Oil palm biomass in Indonesia: Thermochemical upgrading and its utilization

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ABSTRACT

Indonesia is the world's largest palm oil producing country. The oil palm industry (plantation and milling) generates large amounts of solid waste in the form of empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fiber (MF), oil palm fronds (OPF), and oil palm trunks (OPT). This leftover waste, collectively termed oil palm biomass (OPB), causes severe environmental pollution, thereby threatening the sustainability of the oil palm industry. Upgrading OPB by thermochemical processes (torrefaction and pyrolysis) has attracted significant interest as a means of recycling the residues and mitigating the environmental damage. This study reviews the previous research on the environment-friendly utilization of OPB in Indonesia. First, general information is presented on OPB in Indonesia (availability, properties, and governmental policy). Second, the torrefaction of OPB for the production of upgraded solid fuel is summarized. Third, the pyrolysis of OPB to produce biochar is reviewed for use as a soil amendment and in carbon storage. The market perspective and life cycle assessment (LCA) of the thermally treated OPB are discussed, targeting the generation of electricity (OPB torrefaction) and agricultural soil enhancement (OPB biochar). The recycling of OPB is expected to contribute to the sustainability and economic success of the oil palm industry and also the net-zero 2060 in Indonesia.

1. Introduction

Indonesia is a leading palm oil producer, supplying approximately 60% of the palm oil used in the world [1]. The oil palm industry is Indonesia's most crucial agricultural business and accounts for approximately 7.5% of total exports [2]. The productivity is much higher for oil palms (3–5 t/ha/yr) than for other oilseeds, such as rapeseed (1 t/ha/yr), soybean (0.375 t/ha/yr), and sesame (0.16 t/ha/yr) [3,4]. In addition, the manual labor requirements are much lower for oil palm plantations than for other oil crops, leading to lower production costs [5]. The higher productivity and better economics of palm oil have led to its widespread use in many industries, including food, cosmetics, and biofuels [6]. The demand for palm oil has increased

to such an extent that it is now the world's most-produced vegetable oil [7]. Of the total global palm oil production, its use as a food ingredient accounts for 71%, followed by the cosmetics (24%) and biofuel (5%) [8]. In many food types, such as baked goods, frozen foods, butters, snacks, chips, and chocolates, palm oil is preferred due to its neutral taste, texture, and functionality [9]. In the energy sector, the main product is crude palm oil (CPO)-based biodiesel. The Indonesian government promotes biofuels as a means of ensuring energy security and low CO_2 emissions, such as the implementation of B30 (the blending of 30% biodiesel and 70% diesel) in 2019 and B40 in 2021 [10].

All these uses have stimulated the production of palm oil in Indonesia. However, environmental concerns might restrain the further spread of the oil palm industry. Deforestation due to the expansion of palm tree plantations has been blamed as a cause of significant

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List of abbreviations

AFOLU	Agriculture, forestry, and other land use
CDM	Clean development mechanism
CEC	Cation exchange capacity
CHP	Combined heat and power
COMB	Counter-flow multi baffle
COP26	The 2021 united nations climate change conference
CPO	Crude palm oil
DME	Dimethyl ether
EFB	Empty fruit bunch
ETS	Emission trading system
FFB	Fresh fruit bunch
FiT	Feed-in tariffs
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
HGI	Hardgrove grindability index
HHV	Higher heating value
HTC	Hydrothermal carbonization
HTT	Highest treatment temperature
ISPO	Indonesian sustainable palm oil
IPCC	Intergovernmental panel on climate Change
LCA	Life cycle assessment
MF	Palm mesocarp fiber
NETs	Negative emission technologies
NZE	Net-zero emissions
OPB	Oil palm biomass
OPF	Oil palm frond
OPT	Oil palm trunk
PKC	Palm kernel cake
PKO	Palm kernel oil
PKS	Palm kernel shell
PM	Particulate matters
RSPO	Roundtable on sustainable palm oil
SOC	Soil organic carbon

Units

GtCO$_2$eq/yr	Gigatonne of CO$_2$ equivalent per year
GW	Gigawatt
kg CO$_2$/MWh	Kilogram CO$_2$ per Megawatt Hour
Mha	Million hectares
MJ/kg	Megajoules per kilogram
Mt	Million tonnes
Mt/yr	Million tonne per year
MWe	Megawatts electric
t/ha	Tonne per hectare
t/ha/yr	Tonne per hectare per year
USD/t	United states dollar per tonne
w/w	Weight per weight

anthropogenic greenhouse gas (GHG) emissions [11]. The monoculture of oil palm trees can also decrease soil carbon and the biodiversity of the harvested area [12]. In addition, the lifecycle of palm oil production (harvesting, milling of fresh fruit bunches (FFB), and planting) creates a massive amount of solid waste in the form of oil palm biomass (OPB) [13]. OPB consists of empty fruit bunches (EFB), palm kernel shells (PKS), palm mesocarp fiber (MF), oil palm fronds (OPF), and oil palm trunks (OPT). Many of these wastes are randomly abandoned on the soil surface due to a lack of dumping space, and the decaying wastes emit an unpleasant odor and hazardous methane gas [7,14]. Even when these materials are landfilled, harmful leachate can be released and pollute waterbodies [15]. Solid wastes are commonly burned in the field, resulting in the emission of GHGs and fine particulate matter, mostly with an aerodynamic diameter of 10 μm (PM$_{10}$). PM$_{10}$ is known to infiltrate deeply into the human lung and possibly cause respiratory and cardiovascular problems [16]. It can also translocate to the central nervous system and cause brain inflammation. Long-term exposure to PM$_{10}$ is linked to the pathogenesis of neurodegenerative diseases (e.g., Alzheimer's disease) [17]. Environment-friendly disposal of OPB is rare in Indonesia.

The sustainability of the Indonesian oil palm industry can be improved with adequate management of OPB [18]. Two major buyers are currently forcing this improvement: the United States under the Renewable Fuel Standard (RFS2) program and the European Union under the Renewable Energy Directive (EU RED) [19]. The Roundtable on Sustainable Palm Oil (RSPO), established in 2004, lists the requirements for the sustainable production of palm oil [20]. In 2012, the European Commission (EC) acknowledged that the import of palm oil should only be allowed when the sustainability criteria of the RED are satisfied and certified by RSPO [21]. A certified case can reduce GHG emissions by up to 36% compared to a non-certified one, supporting the use of technical regulation to encourage oil palm stakeholders to apply the suggested management practices [22]. Accordingly, many Indonesian exporters now adopt the eco-friendly disposal of OPB.

Similar efforts have been made by the Indonesian government to mitigate the adverse environmental impact of the oil palm industry. Indonesian Sustainable Palm Oil (ISPO) was established in 2011 to support the sustainable practices of small and medium-sized businesses by implementing a certification system [23]. In addition, the Oil Palm Plantations Fund Management Agency (BPDPKS: *Badan Pengelola Dana Perkebunan Kelapa Sawit*) was also established in 2015 [24] to support the oil palm industry in five areas: human resources/training, R&D, promotion/advocacy, replanting, and facility/infrastructure [25]. BPDPKS has funded 169 R&D projects as of 2015–2018, and 32 projects have investigated OPB utilization and management [26–29].

OPB has been actively pursued as a low-cost feedstock for solid fuel and biochar to reduce the amounts of OPB in landfills, and these uses represent some of Indonesia's most practical means of achieving net-zero carbon emissions (carbon neutrality) [30]. Many technical projects have focused on methods for using wet, bulky, hygroscopic, and non-homogeneous OPB. As a solid fuel, OPB shows low combustion efficiency due to its low energy density, and it emits substantial combustion smoke. Torrefaction of raw OPB can generate high-quality solid fuel for combustion and gasification that is also carbon-neutral [31]. Co-firing is a significant consumption strategy that provides a relatively quick reduction in the use of fossil fuels and therefore GHG emissions [32,33]. The pyrolysis of biomass produces biochar capable of long-term carbon sequestration and soil enhancement [34]. The thermal upgrading of OPB can encourage oil palm stakeholders to mitigate climate change while achieving economic benefits in the energy and agriculture sectors. The thermochemical process is usually energy intensive; therefore, the use of excess energy, such as pyrolysis gases (CO, H$_2$, and CH$_4$) and tar, is critical for securing economic feasibility [35].

OPB utilization in Malaysia has been described as solid fuel for power generation, a source of biomaterial, and liquid biofuel [36]. The production and characterization of torrefied OPB and its economic evaluation have been done [37]. Physical, bio-chemical, and thermo-chemical conversion of OPB have been reviewed, with an emphasis on biorefinery applications [38]. Yek et al. compared conventional and microwave-based technology for OPB torrefaction [39]. Thermochemical hydrogen production technologies, such as conventional gasification, supercritical gasification, and pyrolysis, were also reviewed using OPB feedstock in Malaysia [40,41]. Kong et al. studied OPB biochar and its challenges for application in Malaysia [19]. Although a substantial

amount of OPB is generated in Indonesia, an extensive review of the valorization of OPB in Indonesia is still lacking, especially regarding its practical use in Indonesia.

This study provides general information about the oil palm industry and its OPB by-products in terms of availability, properties, and government policy in Indonesia. Thermochemical conversion, focusing on torrefaction and pyrolysis of OPB, is then reviewed, including process overviews and product characteristics. The potential market for the upgraded OPB is discussed, especially in terms of renewable energy and agriculture. Finally, the environmental influence of OPB solid fuel and biochar is described based on the life cycle assessment (LCA). This review targets the eco-friendly valorization of OPB, which can contribute to improving the sustainability of the oil palm industry for net-zero emissions (NZE) by 2060 in Indonesia.

2. Oil palm biomass in Indonesia

2.1. Availability and utilization of oil palm biomass

The oil palm tree (Elaeis guineensis) was introduced to Indonesia in 1848 from West Africa and then spread to Southeast Asia [42]. Oil palm plantations are concentrated in tropical areas with appropriate climate and soil conditions, as in Indonesia [3]. Oil palm plantations in Indonesia are now concentrated in seven provinces: South Sumatra, North Sumatra, Riau, Jambi, West Kalimantan, Central Kalimantan, and East Kalimantan (Fig. 1).

Most of the plantation area is distributed in Kalimantan and Sumatra (85% in 2019) [44]. The plantation area for oil palms has expanded exponentially: it was only 6000 ha in 1919 but nearly 15 million ha in 2020 (Fig. 2) [19,45]. Accordingly, the production of oil palm fruit (FFB) has grown significantly (Fig. 2). From 1990 to 2010, the average expansion of plantation land was 7% per year and 6.6% per year from 2010 to 2019 [46]. The crop yield remained constant (Fig. 2). In Indonesia, the average production of FFB is 16.6 t/ha, which is comparable to that of Malaysia (16.5 t/ha) [1].

