent in the deacidification of bio-oil from oil palm biomass. To date, bio-oil production from pyrolysis of oil palm biomass has received much attention in laboratory scale research. However, the demonstration in larger scale, especially for bio-oil production from co-pyrolysis and catalytic co-pyrolysis of oil palm biomass is still lacking, and thus continuous research is important to accelerate its development in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

References

[1] E. Onoja, S. Chandren, F. Razak, N. Mahat, R. Wahab, Oil Palm (Elaeis guineensis) biomass in Malaysia: The present and future prospects, Waste Biomass Valorization (2018).

[2] M.F. Awalludin, O. Sulaiman, R. Hashim, W.N.A.W. Nadhari, An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction, Renew. Sustain. Energy Rev. 50 (2015) 1469–1484.

[3] S.Y. Lee, R. Sankaran, K.W. Chew, C.H. Tan, R. Krishnamoorthy, D.-T. Chu, P.-L. Show, Waste to bioenergy: A review on the recent conversion technologies, BMC Energy 1 (2019) 4.

[4] J.D. Martínez, A. Veses, A.M. Mastral, R. Murillo, M.V. Navarro, N. Puy, A. Artigues, J. Bartrolí, T. García, Co-pyrolysis of biomass with waste tyres: Upgrading of liquid bio-fuel, Fuel Process. Technol. 119 (2014) 263–271.

[5] F. Abnisa, A. Arami-Niya, W.M.A. Wan Daud, J.N. Sahu, I.M. Noor, Utilization of oil palm tree residues to produce bio-oil and bio-char via pyrolysis, Energy Convers. Manage. 76 (2013) 1073–1082.

[6] M.P.O.B. (MPOB), Oil palm planted area as at December 2020 (hectares), Malaysia Palm Oil Board (MPOB), (2021). http://bepi.mpob.gov.my/index.php/en/area/area-2020/oil-palm-planted-area-as-at-dec-2020.html. Accessed March 21, 2021.

[7] M.P.O.B. (MPOB), Fresh fruit bunch (FFB) proceesed by mill for the month of December 2020, Malaysian Palm Oil Board (MPOB), (2021). http://bepi.mpob.gov.my/index.php/en/sectoral-status/sectoral-status-2020/ffb-processed-by-mill-2020.html. Accessed March 21, 2021.

[8] N. Hamzah, K. Tokimatsu, K. Yoshikawa, Solid fuel from oil palm biomass residues and municipal solid waste by hydrothermal treatment for electrical power generation in Malaysia: a review, Sustainability 11 (2019).

[9] S.H. Chang, An overview of empty fruit bunch from oil palm as feedstock for bio-oil production, Biomass Bioenergy 62 (2014) 174–181.

[10] S.H. Shuit, K.T. Tan, K.T. Lee, A.H. Kamaruddin, Oil palm biomass as a sustainable energy source: a Malaysian case study, Energy 34 (2009) 1225–1235.

[11] H.P.S. Abdul Khalil, M.R. Nurul Fazita, A.H. Bhat, M. Jawaid, N.A. Nik Fuad, Development and material properties of new hybrid plywood from oil palm biomass, Mater. Des. 31 (2010) 417–424.

[12] R. Hashim, W.N.A. Wan Nadhari, A. Nadhari, O. Sulaiman, M. Sato, S. Hiziroglu, F. Kawamura, T. Sugimoto, E. Tay, G. Seng, R. Tanaka, Properties of binderless particleboard panels manufactured from oil palm biomass, Bioresources 7 (2012).

[13] N. Nipattummakul, I.I. Ahmed, S. Kerdsuwan, A.K. Gupta, Steam gasification of oil palm trunk waste for clean syngas production, Appl. Energy 92 (2012) 778–782.

[14] W.R. Wan Daud, M. Ibrahim, K.N. Law, N. Razali, Influences of the operating variables of acetosolv pulping on pulp properties of oil palm frond fibres, Maderas-Cienc Tecnol. 13 (2010) 193–202.

[15] A.V. Bridgwater, Review of fast pyrolysis of biomass and product upgrading, Biomass Bioenergy 38 (2012) 68–94.

[16] S. Yaman, Pyrolysis of biomass to produce fuels and chemical feedstocks, Energy Convers. Manage. 45 (2004) 651–671.

[17] A. Krutof, K. Hawboldt, Upgrading of biomass sourced pyrolysis oil review: focus on co-pyrolysis and vapour upgrading during pyrolysis, Biomass Convers. Biorefin. 8 (2018).