Since 2008, Indonesia has been a leading palm oil producer, accounting for 60% of the global FFB production in 2019 [1]. About 41% of the plantation area is owned by smallholders, and the remainder is under large-scale plantation management [47]. Around 60% of all industrial cropland, including coconut, rubber, coffee, cocoa, sugarcane, tea, and tobacco, is devoted to oil palm plantations [48]. The oil palm industry is projected to increase as the demand for CPO, palm kernel oil (PKO), and palm kernel cake (PKC) is expected to rise [49].

The oil palm industry generates a huge amount of solid waste that adversely affects the environment [50]. The life cycle of oil palm production and its mass balance are shown in Fig. 3. Only 10% of the overall process (milling and plantation) outcome is edible oil, and the remaining
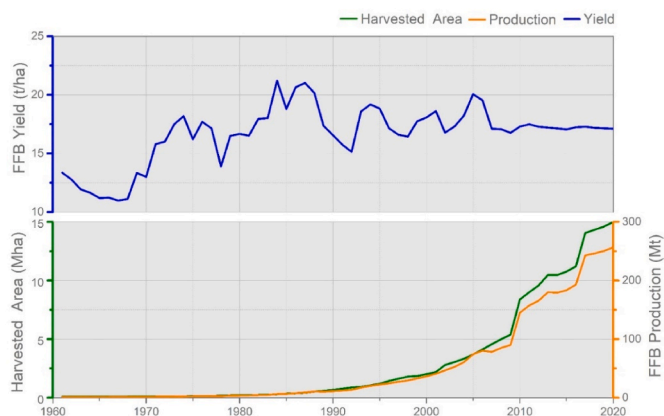

Fig. 2. The Oil palm industry in Indonesia from 1961 to 2020 [1].

90% is OPB [41]. During the milling process (FFB to CPO), 22–23% EFB (from 100% FFB), 5.2–7% PKS, and 11–15% MF are obtained from FFB stripping, nut-cracking (or shell/kernel separation), and depericarping (or nut/fiber separation), respectively [19,51,52]. Consequently, every ton of FFB generates approximately 230 kg EFB, 65 kg PKS, and 130 kg MF on a wet basis. Based on the production amount per area (ha), around 16.4 t/ha FFB in 2019 released 3.7 t/ha EFB, 1.1 t/ha PKS, and 2.1 t/ha MF. In the same year, the total production of FFB was approximately 256 million tons (Mt), and generated 59 Mt of EFB, 17 Mt of PKS, and 33 Mt of MF [1].

OPF and OPT are released mainly during the replanting process, which occurs at 25- to 30-year intervals when productivity decreases. On a dry basis, replanting generates 14.4 t/ha of OPF and 66 t/ha of OPT [54]. Two to three fronds (OPF) are also pruned from each tree in a regular visit, once every two weeks during FFB harvesting or biannual maintenance [13,55]. In 2005, 43.1 Mt/yr of OPF and 13.9 Mt/yr of OPT were obtained, and in 2020, these amounts were 28.9 Mt/yr of OPF and 59.7 Mt/yr of OPT [3,56]. A substantial growth in OPF and OPT was accompanied by the expansion of plantation acreage. A significant increase in released OPT was the result of the replanting season. Due to the large amounts of OPB released, the oil palm industry (plantation and milling) is included as one of the three major biomass sources in Indonesia. The other sources are primary (rice straw, corn stalks, and cassava stems) and secondary (rice husks and corn cobs) agricultural residues [57].

Only a small portion of OPB is utilized for various purposes (Fig. 4), such as solid fuel, mulching, and precursors of functional materials (fertilizer, activated carbon, and composite), either to fulfill environmental obligations or to increase profit [58].
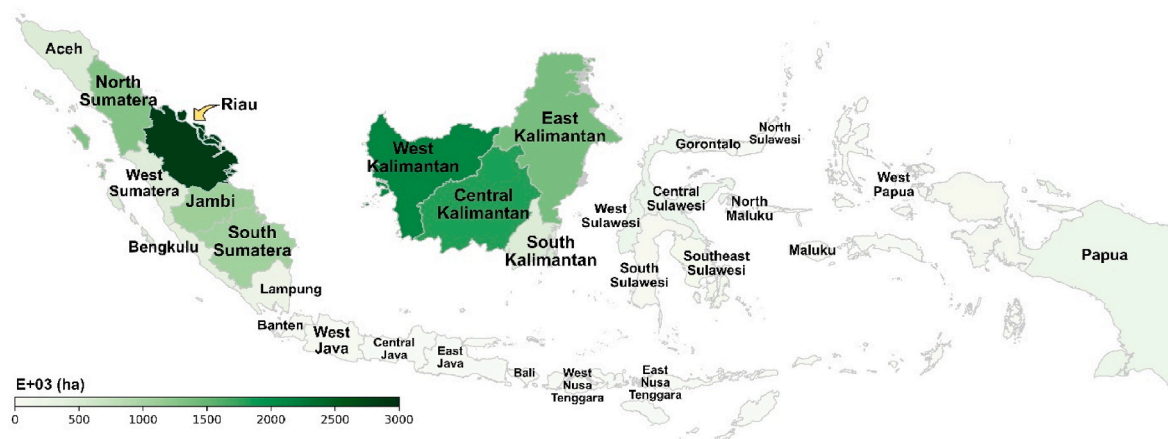

Fig. 1. The distribution of oil palm plantation area in Indonesia, 2021 [43].
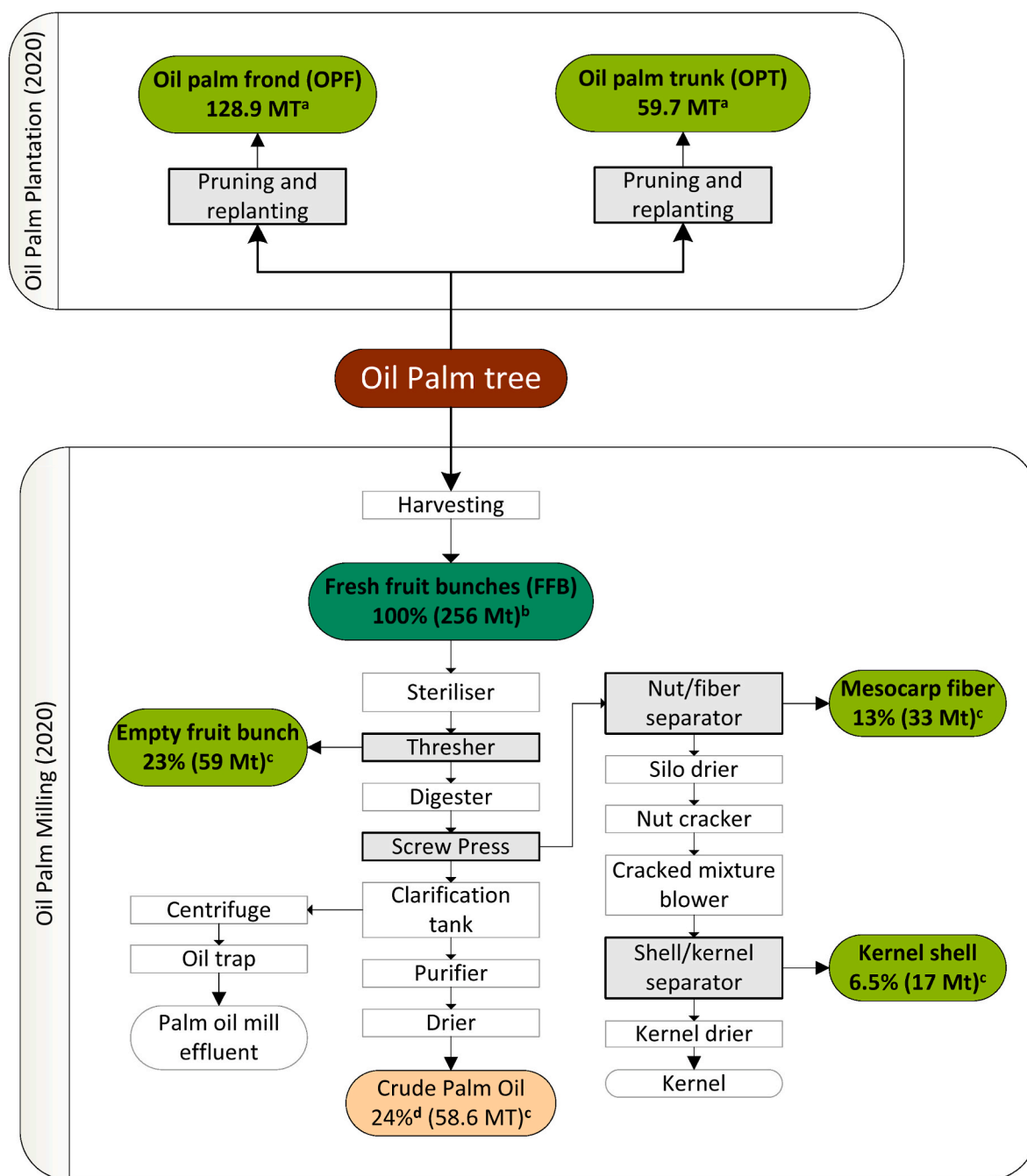
Fig. 3. The life cycle of oil palm production and its mass balance in Indonesia (adapted from Ref. [53]), [a,d] from Ref. [3]; [b] calculated using FFB productivity (16.6 t/ha) and plantation area (14.9 Mha); [c] estimated out of 100% FFB (256 Mt).

EFB is not being managed appropriately and is typically burned in an open field or incinerator. The resulting potassium-rich ash is sold as cheap fertilizer (around $60/t). Incineration is not recommended since it causes air pollution [59]. Alternatively, EFB for use as organic fertilizer is left to decompose naturally in the soil. However, the composting of raw EFB emits an undesirable smell [60]. Dried EFB is sometimes used as fuel in boilers with MF and PKS. PKS is a relatively good solid fuel and is usually exported to EU countries, Japan, and South Korea [61]. Local use of PKS fuel is limited. MF is mainly used as boiler fuel to produce either steam or electricity for the oil palm plant and nearby houses owned by the workers [62,63]. Some of the combined heat and power (CHP) plants use MF and PKS fuel [18]. A tiny fraction of the chopped-down OPT is chipped on-site, piled up with OPF and EFB, and used as mulch to increase soil organic carbon, inhibit weed growth, and

reduce soil erosion [54,64]. OPT is rarely used for furniture logs [4]. A substantial amount of OPB, particularly EFB, OPT, and OPF, remains unutilized, and the environmental issues become more serious each year.