[18] J. Akhtar, N. Saidina Amin, A review on operating parameters for optimum liquid oil yield in biomass pyrolysis, Renew. Sustain. Energy Rev. 16 (2012) 5101–5109.

[19] R.E. Guedes, A.S. Luna, A.R. Torres, Operating parameters for bio-oil production in biomass pyrolysis: a review, J. Anal. Appl. Pyrolysis 129 (2018) 134–149.

[20] F. Abnisa, W.M.A. Wan Daud, A review on co-pyrolysis of biomass: an optional technique to obtain a high-grade pyrolysis oil, Energy Convers. Manage. 87 (2014) 71–85.

[21] X. Zhang, H. Lei, S. Chen, J. Wu, Catalytic co-pyrolysis of lignocellulosic biomass with polymers: A critical review, Green Chem. 18 (15) (2016) 4145–4169.

[22] L. Zhang, Z. Bao, S. Xia, Q. Lu, K. Walters, Catalytic pyrolysis of biomass and polymer wastes, Catalysts 8 (12) (2018) 659.

[23] N. Abdullah, F. Sulaiman, Z. Aliasak, A case study of pyrolysis of oil palm wastes in Malaysia, AIP Conf. Proc. 1528 (2013) 331–336.

[24] N.N. Kasim, A.R. Mohamed, K. Ismaili, An upgraded bio oil derived from untreated and treated empty fruit bunches (EFB) by catalytic pyrolysis : A review, J. Adv. Res. Eng. Knowl. 4 (2018) 8–16.

[25] S.S. Qureshi, S. Nizamuddin, H.A. Baloch, M.T.H. Siddiqui, N.M. Mubarak, G.J. Griffin, An overview of OPS from oil palm industry as feedstock for bio-oil production, Biomass Convers. Biorefin. 9 (4) (2019) 827–841.

[26] S.W. Kim, B.S. Koo, J.W. Ryu, J.S. Lee, C.J. Kim, D.H. Lee, G.R. Kim, S. Choi, Bio-oil from the pyrolysis of palm and Jatropha wastes in a fluidized bed, Fuel Process. Technol. 108 (2013) 118–124.

[27] W.A. Khandhay, G. Kabir, B.H. Hameed, Catalytic pyrolysis of oil palm mesocarp fibre on a zeolite derived from low-cost oil palm ash, Energy Convers. Manage. 127 (2016) 265–272.

[28] S.-H. Kong, S.-K. Loh, R.T. Bachmann, S.A. Rahim, J. Salimon, Biochar from oil palm biomass: a review of its potential and challenges, Renew. Sustain. Energy Rev. 39 (2014) 729–739.

[29] A. Palamanit, P. Khongphakdi, Y. Tirawanichakul, N. Phusunti, Investigation of yields and qualities of pyrolysis products obtained from oil palm biomass using an agitated bed pyrolysis reactor, Biofuel Res. J. 6 (4) (2019) 1065–1079.

[30] F. Abnisa, A. Arami-Niya, W.M.A.W. Daud, J.N. Sahu, Characterization of bio-oil and bio-char from pyrolysis of palm oil wastes, BioEnergy Res. 6 (2) (2013) 830–840.

[31] S.-J. Kim, S.-H. Jung, J.-S. Kim, Fast pyrolysis of palm kernel shells: Influence of operation parameters on the bio-oil yield and the yield of phenol and phenolic compounds, Bioresour. Technol. 101 (2010) 9294–9300.

[32] L. Zhou, Y. Wang, Q. Huang, J. Cai, Thermogravimetric characteristics and kinetic of coal /plastic blends co-pyrolysis, in: 23rd Annual International Pittsburgh Coal Conference, PCC - Coal-Energy, Environment and Sustainable Development, 2006.

[33] S.S. Park, D.K. Seo, S.H. Lee, T.-U. Yu, J. Hwang, Study on pyrolysis characteristics of refuse plastic fuel using lab-scale tube furnace and thermogravimetric analysis reactor, J. Anal. Appl. Pyrolysis 97 (2012) 29–38.

[34] H. Zhang, J. Nie, R. Xiao, B. Jin, C. Dong, G. Xiao, Catalytic co-pyrolysis of biomass and different plastics (polyethylene, polypropylene, and polystyrene) to improve hydrocarbon yield in a fluidized-bed reactor, Energy Fuels 28 (2014) 1940–1947.

[35] E. Ansah, L. Wang, A. Shahbazi, Thermogravimetric and calorimetric characteristics during co-pyrolysis of municipal solid waste components, Waste Manage. 56 (2016) 196–206.

[36] B. Han, Y. Chen, Y. Wu, D. Hua, Z. Chen, W. Feng, M. Yang, Q. Xie, Co-pyrolysis behaviors and kinetics of plastics-biomass blends through thermogravimetric analysis, J. Therm. Anal. Calorim. 115 (2014) 227–235.

[37] B.G.R.S. Bhd, Empty fruit bunch, (n.d.). https://www.bmgreen.com.my/wp01/biomass-biofuel/empty-fruit-bunch/. Accessed November 17, 2020.

[38] A.E.M.S. Bhd, Mesocarp fibres, (n.d.). https://allgreen.com.my/portfolio/mesocarp-fibres/. Accessed November 17, 2020.

[39] H. International, Biomass, Hyperfusion International, (n.d.). https://hyperfusionint.wixsite.com/hfibiomassenergy/hfi-biomass. Accessed November 17, 2020.

[40] G.G. Synergy, Palm kernel shell (PKS), (n.d.). http://www.ggs.my/ggs-products/pks-kernel-shell. Accessed November 17, 2020.

[41] Heuze V., Tran G., Sauvant D., Lebas F., Oil palm fronds and oil palm crop residues, Feedipedia, a programme by INRAE, CIRAD, AFZ and FAO, (2015). https://www.feedipedia.org/node/6916. Accessed November 17, 2020.

[42] E. Project, Oil palm, Eden Project, (n.d.). https://www.edenproject.com/learn/for-everyone/plant-profiles/oil-palm. Accessed November 17, 2020.

[43] G. Bensidhom, A. Ben Hassen-Trabelsi, K. Alper, M. Sghairoun, K. Zaafouri, I. Trabelsi, Pyrolysis of date palm waste in a fixed-bed reactor: characterization of pyrolytic products, Bioresour. Technol. 247 (2018) 363–369.

[44] P. Patwardhan, Understanding the Product Distribution from Biomass Fast Pyrolysis, Iowa State University, 2010.

[45] I. Mohammed, Y.A. Abakr, K. Feroz, Y. Suzana, I. Mohamed Alshareef, S. Chin, Pyrolysis of oil palm residues in a fixed bed tubular reactor, J. Power Energy Eng. 03 (2015) 185–193.

[46] S. Fukuda, Pyrolysis investigation for bio-oil production from various biomass feedstocks in Thailand, Int. J. Green Energy 12 (2015) 215–224.

[47] J.-W. Park, J. Heo, H.V. Ly, J. Kim, H. Lim, S.-S. Kim, Fast pyrolysis of acid-washed oil palm empty fruit bunch for bio-oil production in a bubbling fluidized-bed reactor, Energy 179 (2019) 517–527.

[48] N. Abdullah, F. Sulaiman, The properties of the washed empty fruit bunches of oil palm, J. Phys. Sci. 24 (2013) 117–137.

[49] M.A. Sukiran, S.K. Loh, N.A. Bakar, Conversion of pre-treated oil palm empty fruit bunches into bio-oil and bio-char via fast pyrolysis, J. Oil Palm Res. 30 (2018) 121–129.

[50] X. Lim, A. Sanna, J.M. Andrésen, Influence of red mud impregnation on the pyrolysis of oil palm biomass-EFB, Fuel 119 (2014) 259–265.

[51] L. Dai, Y. Wang, Y. Liu, R. Ruan, C. He, Z. Yu, L. Jiang, Z. Zeng, X. Tian, Integrated process of lignocellulosic biomass torrefaction and pyrolysis for upgrading bio-oil production: A state-of-the-art review, Renew. Sustain. Energy Rev. 107 (2019) 20–36.

[52] M.A. Sukiran, F. Abnisa, W.M.A.W. Daud, N.A. Bakar, A.A. Aziz, S.K. Loh, Upgrading of oil palm biomass by torrefaction process: A preliminary study, AIP Conf. Proc. 2168 (2019), 020059.

[53] M. Sukiran, N.K. Abu Bakar, C. Chin, Optimization of pyrolysis of oil palm empty fruit bunches, J. Oil Palm Res. 21 (2009).

[54] K. Azduwin, M.J.M. Ridzuan, A.R. Mohamed, S.M. Hafis, Pyrolysis of empty fruit bunch (EFB) in a vertical fixed bed reactor, Appl. Mech. Mater. 695 (2015) 228–231.