2.2. Properties of oil palm biomass

Lignocellulosic biomass, compared to other biomass sources, is the most abundant, cheapest, and most widely available biomass on the planet. It has been identified as an economically feasible and ecologically effective starting material for thermochemically treated solid products [65]. OPB is also lignocellulosic biomass, comprising hemicellulose, cellulose, lignin (Fig. 5), and others (extractives and inorganic components). The lignocellulosic component differs among OPB,
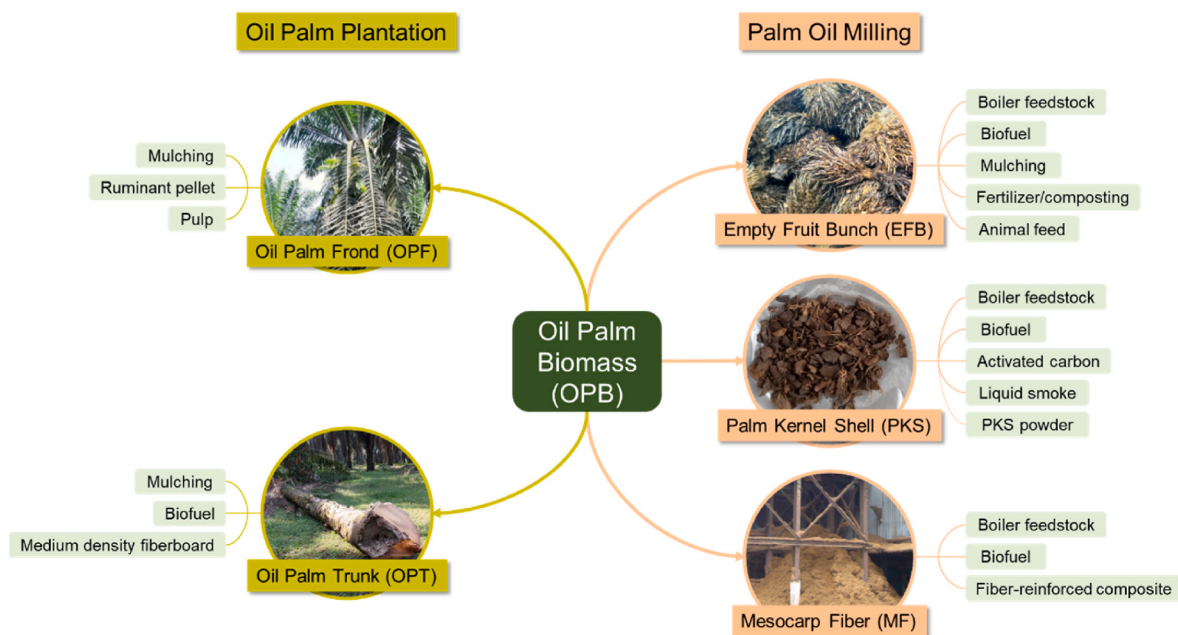
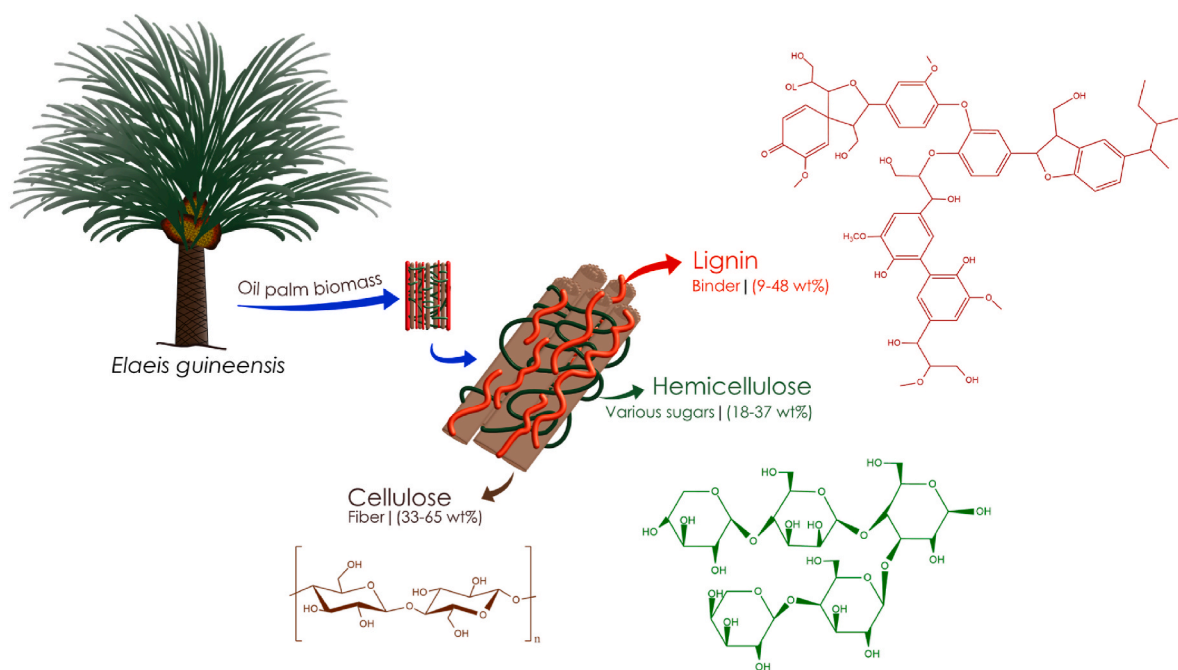**Fig. 4.** Utilization of OPB in Indonesia.

Fig. 5. Lignocellulosic OPB composed of hemicellulose, cellulose, and lignin.

determining their properties and behavior when heated.

Hemicellulose is a polymer of monosaccharides such as glucose, mannose, galactose, xylose, arabinose, 4-*O*-methylglucuronic acid, and galacturonic acid. Cellulose is a linear homopolysaccharide with a basic unit named cellobiose (two glucose anhydrides) [37]. Lignin is a complex polymer composed of different propylbenzene units connected by various ethers and C–C bonds [66]. Generally, cellulose and hemicellulose are firmly bound to lignin, where hemicellulose acts as a linking agent [67]. The physicochemical properties of representative OPB are shown in Table 1. Note that the properties might vary extensively depending on the genetic and environmental factors of the palm tree [68].

Most of the OPB materials show a relatively high content of cellulose (33–65%) compared to that of hemicellulose (18–37%) and lignin (9–49%). PKS contains relatively high lignin (48.6%) and low hemicellulose (18.2%) content. On the contrary, OPF and OPT have a much lower lignin content (9–11%) than the others. Each part of the lignocellulosic material breaks down at a different temperature. Hemicellulose degrades at 200–300 °C, cellulose at 300–400 °C, and lignin at 200–900 °C [54]. The aromatic C–C bond of lignin has a higher binding energy (519 kJ/mol) than the aliphatic C–C bond (348 kJ/mol) of hemicellulose and cellulose. Consequently, lignin is thermally more stable than the other two and generates more solid products when heated [32,37]. Regardless of the difference in the chemical structure,

Table 1
Physicochemical properties of oil palm biomass.

Oil Palm Biomass*	EFB	PKS	MF	OPF	OPT
Lignocellulosic content[a] (wt%)					
Hemicellulose	24.5	18.2	38.0	20.7[a]	26.0[a]
Cellulose	49.1	33.2	35.9	54.4[a]	39.4[a]
Lignin	26.5	48.6	26.1	9.0[a]	6.6[a]
Ref.	[50]	[50]	[69]	[13]	[13]
Proximate analysis (db[b], wt%)					
Moisture content (as received)	65–68	11–13	35–39	65–76	69–82
Fixed carbon	15.4	26.1	18.2	17.9	16.2
Volatile matter	79.2	72.6	75.4	78.9	79.9
Ash content	5.5	1.4	5.8	3.1	3.7
Ref.	[13,70]	[13,70]	[13, 70]	[13,70]	[13, 70]
Ultimate analysis (daf[c], wt%)					
C	45.5	50.6	53.5	55.6	55.8
H	5.9	6.5	7.1	7.7	7.8
O[d]	46.5	34.5	38.2	36.4	35.9
N	1.2	8.4	1.1	0.2	0.5
S	0.7	0.0	0.1	<0.01	<0.01
Ref.	[71]	[71]	[13]	[13]	[13]
Ash composition (mg/kg)					
Na	330.5	143.7	375.4	353.2	142.1
Mg	533.8	2438.1	889.7	581.1	1087.0
Si	5103.0	21,407.3	4042.5	3817.1	1667.6
K	2705.6	744.8	2026.1	1630.2	11.0
Ca	285.7	47.9	63	209.2	431.8
Fe	46,331.6	2708.6	7362.2	20,994.0	175.6
Cd	<0.1	–	0.1	0.4	0.1
Pb	–	–	–	–	1.72
Ref.	[13]	[13]	[13]	[13]	[13]
Calorific value					
HHV[e] (MJ/kg)	17.0	19.8	19.6	15.6	16.1
LHV[f] (MJ/kg)	15.8	18.5	18.3	–	–
Ref.	[53]	[53]	[53]	[72]	[13]
Textural properties					
BET surface area (m²/g)	1.5	1.5	1.2	4.0	3.1
Ref.	[30]	[73]	[73]	[74]	[75]

[a] Extractive-materials free.
[b] Dry basis.
[c] Dry ash-free basis, recalculated from the literature values.
[d] Calculated by difference.
[e] Higher heating value.
[f] Lower heating value.

all three components contribute to the formation of volatiles, gases, and char during the thermochemical process [54].

The proximate analysis data are given in Table 1. Raw OPB, as released, has 11–82% moisture content: 11–13% for PKS, 35–39% for MF, and 65–82% for EFB, OPF, and OPT [70]. A moisture content of OPB <20% is favored before the thermal treatment, which makes the drying process inevitable. OPB is typically dried using natural sunlight in Indonesia [13]. All the OPB samples have >72% volatile matter and 15–26% fixed carbon. Due to the relatively high lignin content, PKS has an 8–10% higher fixed carbon content than the others. The fixed carbon and volatile matter ratio usually affects the yield and calorific value of thermally treated solid products and their physicochemical properties [75]. As expected, an OPB sample with a higher fixed carbon content generally results in a product with a higher yield and calorific value [76]. The ash content ranges from 1 to 6% for OPB, with 5.5–6% for EFB and MF, 3–4% for OPF and OPT, and 1.4% for PKS [54,67]. Ash is a mixed metal oxide and remains incombustible, thereby lowering the efficiency of the combustion system [14]. Therefore, solid fuel with a low ash content is preferred [67]. As shown in the ultimate analysis results (Table 1), OPB consists mostly of carbon, oxygen, and hydrogen, with a small amount of nitrogen and sulfur (<1%) also present [77–79]. OPB contain 34–47% oxygen (dry ash free basis). The high oxygen content indicates that raw OPB is unsuitable for direct combustion [80]. Oxygen in OPB is discharged in the form of oxygenated gases (CO$_2$ and

CO) and water (H$_2$O) when heated under oxygen-lean conditions, giving a solid product with a much-reduced oxygen content [81,82].