[55] M. Sukiran, S.K. Loh, N. Abu Bakar, Production of bio-oil from fast pyrolysis of oil palm biomass using fluidised bed reactor, J. Energy Tech. Pol. 6 (2016) 52–62.

[56] M. Nurul Islam, R. Zailani, F. Nasir Ani, Pyrolytic oil from fluidised bed pyrolysis of oil palm shell and its characterisation, Renew. Energy 17 (1) (1999) 73–84.

[57] J.O. Ogunkanmi, D.M. Kulla, N.O. Omisanya, M. Sumaila, D.O. Obada, D. Dodoo-Arhin, Extraction of bio-oil during pyrolysis of locally sourced palm kernel shells: Effect of process parameters, Case Stud. Therm. Eng. 12 (2018) 711–716.

[58] K.L. Chin, P.S. H'ng, H.K. Eng, S.H. Lee, W.C. Lum, Y.Y. Chin, Yield and calorific value of bio oil pyrolysed from oil palm biomass and its relation with solid residence time and process temperature, Asian J. Sci. Res. 8 (3) (2015) 351–358.

[59] M. Sukiran, C. Chin, N.K. Abu Bakar, Bio-oils from pyrolysis of oil palm empty fruit bunches, Am. J. Appl. Sci. 6 (2009).

[60] N. Abdullah, H. Gerhauser, F. Sulaiman, Fast pyrolysis of empty fruit bunches, Fuel 89 (8) (2010) 2166–2166.

[61] G. Chang, P. Miao, X. Yan, G. Wang, Q. Guo, Phenol preparation from catalytic pyrolysis of palm kernel shell at low temperatures, Bioresour. Technol. 253 (2018) 214–219.

[62] H. Yang, R. Yan, H. Chen, D.H. Lee, D.T. Liang, C. Zheng, Mechanism of palm oil waste pyrolysis in a packed bed, Energy Fuels 20 (2006) 1321–1328.

[63] K.H. Khor, K.O. Lim, Z.A.Z. Alimuddin, Laboratory-scale pyrolysis of oil palm trunks, Energy Sources, Part A 32 (2010) 518–531.

[64] K.K. Hooi, Z.A.Z. Alauddin, L.K. Ong, Laboratory-scale pyrolysis of oil palm pressed fruit fibres, J. Oil Palm Res. 21 (2009) 577–587.

[65] A. Abdul Rahman, N. Abdullah, F. Sulaiman, Temperature effect on the characterization of pyrolysis products from oil palm fronds, Adv. Energy Eng. (AEE) (2014) 2.

[66] P. Sakulkit, A. Palamanit, R. Dejchanchaiwong, P. Reubroycharoen, Characteristics of pyrolysis products from pyrolysis and co-pyrolysis of rubber wood and oil palm trunk biomass for biofuel and value-added applications, J. Environ. Chem. Eng. 8 (2020), 104561.

[67] H. Kawamoto, Lignin pyrolysis reactions, J. Wood Sci. 63 (2017) 117–132.

[68] F.-X. Collard, J. Blin, A review on pyrolysis of biomass constituents: Mechanisms and composition of the products obtained from the conversion of cellulose, hemicelluloses and lignin, Renew. Sustain. Energy Rev. 38 (2014) 594–608.

[69] A.R. Mohamed, Z. Hamzah, M.Z. Mohamed Daud, The effects of process parameters on the pyrolysis of empty fruit bunch (EFB) using a fixed-bed reactor, Adv. Mater. Res. 925 (2014) 115–119.

[70] N.N. Omar, N. Abdullah, I.S. Mustafa, F. Sulaiman, Characterisation of oil palm frond for bio-oil production, ASM Sci. J. 11 (2018) 9–22.

[71] S.Y. Cheng, L. Wei, X. Zhao, J. Julson, Application, deactivation, and regeneration of heterogeneous catalysts in bio-oil upgrading, Catalysts 6 (12) (2016) 195, https://doi.org/10.3390/catal6120195.

[72] M. Auta, L.M. Ern, B.H. Hameed, Fixed-bed catalytic and non-catalytic empty fruit bunch biomass pyrolysis, J. Anal. Appl. Pyrolysis 107 (2014) 67–72.

[73] Y.Y. Chong, S. Thangalazhy-Gopakumar, H.K. Ng, L.Y. Lee, S. Gan, Effect of oxide catalysts on the properties of bio-oil from in-situ catalytic pyrolysis of palm empty fruit bunch fiber, J. Environ. Manage. 247 (2019) 38–45.