The ash composition varies with the kind of OPB (Table 1). Generally, the ash in OPB is high in alkali (K and Na) and alkali earth metals (Ca and Mg). Potassium (K) is dominant in EFB (46,332 mg/kg), MF (7362 mg/kg), and OPF (20,994 mg/kg). The sodium (Na) content is higher in EFB (2856 mg/kg), and the content of calcium (Ca) is higher in PKS (21,407 mg/kg) than in others. The alkali metals readily melt at lower temperatures, frequently causing slagging and fouling during the combustion and, consequently, operational problems in the boiler [83, 84]. Some of the inorganic elements in ash (K, Fe, Ca, and Mg) might work as catalysts for secondary reactions, such as cracking and dehydration during pyrolysis, thereby boosting the degradation of lignocellulosic components [85]. Heavy metals such as Cd and Pb are present in trace amounts (<1.7 mg/kg) [13].

OPB has a higher heating value (HHV) of 15.6–19.8 MJ/kg, while the HHV is 17 MJ/kg for EFB, 19.6–19.8 MJ/kg for PKS and MF, and <16.1 MJ/kg for OPF and OPT [86]. The HHVs of PKS and MF are comparable to those of hardwood pellets (19–20 MJ/kg) [87]. By contrast, the HHV of EFB, OPF, and OPT are similar to that of herbaceous biomass (16–18 MJ/kg) [88]. The specific surface area of OPB is a mere 1.2–4.0 m^2/g, corresponding to the rigid structure of the intact plant cell wall [80].

3. Thermochemical conversion technology of biomass for solid biofuel and biochar

Several technologies are commonly used to upgrade biomass waste. Table 2 presents a comparison of the several technologies used for converting biomass into more valuable products in the form of gases, liquids, and solids.

These technologies differ mainly in the final temperature and heating rate, which affect the form of the main product. Among these technologies, torrefaction, slow pyrolysis, microwave carbonization, and hydrothermal carbonization generate solid products, whereas fast pyrolysis, flash carbonization, and gasification produce bio-oils and bio-gases as biomass energy [65]. Hydrothermal carbonization is sometimes referred to as wet torrefaction. The typical costs of the solid products generated by these technologies vary from 28 to 650 US$/t, depending on the complexity of the technology. The following sections describe the details of torrefaction (including hydrothermal carbonization as wet or steam) and pyrolysis (slow pyrolysis and microwave pyrolysis).

3.1. Torrefaction overview

Lignocellulosic biomass, including OPB, has a lower carbon content and calorific value than fossil fuel [91], but the calorific value can be increased by torrefaction under dry or wet conditions [56,92]. Dry torrefaction is the partial decomposition of biomass at 200–300 °C (a ramp rate of <50 °C/min) for around 5–90 min under an oxygen-lean condition [93,94]. The resultant solid (torrefied biomass) consists of an altered polymeric structure and ash [95]. Short residence time and slow ramping are commonly preferred for a high solid yield [96]. The properties of torrefied biomass (i.e., yield, chemical composition, calorific value, and grindability) vary with the torrefaction conditions, such as temperature, residence time, and particle size [37,97]. Although the torrefaction temperature is the predominant factor influencing the product properties, the residence time can also be critical, especially for OPB with a high moisture content (up to 82%) because of the use of torrefaction energy for moisture vaporization [98]. The particle size of the feedstock influences the kinetics of the torrefaction. Smaller particles require less retention time, thereby increasing the energy efficiency [81,99]. Advanced torrefaction technology, such as the counter-flow multi baffle (COMB), can torrefy biomass feedstock in a significantly shorter time (3–10 min) than other technologies [100]. Wet torrefaction or hydrothermal carbonization (HTC) is carried out in compressed water (2–10 MPa) at a relatively low temperature (180–260 °C) and gives a

Table 2
Comparison of thermochemical conversion of biomass (Compiled from Refs. [65,89,90]).

Technology	Temperature (°C)	Residence time	Solid yield (mass %)	Intended product	Cost (US$/t, solid basis)	Technical challenge
Torrefaction	200–300	3–90 min	70	Torrefied biomass	28–33	Self-heating and self-ignition; finding operating conditions with a feasible cooling process
Slow pyrolysis	300–750	minutes–days	15–89	Biochar	51–373	Requiring high reaction temperatures and regulated heat rates; reactor containment corrosion
Fast pyrolysis	300–1000	2 s	12–27	Bio-oil	560	Rapid removal of solid residues; effective recovery of liquids
Microwave pyrolysis	200–600	30 min	25–35	Biochar	650	The issue of hot spots; requirement for microwave absorbers
Hydrothermal carbonization	180–300	5 min–12 h	36–72	Biochar	33–87	Safety; pressure in continuous systems
Flash carbonization	300–600	30 min	37–50	Biochar	NA	The elastic limit of the production equipment materials
Gasification	700–900	10–20 s	5–10	Syngas, heat	380	Tar-induced corrosion; clogging of particulate filters and fuel lines/injectors in an internal combustion engine

hydrophobic solid product (hydrochar) [83]. Although wet torrefaction is less energy-intensive than dry torrefaction, the set-up for a continuous high-pressure process is challenging. Torrefaction degrades hemicellulose and cellulose structures, removing primarily light volatiles [31]. It ends with a mass yield of about 70% due to the loss of 30% condensable and non-condensable gases, but with a much higher energy yield of 90%, giving a densified product [101]. The process temperature is typically maintained at <300 °C to achieve high energy efficiency [102].

As shown in Fig. 6, torrefaction improves the properties of solid biomass fuel.

The torrefied product shows a higher energy density than the raw sample. Volatile matter, such as hydrogen- and oxygen-containing compounds like hydroxyls and ethers, is the main material released during torrefaction [90]. As a result, smoky emissions are reduced, and combustion efficiency is improved. The hydrogen bonding of the product is also weak, increasing its hydrophobicity [104].

The torrefied product is resistant to wetting and biological decomposition, making it highly preferable for long-distance transport and storage [105]. Torrefaction thermally disintegrates the fibrous structure of raw biomass, increasing its brittleness and making it more appealing as a feedstock for co-firing in pulverized coal boilers. The grindability measured by the Hardgrove Grindability Index (HGI) test determines the particle size distribution of torrefied biomass and increases with decreasing hemicellulose content, which is associated with its biological role of strengthening the plant cell wall [98]. In addition, torrefaction can convert various raw materials, regardless of origin, into homogeneous fuels of the same quality. It can reduce the organic chlorine content that causes corrosion of combustion systems.

3.2. Pyrolysis overview

Pyrolysis is a thermochemical conversion at 300–750 °C in an inert or oxygen-lean atmosphere [13,106]. This endothermic reaction produces biochar, organic liquids (tar and pyroligneous acid), and non-condensable gases (CO, CO_2, H_2, and CH_4) [107,108]. Biochar is typically the main intended product of the slow pyrolysis (5–10 °C/min) and is derived from organic waste, such as forestry residue, crop residue, and animal manure [109,110]. The properties of biochar are mainly

determined by the feedstock and pyrolysis conditions (pyrolysis temperature, residence time, and heating rate) [111]. The feedstock primarily influences the chemical composition (carbon and ash content) and pore structure [112]. For example, manure-derived biochar may boost the availability of nutrients in the soil due to its high nutrient content (N, P, and K), whereas plant-based biochar containing more recalcitrant carbon may perform better as a carbon sequestrator [113]. The pyrolysis temperature determines the relative amounts of fixed carbon, pore structure, and pH. The yield decreases significantly when the pyrolysis temperature increases from 200 °C to 300 °C but becomes relatively steady at 300–700 °C [34]. The weight loss at lower temperatures is most likely due to the volatilization of moisture and labile molecules (volatile matter). When the temperature is raised above 700 °C, no significant increase occurs in fixed carbon content [54]. The impact on the yield is less for the residence time than for temperature, especially for pyrolysis at the higher temperature region, where the secondary reactions are dominant [114]. Slow pyrolysis is regarded as a sustainable approach since it produces less harmful gases [115]. Microwave-assisted pyrolysis, known as dielectric heating, readily transfers the heat from the surface to the center of a material, which speeds up the reaction with high energy efficiency [116]. Lam et al. pyrolyzed PKS at 583 °C with a 700 W microwave and at 457 °C with a 600 W microwave and successfully maintained high biochar yield up to 83% in short process time [117]. However, this is not commercialized yet.

3.3. Possible conversion mechanism of oil palm biomass

The reaction pathways are almost the same for both torrefaction and pyrolysis, since these processes differ only in the final temperature. As shown in Fig. 7, the thermochemical conversion of biomass is a highly complex, three-stage process [65].

The first stage of the charring reaction includes mainly dehydration, bond breakage, and fragmentation of methoxy, carboxyl, and acetyl groups, which happen in the torrefaction temperature region (<300 °C). It is often considered a pre-treatment for pyrolysis and gasification. Torrefied OPB is the product of the first stage and usually obtained at a higher yield. The yield of OPB products varies depending on the feedstock type, as their lignocellulosic content is different. Depolymerization, fragmentation, and secondary reactions are dominant in the second stage (300–550 °C). Each type of lignocellulosic material (hemicellulose, cellulose, and lignin) undergoes different reaction mechanisms [65]. Condensation of polycyclic structure happens in the third stage, resulting in a naturally non-degradable char. Ash-forming elements in biomass exist in the form of water-soluble salt, ion-exchangeable species, minerals, and covalently bonded sulfur and chlorine. Most of the ash becomes acid-soluble material after torrefaction process (240–280 °C), which improves the acid-washing efficiency for reducing ash in torrefied biomass [119].

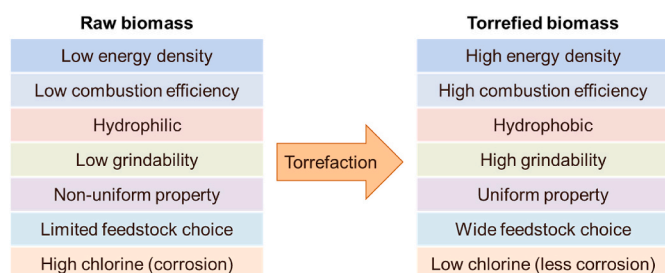| Raw biomass		Torrefied biomass
Low energy density		High energy density
Low combustion efficiency		High combustion efficiency
Hydrophilic	Torrefaction	Hydrophobic
Low grindability		High grindability
Non-uniform property		Uniform property
Limited feedstock choice		Wide feedstock choice
High chlorine (corrosion)		Low chlorine (less corrosion)

Fig. 6. Advantages of torrefied biomass fuel, compared to raw biomass [103].
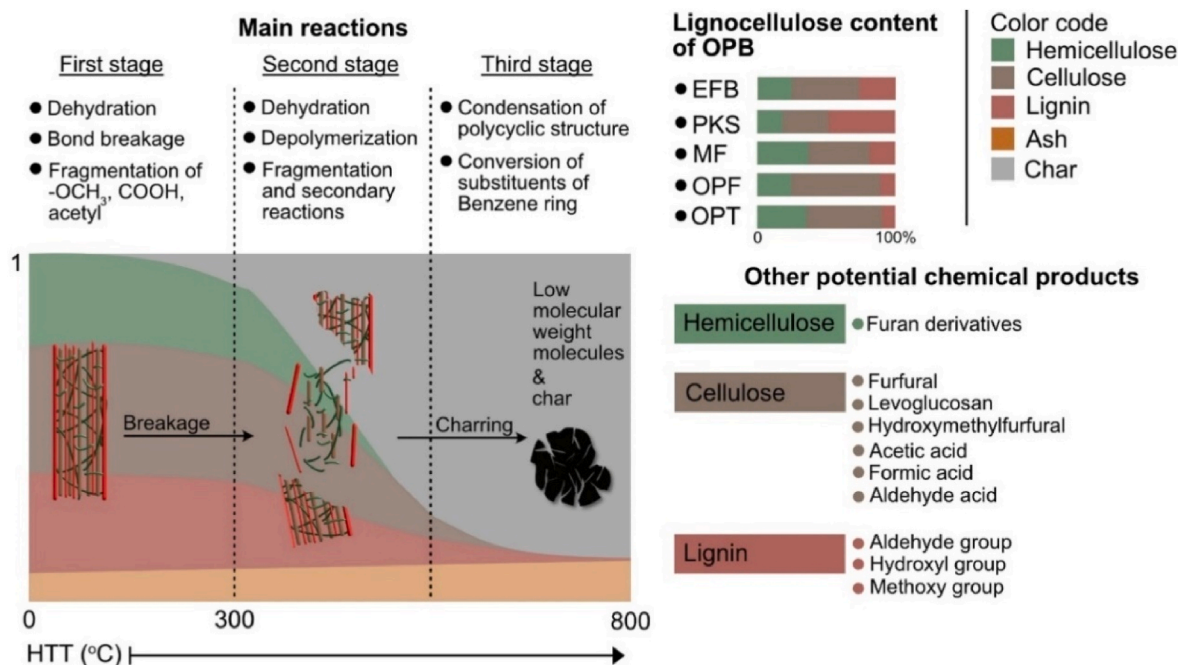
Fig. 7. Illustration of the biomass pyrolysis process, reactions, and phase development with increasing highest treatment temperature (HTT). Throughout the process, the lignocellulosic content was degraded and transformed into a char phase. Adapted with permission from Ref. [118]. Copyright 2017 American Chemical Society.

4. Torrefied oil palm biomass for solid biofuel and its potential market

4.1. Properties of torrefied oil palm biomass

Torrefaction improves the properties of OPB as a solid fuel. Table 3 shows the mass yield, HHV, and the ultimate analysis results of torrefied OPB and the values for woody biomass and raw coal for comparison purposes. Torrefaction generally targets high yield for better economics [120]. The yield of the torrefied OPB decreases with increasing temperature, due to the loss of volatile matter and non-condensable gases (H_2O, CO_2, CO, H_2, and CH_4) [53]. When torrefied under dry conditions, the yield of torrefied EFB is 43% at 220 °C, 37% at 250 °C, and only 24% at 300 °C. Similarly, it is 63% at 220 °C, 60% at 250 °C, and 52% at 300 °C for MF, and 79% at 250 °C, 68% at 275 °C, and 55% at 300 °C for OPF. However, the yield of PKS remains >70% even when torrefied at 300 °C, which is the highest value among all the others (24–55% when torrefied at the same temperature). This most likely reflects the relatively high lignin content of PKS.

An increase in the calorific value is one of the benefits of torrefaction. The thermal decomposition of less stable hemicellulose increases the carbon content and decreases the oxygen content, leading to an increased calorific value [76]. Table 3 shows that the HHV of torrefied OPB (dry condition) is comparable to that of torrefied woody biomass and raw coal, ranging from 16 to 23 MJ/kg. The HHV of many low-rank coals is between 15.4 and 23.0 MJ/kg, and torrefied OPB has a higher HHV value than lignite. Carbon and oxygen are still the dominant elements in torrefied OPB. The carbon content is mainly 45–55%, and that of oxygen is 40–45% after dry torrefaction. HTC at temperatures above 300 °C results a significant increase in carbon content (10–20%) and a decrease in oxygen content (10–20%). A decrease in hydrogen content (<2%) is also observed. The content of sulfur and nitrogen remains essentially unchanged. The combustion behavior of solid fuel is characterized by the ratio of hydrogen to carbon (H/C) and oxygen to carbon (O/C) [107]. As shown in Fig. 8, the van Krevelen diagram (atomic ratio of H/C and O/C) places torrefied OPB between raw OPB and low-rank coals. The relatively low H/C value of torrefied OPB indicates an

increase in more stable aromatic compounds [124].

Table 4 provides the proximate analysis results for torrefied OPB. The content of volatile matter decreases with increasing the reaction temperature. When thermally treated at >300 °C, OPF and OPT contain 50–70% volatile matter. Accordingly, the content of fixed carbon is generally <50%. The ash content is 1–6% and relatively high for EFB and PKS. Incombustible ash should be kept to a minimum in solid fuel [37]. The specific surface area is < 10 m^2/g for torrefied EFB and 28 m^2/g for torrefied PKS.

4.2. Torrefied oil palm biomass as solid fuel

A key term in the energy sector is net-zero (carbon neutral), which requires the replacement of fossil fuels with sustainable energy sources [32]. One of the most promising fuels is non-edible biomass, such as OPB [126]. OPB is a solid fuel with a zero-emission factor and contains a negligible amount of nitrogen and sulfur (lower NOx and SOx emissions) [75,127]. An enormous amount of OPB is generated in a relatively concentrated area and can be handled at a reasonably low cost for collection and logistics. Using raw OPB as commodity fuel is not recommended because of its low energy density, poor combustion behavior (much smoke), and hygroscopic nature.

The biomass densification process (pelletization and briquetting) is usually done through drying, chipping, grinding, and densifying step, and which can overcome the above weaknesses. It is a mature and cheap option and proceeds with the feedstock containing 15–20% moisture [128]. However, the humid condition might induce pellet disintegration, moss development, and bio-organic decomposition [129]. Further efforts should be made to ensure the market-level quality of the OPB pellet, such as its physical strength [130]. Torrefaction converts OPB to a high-quality solid fuel–like coal. The best case is achieved through a trade-off between fuel quality and cost [131]. Torrefied PKS emits less CO and CH_4 and induces less fouling than raw PKS [101]. Co-firing of OPB might emit less SOx because the blending dilutes sulfur in coal [104].

Ash in OPB has a relatively high amount of alkali and alkaline earth metal oxides (Tables 1 and 5), which can react with silicon-containing

Table 3

Mass yield, HHV, and ultimate analysis of torrefied OPB, woody biomass, and raw coal.

Feedstock	Condition	HTT[a] (°C)	Yield (%)	HHV[b] (MJ/kg)	Ultimate Analysis (daf[c], wt%)					Ref.
					C	H	O[d]	N	S	
Oil Palm Biomass										
EFB	dry	220	43.2	16.1	49.6	5.0	44.0	1.3	0.1	[53]
		250	36.9	16.6	49.2	5.2	44.1	1.4	0.1	
		300	24.2	19.4	50.4	4.5	43.9	1.3	0.02	
	dry	200	–	18.4	47.5	4.8	46.4[e]	1.2	0.2	[50]
		220		18.9	48.3	4.7	45.6[e]	1.2	0.1	
		240		19.4	49.3	4.7	44.7[e]	1.3	0.1	
		260		19.9	49.6	4.5	44.5[e]	1.3	0.1	
		280		22.2	49.8	4.5	44.0[e]	1.5	0.1	
		300		22.4	51.6	4.2	42.7[e]	1.4	0.1	
	HTC[f] (20 min)	150	76.0	20.0	51.7	6.2	41.0	1.0	0.2	[30]
		250	62.0	22.1	57.9	4.4	36.4	1.1	0.3	
		350	49.0	27.2	69.0	4.3	25.2	1.2	0.3	
	HTC[f] (22 h)	180	–	–	51.2	5.9	42.3	0.5	–	[14]
		200			53.4	5.3	40.6	0.8		
		220			62.8	5.3	30.9	0.9		
PKS	dry	220	77.4	17.5	47.9	6.6	45.0	0.4	0.02	[53]
		250	73.8	17.8	53.7	5.9	39.9	0.5	0.01	
		300	71.3	20.6	56.2	5.3	38.0	0.5	0.02	
	dry	250	64.7	20.3	53.7	5.0	40.8	0.4	–	[96]
MF	dry	220	63.1	17.8	48.1	5.6	44.3	1.9	0.1	[53]
		250	60.0	18.1	50.3	5.5	42.3	1.8	0.1	
		300	52.4	21.1	50.8	5.1	41.8	2.2	0.1	
	dry	200	–	19.3	47.9	4.9	45.9[e]	1.2	0.1	[50]
		220		19.7	47.7	4.7	46.2[e]	1.3	0.1	
		240		20.1	47.9	4.7	45.9[e]	1.4	0.1	
		260		20.8	50.5	4.3	43.6[e]	1.6	0.1	
		280		22.1	51.1	3.9	43.3[e]	1.6	0.1	
		300		23.7	51.5	3.8	43.0[e]	1.6	0.0	
OPF	dry	250	79.0	19.9	44.5	5.7	47.4	2.4	0.0	[121]
		275	68.0	21.3	47.7	5.4	44.5	2.4	0.0	
		300	55.0	23.4	53.4	4.8	39.6	2.2	0.0	
	HTC[f] (2 MPa)	200	58.3	20.5	53.6	5.7	40.4	0.2	0.1	[56]
		240	52.0	23.0	58.6	5.4	35.7	0.3	0.1	
		270	42.5	26.7	69.4	4.9	25.3	0.4	0.1	
		300	38.4	27.3	71.1	4.9	23.5	0.4	0.1	
		330	36.7	29.0	73.9	4.9	20.7	0.4	0.1	
		350	35.1	29.7	75.1	4.8	19.5	0.4	0.1	
OPT	dry	350	27.8	19.6	67.9	3.5	26.7	1.4	0.4	[76]
	HTC[f] (2 Mpa)	200	67.8	19.9	51.4	5.9	42.1	0.4	0.1	[56]
		240	56.9	22.6	57.5	5.6	36.2	0.6	0.1	
		270	41.7	27.0	69.3	5.1	24.6	0.8	0.1	
		300	38.7	28.0	71.4	5.0	22.6	0.8	0.1	
		330	36.9	29.4	73.4	4.9	20.6	1.0	0.1	
		350	35.3	29.7	75.3	4.9	18.6	1.0	0.2	
Woody biomass										
Leucaena leucocephala	dry	260	78.8	18.9	51.9	6.1	41.6	0.4	–	[122]
		280	60.8	19.7	54.1	5.9	39.6	0.4		
		300	41.5	22.1	60.1	5.5	33.9	0.5		
Coal										
Sub-bituminous coal[g]	–	–	23.0	57.7	4.0	17.2[e]	1.0	0.1		[123]
Lignite[h]	–	–	15.4	37.7	3.0	10.7[e]	0.7	0.9		[123]