[74] K.W. Cheah, S. Yusup, N.S. Muda, N.Z. Abdul Kapor, Comparative study of H-ZSM 5 zeolite and graphite nanofiber (GNF) in catalytic pyrolysis of oil palm fronds (OPF), Int. J. Biomass Renewables 5 (2018) 14–20.

[75] S.-Y. No, Application of bio-oils from lignocellulosic biomass to transportation, heat and power generation: A review, Renew. Sustain. Energy Rev. 40 (2014) 1108–1125.

[76] H. Hassan, J.K. Lim, B.H. Hameed, Catalytic co-pyrolysis of sugarcane bagasse and waste high-density polyethylene over faujasite-type zeolite, Bioresour. Technol. 284 (2019) 406–414.

[77] R.K. Mishra, K. Mohanty, Co-pyrolysis of waste biomass and waste plastics (polystyrene and waste nitrile gloves) into renewable fuel and value-added chemicals, Carbon Resour. Convers. 3 (2020) 145–155.

[78] E. Kusrini, D. Supramono, M. Alhamid, S. Pranata, L. Wilson, A. Usman, Effect of polypropylene plastic waste as co-feeding for production of pyrolysis oil from palm empty fruit bunches, Evergreen 6 (2019) 92–97.

[79] E. Kusrini, D. Supramono, V. Degirmenci, S. Pranata, A.A Bawono, N. Ani, Improving the quality of pyrolysis oil from co-firing high-density polyethylene plastic waste and palm empty fruit bunches, Int. J. Technol 9 (7) (2018) 1498.

[80] M.A. Al-Maari, M.A. Ahmad, A.T.M. Din, H. Hassan, A.M. Alsobaai, Co-pyrolysis of oil palm empty fruit bunch and oil palm frond with low-density polyethylene and polypropylene for bio-oil production, Arab. J. Chem. 14 (2021), 103282.

[81] S. Simanungkalit, D. Mansur, M.A. Fitriady, Effect of plastic blends on slow pyrolysis of oil palm empty fruit bunch, AIP Conf. Proc. 2024 (2018) 020003.

[82] F. Abnisa, W.M.A. Wan Daud, S. Ramalingam, M.N.B.M. Azemi, J.N. Sahu, Co-pyrolysis of palm shell and polystyrene waste mixtures to synthesis liquid fuel, Fuel 108 (2013) 311–318.

[83] T. Thoharudin, M. Nadjib, T.H.A. Santosa, Juliansyah, A. Zuniardi, R. Shihabudin, Properties of co-pyrolysed palm kernel shell and plastic grocery bag with CaO as catalyst, IOP Conf. Ser.: Earth Environ. Sci. 209 (2018), 012041.

[84] R. Mamat, M.R. Hainin, N. Abdul Hassan, N.A. Abdul Rahman, M.N. M. Warid, M. K. Idham, A review of performance asphalt mixtures using bio-binder as alternative binder, Jurnal Teknologi 77 (2015).

[85] M. Chaichan, Combustion and emissions characteristics for DI diesel engine run by partially-premixed (PPCI) low temperature combustion (LTC) mode, Int. J. Mech. Eng. Technol. 2 (2014) 7–16.

[86] H. Shafaghat, H.W. Lee, Y.F. Tsang, D. Oh, J. Jae, S.-C. Jung, C.H. Ko, S.S. Lam, Y.-K. Park, In-situ and ex-situ catalytic pyrolysis/co-pyrolysis of empty fruit bunches using mesostructured aluminosilicate catalysts, Chem. Eng. J. 366 (2019) 330–338.

[87] D. Ro, Y.-M. Kim, I.-G. Lee, J. Jae, S.-C. Jung, S.C. Kim, Y.-K. Park, Bench scale catalytic fast pyrolysis of empty fruit bunches over low cost catalysts and HZSM-5 using a fixed bed reactor, J. Cleaner Prod. 176 (2018) 298–303.

[88] V. Balasundram, K.K. Zaman, N. Ibrahim, R.M. Kasmani, R. Isha, M.K. Abd. Hamid, H. Hasbullah, Catalytic upgrading of pyrolysis vapours over metal modified HZSM-5 via in-situ pyrolysis of sugarcane bagasse: Effect of nickel to cerium ratio on HZSM-5, J. Anal. Appl. Pyrolysis 134 (2018) 309–325.

[89] H. Iftikhar, M. Zeeshan, S. Iqbal, B. Muneer, M. Razzaq, Co-pyrolysis of sugarcane bagasse and polystyrene with ex-situ catalytic bed of metal oxides/HZSM-5 with focus on liquid yield, Bioresour. Technol. 289 (2019) 121647.

[90] Clarivate, Web of science, in, Clarivate, 2021.

[91] F. Campuzano, R.C. Brown, J.D. Martínez, Auger reactors for pyrolysis of biomass and wastes, Renew. Sustain. Energy Rev. 102 (2019) 372–409.

[92] A. Gonzalez-Quiroga, P.A. Reyniers, S.R. Kulkarni, M.M. Torregrosa, P. Perreault, G.J. Heynderickx, K.M. Van Geem, G.B. Marin, Design and cold flow testing of a gas-solid vortex reactor demonstration unit for biomass fast pyrolysis, Chem. Eng. J. 329 (2017) 198–210.

[93] Senshou Seiki, Electric pyrolysis plant, Senshou Seiki, (2021). http://senshouseiki .co.jp/en_more/index.html. Accessed February 7.

[94] TNB Research, Renewable energy & green technology, TNB Research, (2021). http://www.tnbr.com.my/advanced-research/renewable-energy-green-tech nology/. Accessed February 7, 2021.

[95] N. Online, Maps of the world continents and regions, (n.d.). https://www.nation sonline.org/oneworld/continents_map.htm. Accessed March 9, 2021.

[96] B.T.G. (BTG), Fast pyrolysis, (n.d.). https://www.btgworld.com/en/rtd/technolo gies/fast-pyrolysis. Accessed July 25, 2021.

[97] Alucha, What we do, Alucha, (n.d.). https://www.alucha.com/. Accessed July 25, 2021.

[98] A. Oasmaa, J. Lehto, Y. Solantausta, S. Kallio, Historical review on VTT fast pyrolysis bio-oil production and upgrading, Energy Fuels 35 (2021) 5683–5695.

[99] Q.T. Trinh, A. Banerjee, K.B. Ansari, D.Q. Dao, A. Drif, N.T. Binh, D.T. Tung, P.M. Q. Binh, P.N. Amaniampong, P.T. Huyen, M.T. Le, Upgrading of bio-oil from biomass pyrolysis: Current status and future development, in: S. Nanda, D.-.V. N. Vo, P.K. Sarangi (Eds.), Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals, Springer Singapore, Singapore, 2020, pp. 317–353.

[100] Ensyn, ENSYN The world's leading biocrude producer: Investing in the bioeconomy, (2017). https://www.energy.gov/sites/prod/files/2017/10/f38/ jacobs_bioeconomy_2017.pdf. Accessed July 25, 2021.

[101] Y.H. Chan, R.R. Tan, S. Yusup, H.L. Lam, A.T. Quitain, Comparative life cycle assessment (LCA) of bio-oil production from fast pyrolysis and hydrothermal liquefaction of oil palm empty fruit bunch (EFB), Clean Technol. Environ. Policy 18 (2016) 1759–1768.

[102] E.A. Ocampo Batlle, Y. Castillo Santiago, O.J. Venturini, J.C. Escobar Palacio, E. E. Silva Lora, D.M. Yepes Maya, A.R. Albis Arrieta, Thermodynamic and environmental assessment of different scenarios for the insertion of pyrolysis technology in palm oil biorefineries, J. Cleaner Prod. 250 (2020) 119544.

[103] A. Niño-Villalobos, J. Puello-Yarce, Á.D. González-Delgado, K.A. Ojeda, E. Sánchez-Tuirán, Biodiesel and hydrogen production in a combined palm and jatropha biomass biorefinery: Simulation, techno-economic, and environmental evaluation, ACS Omega 5 (2020) 7074–7084.

[104] T. Srinophakun, P. Hansirisawat, Techno-economic of 100 kW power plant from microwave-assisted biodiesel pyrolysis, Int. J. Renew. Energy Res. 10 (2020) 1021–1030.

[105] T.X. Do, Y.-I. Lim, H. Yeo, Techno-economic analysis of biooil production process from palm empty fruit bunches, Energy Convers. Manag. 80 (2014) 525–534.

[106] K. Darojat, W. Hadi, D.E. Rahayu, Life cycle assessment (LCA) utilization of oil palm empty fruit bunches as bioenergy, AIP Conf. Proc. 2194 (2019) 020019.

[107] Y. Peryoga, M. Dewi Solikhah, A. Agus Raksodewanto, Production cost assessment of palm empty fruit bunch conversion to bio-oil via fast pyrolysis, Int. J. Adv. Sci. Eng. Inf. Technol. 4 (2014) 394–400.