[a] Highest treatment temperature.
[b] Higher heating value.
[c] Dry ash-free basis, recalculated from the literature values.
[d] Calculated by difference.
[e] Dry basis.
[f] Hydrothermal carbonization.
[g] Adaro coal (Indonesia).
[h] Texas, USA.

compounds and form alloys with low melting points [83]. Slagging and fouling may occur in the combustion system and then decrease the thermal efficiency, causing frequent shutdowns for maintenance [94]. Torrefaction may facilitate the release of alkali and alkaline earth metal oxides from the readily decomposed hemicellulose and extractive portions [83]. Table 5 shows less alkali and alkaline earth oxides in torrefied EFB, OPF, and OPT than in raw OPB. However, the remaining ash could still be problematic. The slagging and fouling issue should be investigated further with the spread of torrefied OPB as co-firing fuel.

Chlorine compounds may corrode water tubes and the boilers, mainly due to HCl emissions and sticky alkali-chlorine-salt deposition (i. e., KCl, NaCl, and CaCl₂) [134]. Torrefaction can markedly reduce the chlorine content in both EFB and PKS. As shown in Table 6, 90–98% and 80–95% reductions in EFB and PKS, respectively, after torrefaction at 230 and 300 °C have been reported [135]. The other torrefied biomass contains up to 90% less chlorine than the raw biomass [136]. The chlorine is commonly released in the form of HCl during torrefaction [119].
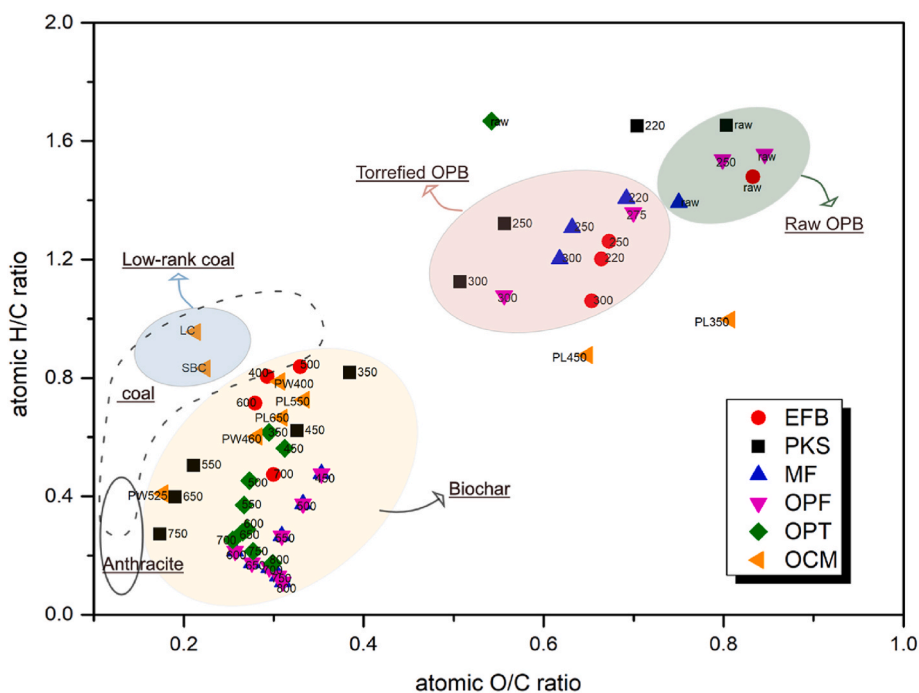
Fig. 8. Van Krevelen diagram of OPB and other biomass materials. OCM = Other Carbon Materials; LC = Lignite coal; SBC = Sub-bituminous coal; PW = Poplar wood; PL = Poultry litter (Calculation based on Table 3 & Table 8).

Torrefied OPB fuel can be utilized when combined with advanced torrefaction technology, which is still in its early stages in Indonesia. The thermochemical conversion is typically conducted with a batch-type reactor or a small-scale rotary kiln. A continuous process is needed to ensure the quality and quantity of solid fuel. In addition, recycling the combustible byproducts of the pyrolysis (torgas and tar) should be implemented to achieve a high energy efficiency of the conversion.

4.3. Market for torrefied oil palm biomass in Indonesia

The reliance on fossil fuels as a source of energy for heating and power will continue for at least the next 30 years [137]. Indonesia pursues status as a middle-upper country by 2025 and a developed country (prosperous Indonesia) by 2045 [138]. Accordingly, power generation has been expanded via the megaproject that started in 2015, targeting 35 GW to be completed by 2029. The generation capacity is approximately 70 GW in 2019, 15 GW more than in 2015 [139]. Fig. 9 shows Indonesia's total primary energy consumption and net electricity generation by fuel type (2020). Fossil fuels are still dominant in both the energy mix (86%) and electricity generation (82%) in Indonesia, resulting in significant CO_2 emissions [140]. Coal in the power generation sector (62%) is responsible for nearly 212 Mt of CO_2 released in 2019 [141]. Biomass energy accounts for 7% of primary energy consumption and 4% of power generation.

Indonesia has set a target to replace fossil fuels with renewables [142]. The portion of renewable energy in the primary energy mix was set at >23% by 2025 and > 31% by 2050 [143]. Indonesia declared it would reach NZE by 2060 or earlier at the 2021 United Nations Climate Change Conference of the Parties (COP26) in Glasgow [144]. Accordingly, the Indonesian government strongly promotes the use of renewable resources, such as biomass. As shown in Table 7, PKS, MF, and EFB are being used as fuel for small-scale CHP plants in Kalimantan, Riau, and Sumatra [61]. An economic advantage can be achieved from electricity sales to the state electricity company (PLN: *Perusahaan Listrik Negara*) under a feed-in-tariff (FIT) system and emission trading systems (ETS) that will soon be employed in Indonesia. The cost of OPB fuel is far less than that of diesel [145].

A significant demand for biomass fuel, including OPB, exists in the co-firing sector [146]. The fuel can be used with minimal modification to existing facilities, making it the most feasible option economically [93]. The co-firing can reduce GHG emissions. A coal-fired power plant emits 700–900 kg CO_2/MWh, whereas torrefied biomass can recapture 847 kg CO_2/MWh [131]. The PLN of Indonesia has demonstrated co-firing at 26 steam power plants, including the co-firing of raw PKS (50%) in eight power plants [147]. Torrefied beech wood thermally treated at 250 °C has also been tested in the co-firing system in Indonesia [32]. Moreover, all the coal-fired power plants in Indonesia (total capacity of 18 GW, 114 units at 52 locations) have also planned biomass co-firing until 2024, and OPB is considered one of the most economical feedstocks [142,147].

Torrefied OPB can be a feedstock for gasification and heat generation (combustion) in the iron-making and cement industries. A $2.3 billion low-rank coal gasification project was initiated in South Sumatra in January 2022 and is to be finalized in 2025. Construction of an additional gasification plant is already planned at East Kalimantan, where 3.2 Mt of dimethyl ether (DME) is to be produced using two gasifiers [148]. Isgiyarta et al. reported that torrefied OPF treated at 200 °C was acceptable as a gasification feedstock and was technically and economically feasible for distributed power generation (100 kW scale) in remote areas [149]. These might open the opportunity for torrefied OPB as a gasification feedstock, since a significant amount of OPB is released in Sumatra and Kalimantan.

The iron-making industry has used coal as the main heating fuel and reducing agent. About 320 steel plants are distributed in Indonesia, consuming coal and thus emitting CO_2. Use of the upgraded OPB (torrefied or pyrolyzed) as a coal substitute is attractive to mitigate the GHG emissions. Wood torrefied at 250 °C reduced iron oxide at a significantly lower temperature (onset at 300 °C) than graphite (>950 °C) due to its high volatile matter content [150]. Meanwhile, iron ore mixed with 30% raw PKS was optimally reduced at 800 °C [151]. Use of 20% raw PKS reduced the low grade iron ore at 900 °C, reducing CO_2 emission up to 19% [152]. The energy-intensive cement industry is also a potential consumer of OPB in Indonesia. Rahman et al. simulated the use of various agricultural biomass as fuel for cement kilns and showed an

Table 4

Proximate analysis and specific surface area of torrefied OPB.

Feedstock	Condition	HTT[a] (°C)	Proximate analysis (db[b], wt%)			BET SSA[e] (m²/g)	Ref.
			FC[c]	VM[d]	Ash		
EFB	Dry	220	19.9[g]	78.2[g]	1.9[g]	–	[69]
	HTC[f] (30 min)	180	12.8	82.6	4.6	–	[91]
		200	21.9	73.6	4.5		
		220	24.1	70.7	5.2		
	HTC[f] (60 min)	180	17.5	78.2	4.3	–	[91]
		200	24.4	69.7	6.0		
		220	29.5	64.6	6.0		
	HTC[f] (20 min)	150	18.1[g]	77.7[g]	4.2[g]	6.1	[30]
		250	28.9[g]	66.6[g]	4.4[g]	8.0	
		350	45.0[g]	50.4[g]	4.6[g]	2.0	
PKS	Dry	250	26.3	67.0	6.4	27.5	[106]
	Dry	250	23.0	68.2	8.8	–	[96]
	Dry	220	21.3[g]	74.0[g]	4.6[g]	–	[69]
MF	Dry	220	22.5[g]	73.7[g]	3.9[g]	–	[69]
OPF	Dry	200	12.4	85.3	2.3	–	[125]
		225	16.3	80.4	3.4		
		250	19.7	77.4	3.0		
		275	21.4	74.0	4.8		
		300	27.0	69.7	3.4		
	HTC[f] (30 min)	200	20.2[g]	78.5[g]	1.3	–	[56]
		240	29.3[g]	69.4[g]	1.3		
		270	45.4[g]	53.5[g]	1.2		
		300	47.6[g]	51.4[g]	1.0		
OPT	Dry	200	15.9[g]	82.3[g]	1.8	–	[56]
		240	26.1[g]	72.1[g]	1.8		
		270	44.1[g]	53.7[g]	2.2		
		300	47.8[g]	50.1[g]	2.1		
	Dry (30 min)	300	20.2	76.5	3.3	–	[98]
	(45 min)	300	22.0	74.5	3.6		
	(60 min)	300	31.4	64.6	4.0		

[a] Highest treatment temperature.
[b] Dry basis.
[c] Fixed carbon.
[d] Volatile matter.
[e] BET surface area.
[f] Hydrothermal carbonization.
[g] Re-calculated from literature values.

improvement of 3% energy efficiency and 3.5% CO_2 reduction [153].