[108] J. Chattopadhyay, T.S. Pathak, R. Srivastava, A.C. Singh, Catalytic co-pyrolysis of paper biomass and plastic mixtures (HDPE (high density polyethylene), PP (polypropylene) and PET (polyethylene terephthalate)) and product analysis, Energy 103 (2016) 513–521.

[109] Q. Jin, X. Wang, S. Li, H. Mikulčić, T. Bešenić, S. Deng, M. Vujanović, H. Tan, B. M. Kumfer, Synergistic effects during co-pyrolysis of biomass and plastic: gas, tar, soot, char products and thermogravimetric study, J. Energy Inst. 92 (1) (2019) 108–117.

[110] Q.H. Ng, B.L.F. Chin, S. Yusup, A.C.M. Loy, K.Y.Y. Chong, Modeling of the co-pyrolysis of rubber residual and HDPE waste using the distributed activation energy model (DAEM), Appl. Therm. Eng. 138 (2018) 336–345.

[111] D. Xu, S. Yang, Y. Su, L. Shi, S. Zhang, Y. Xiong, Simultaneous production of aromatics-rich bio-oil and carbon nanomaterials from catalytic co-pyrolysis of biomass/plastic wastes and in-line catalytic upgrading of pyrolysis gas, Waste Manage. 121 (2021) 95–104.

[112] Y.H. Chan, K.W. Cheah, B.S. How, A.C.M. Loy, M. Shahbaz, H.K.G. Singh, N. R. Yusuf, A.F. Ahmad Shuhaili, S. Yusup, W.A. Wan Abd Karim Ghani, J. Rambli, Y. Kansha, H.L. Lam, B.H. Hong, S.L. Ngan, An overview of biomass thermochemical conversion technologies in Malaysia, Sci. Total Environ. 680 (2019) 105–123.

[113] Z. Wang, K.G. Burra, T. Lei, A.K. Gupta, Co-pyrolysis of waste plastic and solid biomass for synergistic production of biofuels and chemicals-a review, Prog. Energy Combust. Sci. 84 (2021), 100899.

[114] M. El-Halwagi, Sustainable Design Through Process Integration, 2nd ed., Elsevier, United States, 2017.

[115] D. Foo, Process Integration for Resource Conservation, 1st ed., CRC Press, Taylor & Francis Group, United States, 2012.

[116] B. Linnhoff, D. Townsend, D. Boland, G. Hewitt, B. Thomas, A. Guy, R. Marshall, A User Guide on Process Integration for the Efficient use of Energy, Institute of Chemical Engineers, Rugby, 1982.

[117] T. Kan, V. Strezov, T. Evans, J. He, R. Kumar, Q. Lu, Catalytic pyrolysis of lignocellulosic biomass: A review of variations in process factors and system structure, Renew. Sustain. Energy Rev. 134 (2020) 110305.

[118] Q. Feng, Y. Lin, Integrated processes of anaerobic digestion and pyrolysis for higher bioenergy recovery from lignocellulosic biomass: A brief review, Renew. Sustain. Energy Rev. 77 (2017) 1272–1287.

[119] C. Deng, R. Lin, X. Kang, B. Wu, R. O'Shea, J.D. Murphy, Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis, Renew. Sustain. Energy Rev. 128 (2020), 109895.

[120] M. Sharifzadeh, C.J. Richard, K. Liu, K. Hellgardt, D. Chadwick, N. Shah, An integrated process for biomass pyrolysis oil upgrading: A synergistic approach, Biomass Bioenergy 76 (2015) 108–117.

[121] S.L. Ngan, B.S. How, S.Y. Teng, W.D. Leong, A.C.M. Loy, P. Yatim, M.A. B. Promentilla, H.L. Lam, A hybrid approach to prioritize risk mitigation strategies for biomass polygeneration systems, Renew. Sustain. Energy Rev. 121 (2020), 109679.

[122] J. Zetterholm, E. Wetterlund, K. Pettersson, J. Lundgren, Evaluation of value chain configurations for fast pyrolysis of lignocellulosic biomass—Integration, feedstock, and product choice, Energy 144 (2018) 564–575.

[123] T. Kohl, T.P. Laukkanen, M.P. Järvinen, Integration of biomass fast pyrolysis and precedent feedstock steam drying with a municipal combined heat and power plant, Biomass Bioenergy 71 (2014) 413–430.

[124] A.I. Stankiewicz, J.A. Moulijn, Process intensification: Transforming chemical engineering, Chem. Eng. Prog. 96 (2000) 22–34.