Utilization of torrefied OPB fuel has many advantages, such as (1) Mitigation of GHG emissions in coal-fired power plants and other heat-related industries; (2) OPB waste recycling in oil palm cultivation and urban areas; (3) Prevention of methane gas released from landfills; (4) Use of the combustion residue (ash) as fertilizer and clinker substitute in cement industry; (5) Low sensitivity to fuel price fluctuations; (6) Improvement of the economic situation in a rural area; and (7) Lower handling (transportation and logistics) cost [37,104,154–157]. The torrefaction of OPB can provide the proper disposal/utilization mechanisms and provide extra revenue for the oil palm industry [158]. However, high transportation costs from remote areas to the used facilities are a challenge yet to be addressed.

Table 6

Chlorine content of raw and torrefied OPB [135].

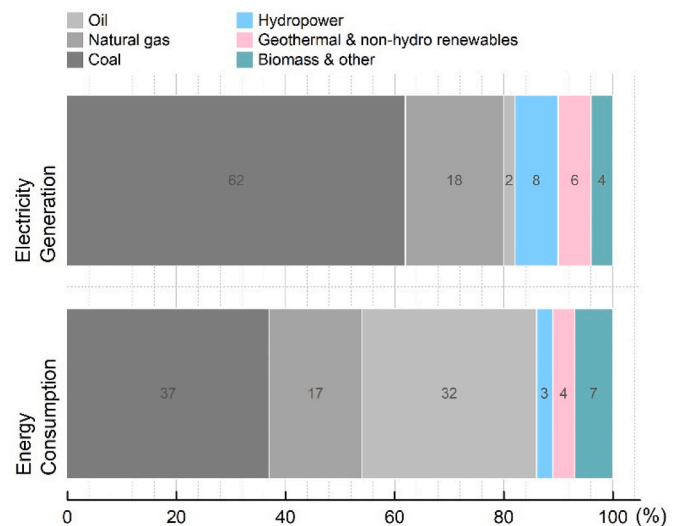| Sample	Raw (mg/kg)	230 °C (mg/kg)	300 °C (mg/kg)
EFB	501.6	58.0	12.4
PKS	193.0	38.3	9.1

Fig. 9. Indonesia's total primary energy consumption and net electricity generation by fuel type in 2020 [140].

Table 5

Ash composition of raw and torrefied oil palm biomass at different temperatures.

Sample	Mineral composition (wt%)											Ref.
	SiO₂	Al₂O₃	CaO	MgO	Na₂O	K₂O	SO₃	P₂O₅	Fe₂O₃	TiO₂	other	
EFB	12.1	0.3	9.6	1.9	0.1	55.5	1.67	3.6	–	–	–	[84]
EFB	19.0	2.5	7.9	4.4	3.3	48.9	4.0	3.0	5.5	0.7	–	[132]
EFB-180	28.6	6.8	10.7	5.9	6.1	27.0	4.9	2.5	6.6	0.7		
OPF	12.2	0.2	52.7	16.0	–	8.3	7.2	2.4	0.4	–	0.1	[56]
OPF-200	28.7	0.8	51.3	6.0		3.7	5.8	1.1	1.4		0.1	
OPF-240	32.9	1.5	39.5	7.5		4.4	8.3	2.5	2.0		0.1	
OPF-270	39.1	1.6	28.8	7.6		4.6	12.4	2.9	1.2		0.1	
OPF-300	29.6	2.2	30.8	6.9		5.5	15.2	5.4	2.2		0.1	
OPF-330	16.6	2.6	37.1	8.5		6.0	16.3	8.1	2.5		0.1	
OPF-350	16.4	2.7	36.5	8.5		5.7	16.0	7.8	3.0		0.1	
OPT	14.9	0.2	23.5	15.6	–	24.5	10.7	8.7	0.7	–	0.1	[56]
OPT-200	39.8	0.7	18.8	8.4		13.2	9.5	7.3	1.1		0.1	
OPT-240	44.4	0.8	15.2	5.8		9.2	9.2	13.1	1.4		0.1	
OPT-270	44.0	0.8	16.4	4.6		7.4	9.9	14.8	1.2		0.1	
OPT-300	41.4	1.5	18.2	4.6		5.4	7.9	18.2	1.7		0.1	
OPT-330	22.8	1.2	27.3	5.1		6.8	9.6	23.0	2.6		0.2	
OPT-350	22.8	0.8	22.1	11.8		5.2	9.3	18.4	3.1		0.1	
Wood pellet	4.3	1.3	55.9	8.5	0.6	16.8	1.3	3.9	1.5	0.1	5.9	[133]

OPB-X: X = torrefaction temperature (°C).

Table 7
Oil palm biomass-based heat and power plants in Indonesia [61].

Fuel	Capacity	Location	Owner
PKS	10 MWe	West Kalimantan	PT Rezeki Perkasa Sejahtera Lestari
PKS	2 MWe	Central Kalimantan	PT Atman
PKS	10 Mt/h steam	North Sumatra	PT Multimas Nabati Asahan
EFB and PKS	2 × 10 MWe	Dumai	Wilmar Group
EFB and PKS	2 × 10 MWe	Kuala Tanjung	Wilmar Group
EFB and PKS	6 MWe	North Sumatra	PT Medan Sugar Industry
EFB, MF, PKS, wood chip	6 MWe	West Bangka	Kencana Agri Ltd
EFB, MF, PKS, wood chip	6 MWe	Belitung	Kencana Agri Ltd

5. Biochar from oil palm biomass and its potential utilization

5.1. Properties of biochar from oil palm biomass

Tables 8 and 9 show the properties of OPB biochar, which vary significantly depending on the study, probably due to different pyrolysis conditions and palm tree origins. Table 8 shows the variation in the OPB biochar yield with the pyrolysis temperature. As expected, the biochar yield decreases as the temperature increases due to the degradation of lignocellulosic components into small molecules [106]. The yield decreases from 42% (300 °C) to 23% (700 °C) for EFB biochar, from 46% (350 °C) to 31% (750 °C) for PKS biochar, from 35% (450 °C) to 26% (800 °C) for MF, from 35% (450 °C) to 30% (800 °C) for OPF, and from 29% (400 °C) to 23% (500 °C) for OPT. The elemental composition varies with the pyrolysis temperature. The carbon content increases with the temperature. OPB biochar generally has a carbon content >60% when pyrolyzed above 400 °C, while PKS biochar has the highest carbon content (70–86%). OPB biochar with >60% carbon content is resistant to chemical degradation, making it a favorable choice for long-term carbon sequestration [159]. OPB biochar has a higher C content and lower O and N contents than animal manure biochar. The nitrogen content is higher for EFB biochar than for the other OPB biochars but lower than for manure biochar. The nitrogen content is not much affected by the pyrolysis temperature and depends on the type of OPB (Table 8) [54]. A negligible amount of sulfur is detected in OPB biochar.

As shown in Table 8, the atomic composition of OPB biochar is comparable with that of woody biomass. The van Krevelen diagram shows a similar finding (Fig. 8), as both biochars are positioned in a similar area, whereas manure biochar is placed near torrefied OPB. The H/C and O/C ratios of biochar decrease with an increase in the pyrolysis temperature [159]. Carbonaceous aromatic components develop due to the elimination of hydrogen and oxygen (such as dehydration and decarbonylation/decarboxylation) [106,170]. At lower temperatures (250–350 °C), the surface functional groups of the OPB biochar (hydroxyl, carbonyl, carboxyl, and methoxyl) are retained [170]. However, these are thermally disintegrated at >450 °C, and most oxygenated compounds decompose above 650 °C, making the biochar more hydrophobic [76,106]. Conversely, the atomic content of OPB biochar was not much affected by the pyrolysis time, particularly for PKS [167]. The atomic composition of biochar also depends on the type of feedstock.

The specific surface area of OPB biochar is closely related to the adsorption behavior due to the number of adsorption sites and diffusional kinetics (Table 8) [107]. The BET surface area of EFB biochar is < 6 m^2/g regardless of the pyrolysis temperature, and that of OPT biochar pyrolyzed at 450 °C is also small (2.1 m^2/g). By contrast, the values are much higher for PKS, MF, and OPF than for EFB. The surface area of PKS biochar is 30 m^2/g when pyrolyzed at 350 °C and 404 m^2/g at 650 °C. The pyrolysis of MF and OPF at 600 °C gives surface areas of 266 m^2/g and 592 m^2/g, respectively. PKS biochar shows the highest BET surface area when pyrolyzed at 650 °C, whereas a further increase in the

temperature to 750 °C leads to a slight decrease in the value, which might be due to thermal cracking of biochar and partial collapse of the pore structure [106]. In addition, shrinkage and realignment of the biochar structure occur after prolonged exposure to higher temperatures and reduce the number of pores, resulting in a transition from meso-to macropores [173]. The wood-derived biochars exhibit relatively high surface areas. Poplar and spruce wood biochars have surface areas of 55.7 and 40.4 m^2/g, respectively, when pyrolyzed at 525 °C [124]. The BET surface area of pig manure biochar also increases when pyrolyzed at >500 °C [172].

Table 9 presents the proximate analysis results for OPB biochar. The fixed carbon content is generally >50% and increases with the pyrolysis temperature [67]. The volatile matter content decreases with increasing temperature because of the decomposition of relatively small molecules. PKS biochar shows a relatively high fixed carbon content of 53–87%. MF biochar pyrolyzed at 600–650 °C has a fixed carbon content of 60–70%. However, the composition of OPT biochar varies significantly depending on the study, probably reflecting differences in the pyrolysis conditions and the origin of the palm trees. The ash content is generally high for OPB biochar and varies with the kind and origin of OPB (2–37% when pyrolyzed at 500 °C). PKS biochar is relatively low in ash content. The pyrolysis temperature increases the ash content because of the destructive volatilization and mineral matter conversion of lignocellulosic components [67,75]. An abundance of ash can be helpful as fertilizer [37]. The calorific value of OPB biochar is typically >25 MJ/kg, which is higher than that of low-rank coal. OPB biochar is of less interest as solid fuel because of its low pyrolysis yield. Concerning the total energy value, torrefied OPB with a much higher mass yield is a better solid fuel compared to biochar [76].