[125] T. Van Gerven, A. Stankiewicz, Structure, energy, synergy, time—The fundamentals of process intensification, Ind. Eng. Chem. Res. 48 (5) (2009) 2465–2474.

[126] I. Abdulrahman, V. Máša, S.Y. Teng, Process intensification in the oil and gas industry: A technological framework, Chem. Eng. Process 159 (2021) 108208, https://doi.org/10.1016/j.cep.2020.108208.

[127] E. Hoekstra, K.J.A. Hogendoorn, X. Wang, R.J.M. Westerhof, S.R.A. Kersten, W.P. M. van Swaaij, M.J. Groeneveld, Fast pyrolysis of biomass in a fluidized bed reactor: In situ filtering of the vapors, Ind. Eng. Chem. Res. 48 (10) (2009) 4744–4756.

[128] B. Peterson, C. Engtrakul, A.N. Wilson, S. Dell'Orco, K.A. Orton, S. Deutch, M. M. Yung, A.K. Starace, Y. Parent, D. Chiaramonti, K.A. Magrini, Catalytic hot-gas filtration with a supported heteropolyacid catalyst for preconditioning biomass pyrolysis vapors, ACS Sustain. Chem. Eng. 7 (17) (2019) 14941–14952.

[129] M. Lu, A. Lepore, J.-S. Choi, Z. Li, Z. Wu, F. Polo-Garzon, M. Hu, Acetic acid/propionic acid conversion on metal doped molybdenum carbide catalyst beads for catalytic hot gas filtration, Catalysts 8 (2018).

[130] S.-J. Oh, G.-G. Choi, J.-S. Kim, Production of acetic acid-rich bio-oils from the fast pyrolysis of biomass and synthesis of calcium magnesium acetate deicer, J. Anal. Appl. Pyrolysis 124 (2017) 122–129.

[131] J.-Y. Jeong, U.-D Lee, W.-S. Chang, S.-H. Jeong, Production of bio-oil rich in acetic acid and phenol from fast pyrolysis of palm residues using a fluidized bed reactor: Influence of activated carbons, Bioresour. Technol. 219 (2016) 357–364.

[132] M.D. Solikhah, F.T. Pratiwi, Y. Heryana, A.R. Wimada, F. Karuana, A. A. Raksodewanto, A. Kismanto, Characterization of bio-oil from fast pyrolysis of palm frond and empty fruit bunch, IOP Conf. Series: Mater. Sci. Eng. 349 (2018), 012035.

[133] A.C. Psarras, C.M. Michailof, E.F. Iliopoulou, K.G. Kalogiannis, A.A. Lappas, E. Heracleous, K.S. Triantafyllidis, Acetic acid conversion reactions on basic and acidic catalysts under biomass fast pyrolysis conditions, Mol. Catal. 465 (2019) 33–42.

[134] L. Deng, Y. Fu, Q.-X. Guo, Upgraded acidic components of bio-oil through catalytic ketonic condensation, Energy Fuels 23 (2009) 564–568.

[135] H. Bayahia, Gas-phase ketonization of acetic acid over Co–Mo and its supported catalysts, J. Taibah Univ. Sci. 12 (2018) 191–196.

[136] T.N. Pham, D. Shi, D.E. Resasco, Kinetics and mechanism of ketonization of acetic acid on Ru/TiO$_2$ catalyst, Top. Catal. 57 (2014) 706–714.

[137] R.W. Ashcraft, G.J. Heynderickx, G.B. Marin, Modeling fast biomass pyrolysis in a gas–solid vortex reactor, Chem. Eng. J. 207–208 (2012) 195–208.

[138] S.R. Kulkarni, L.A. Vandewalle, A. Gonzalez-Quiroga, P. Perreault, G. J. Heynderickx, K.M. Van Geem, G.B. Marin, Computational fluid dynamics-assisted process intensification study for biomass fast pyrolysis in a gas–solid vortex reactor, Energy Fuels 32 (2018) 10169–10183.

[139] J. Bridgwater, Mixing of powders and granular materials by mechanical means—A perspective, Particuology 10 (2012) 397–427.

[140] A. Funke, R. Grandl, M. Ernst, N. Dahmen, Modelling and improvement of heat transfer coefficient in auger type reactors for fast pyrolysis application, Chem. Eng. Process 130 (2018) 67–75.

[141] J. Roegiers, Heat and mass transfer modelling of auger reactors. Faculteit Bio-ingenieurswetenschappen, Ghent University, Ghent, Belgium, 2016.