5.2. Biochar for soil enhancement

Food security and sustainability in agriculture should be satisfied simultaneously, as both are closely related to soil nutrients and anthropogenic climate change [174,175]. Extensive use of chemical fertilizers deteriorates the soil ecosystem [176], and the fertilizer costs account for 15–30% of the total production expense. Nevertheless, only a tiny portion of the nutrients gets to the plant due to prior losses through volatilization, leaching, and erosion [177]. Climate-smart soils that can be intensified by the addition of soil organic carbon (SOC), such as biochar, are urgently needed to secure both soil fertility and carbon neutrality [178]. Biochar in the soil has many advantages, as a high carbon content can feed soil microorganisms, increase the soil pH, provide a porous structure with low bulk density for improved water holding and better diffusion of gases, and increase the cation exchange capacity (CEC) for the slow release of nutrients [179]. The improved soil conditions significantly enhanced crop yield.

Biochar interacts with the soil via redox reactions, adsorption-desorption, and precipitation-dissolution to influence the soil's physical, chemical, and biological properties [171,180]. The effect of biochar varies depending on the properties of the biochar and soil, the amount of added biochar, and the type of crop [181,182]. Table 10 shows the soil response to the addition of OPB biochar.

Only a limited number of studies have examined the agricultural performance of OPB biochar in Indonesia. OPB biochar can be sent back to the palm plantation. EFB biochar in the oil palm nursery improves root growth and reduces ammonium-N leaching, and serves as a habitat for *N*-fixing microbes [181,185]. OPF biochar enhances the water-holding capacity and, therefore, oil palm seedling growth by 10% [189]. Combining EFB biochar with fertilizer (or compost) stimulates plant growth, while improving the availability of P, Mg, and Ca [175, 185,190]. OPB biochar can reduce soil bulk density to facilitate root branching and penetration [185]. The water-holding capacity and water transportation are also improved, allowing the plant to more readily manage environmental stress. PKS biochar used for mushroom cultivation promoted the growth rate and percentage of mycelial colonization,

Table 8
Ultimate analysis of biochar from oil palm biomass and other carbonaceous materials.

Feedstock	HTT[a] (°C)	Yield (%)	Ultimate analysis (daf[b], wt%)					BET SSA[d] (m²/g)	Ref.
			C	H	O[c]	N	S		
EFB	300	23–42	59.6	4.0	34.1[e]	2.3	–	4.5	[107]
	400		65.9	4.4	25.7[e]	3.9		5.8	
	500		65.3	4.6	28.7[e]	1.4		4.8	
	600		67.9	4.0	25.3[e]	2.8		4.0	
	700		68.6	2.7	27.4[e]	1.2		3.3	
	650	–	66.5	3.3	29.1[e]	1.1	–	–	[69]
	900	–	82.2	3.8	13.3	0.4	0.1	–	[71]
PKS	350	45.9	70.7	4.8	23.5	0.9	–	29.7	[106]
	450	37.7	76.6	4.0	18.5	0.9		36.3	
	550	34.8	86.9	3.7	8.4	1.0		98.1	
	650	32.6	90.5	3.1	5.3	1.2		404	
	750	31.2	95.5	2.2	1.1	1.2		394.5	
	650	–	83.6	6.2	9.1[e]	1.1	–	–	[69]
	386	–	73.4	4.0	22.1	0.5	0.0	78	[11,166]
	457		75.2	3.6	20.7	0.4	0.0	126	
	583		76.7	3.8	19.0	0.4	0.0	225	
	700 (1 h)	35.9	88.0	2.4	8.4[e]	1.1	0.0	133.2	[167]
	700 (2 h)	31.3	82.6	2.8	13.3[e]	1.2	0.1	11.5	
	700 (3 h)	31.4	89.4	2.4	7.1[e]	1.1	0.0	90.0	
MF	450	34.8	65.2	2.6	30.7	1.5	–	266[f]	[73,168]
	500	33.1	66.6	2.1	29.6	1.7			
	550	31.1	68.8	1.5	28.3	1.3			
	600	30.6	72.4	1.3	24.8	1.4			
	650	29.2	71.4	1.0	26.2	1.4			
	700	28.9	70.0	0.9	27.6	1.4			
	750	28.1	69.5	0.8	28.3	1.4			
	650	–	74.3	3.6	21.6[e]	0.5	–	–	[69]
OPF	450	28–35	55.7	3.2	40.7	0.5	–	592[g]	[6,77,169]
	500		65.6	2.6	31.2	0.6			
	550		68.7	2.0	28.6	0.7			
	600		70.6	1.6	27.2	0.6			
	650		71.1	1.3	27.1	0.5			
	700		72.2	1.1	26.3	0.4			
	750		73.5	1.0	24.9	0.6			
	500	30.2	65.3	2.6	31.4[e]	0.8	–	–	[170]
OPT	450	–	67.9	3.2	28.3	0.7	–	–	[54]
	500		70.8	2.7	25.8	0.7			
	550		71.6	2.2	25.5	0.8			
	600		71.8	1.7	25.9	0.6			
	650		72.1	1.7	25.5	0.7			
	700		73.0	1.5	24.8	0.6			
	750		71.6	1.3	26.4	0.7			
	400	23–29	89.1	3.8	6.3	0.7	0.1	3.1[h]	[75]
	450		91.4	3.6	4.1	0.7	0.1		
	500		93.1	2.9	3.2	0.6	0.1		
	500	33.6	63.7	2.3	33.4[e]	0.6	–	–	[170]
Poplar wood	400	–	69.7	4.6	24.9	0.8	–	3.0	[124]
	460		73.6	3.7	21.7	1.0		8.2	
	525		83.6	2.9	12.4	1.1		55.7	
Spruce wood	400	–	64.7	5.6	28.6	1.0	–	1.8	[124]
	460		82.1	3.4	13.3	1.2		14.2	
	525		82.2	3.1	13.4	1.3		40.4	
Poultry litter	350	–	46.2	3.8	49.6	0.4	0.0	1.8	[171]
	450		51.4	3.8	44.4	0.4	0.0	5.6	
	550		65.8	4.1	29.4	0.5	0.2	18.1	
Pig manure	350	57.5	–	–	–	–	–	4.3	[112]
	500	38.5						47.4	
	650	35.8						42.4	
Pig manure	300		63.9	8.2	21.6	6.4	–	0.7	[172]
	500		69.3	3.0	20.4	7.3		3.5	
	700		75.0	1.6	17.3	6.1		29.6	

[a] Highest treatment temperature.
[b] Dry ash-free basis, recalculated from the literature values.
[c] Calculated by difference.
[d] BET surface area.
[e] Dry basis.
[f] At 600 °C.
[g] At 700 °C activated by N_2.
[h] At 500 °C.

Table 9
Proximate analysis of biochar from oil palm biomass.

Feedstock	HTT[a] (°C)	Proximate analysis (db[b], wt%)			HHV[e] (MJ/kg)	Ref.
		FC[c]	VM[d]	Ash		
EFB	400	31.4	34.8	33.7	16.3	[160]
	600	37.6	23.5	39.0	16.6	
	500	54.3[f]	27.8[f]	17.9[f]	27.5	[67]
	650	38.9[f]	47.8[f]	13.3[f]	26.7	[69]
	900	90.4	0.3	9.3	–	[71]
PKS	400	63.7[f]	34.3[f]	2.0[f]	–	[161]
	500	73.8[f]	24.0[f]	2.1[f]		
	600	80.0[f]	17.3[f]	2.7[f]		
	700	86.4[f]	10.3[f]	3.3[f]		
	800	87.6[f]	7.9[f]	4.5[f]		
	900	86.4[f]	7.3[f]	6.3[f]		
	350	53.3	35.5	11.3	25.0	[106]
	450	62.5	24.7	12.9	30.0	
	550	72.2	14.0	13.9	30.6	
	650	75.9	9.1	15.1	31.1	
	750	77.3	5.3	17.4	31.6	
	500	80.8	12.3	6.9	–	[162]
	600	87.1[f]	9.0[f]	3.9[f]	30.8	[163]
	700	23.6[f]	71.9[f]	4.4[f]	–	[164]
	386	61.1[f]	32.2[f]	6.6[f]	–	[11]
	457	63.7[f]	29.3[f]	7.0[f]		
	583	68.0[f]	25.4[f]	6.6[f]		
	650	75.1[f]	11.9[f]	13.0[f]	30.4	[69,73]
MF	550	65.0[f]	4.9[f]	27.0[f]	24.8	[91]
	650	70.6[f]	17.7[f]	11.7[f]	28.4	[69]
OPF	500	78.8	18.6	2.6	–	[165]
	550	85.7[f]	10.4[f]	3.9[f]	24.2	[91]
OPT	350	30.9	41.3	27.8	19.6	[76]
	400	71.4[f]	20.0[f]	8.6[f]	27.6	[75]
	450	72.0[f]	18.9[f]	9.0[f]	27.9	
	500	76.8[f]	14.6[f]	8.6[f]	28.1	

[a] Highest treatment temperature.
[b] Dry basis.
[c] Fixed carbon.
[d] Volatile matter.
[e] Higher heating value.
[f] Re-calculated from literature values.

mainly due to improved moisture retention [15]. A mixed use of PKS and rice husk biochar reduced the permeability rate of the soil, leading to higher water retention [187]. Mixed biochar also improves the chemical properties, such as pH, the content of SOC and nutrients (P and K), and CEC, of degraded ultisol soil. EFB biochar (pH 8.0) neutralizes the soil water in highly acidic soil (pH < 3.5) by reducing the concentration of aluminum cation (Al^{3+}) and markedly increases the grain yield of rice [181].

Soil enhancement induced by biochar from various biomass sources has also been reported in Indonesia. As shown in Table 11, the pyrolysis products of coconut shells, rice husks, bamboo, and animal manure have been applied to maize and rice paddies under different soil conditions. The addition increases the crop yield by positively affecting the soil pH, SOC, CEC, and nutrient availability. Coconut shell biochar in the ultisol soil of an oil palm plantation increased the soil pH, SOC, and available K [191]. One-time dosing with animal manure biochar improved the cassava productivity for three years [192]. Another study showed that the soil enhancement effect of biochar lasts at least five years for cassava and red chili [193]. Biochar improved the growth of maize, regardless of the soil type [192,194–197]. Rice husk biochar (5–10 t/ha) in the acid sulfate soil of rice paddy fields increased the rice yield [198,199]. Meranti biochar in podzolic soil adsorbed P nutrients and then desorbed to the topsoil, improving plant growth [200]. Biochar plays a role as a soil enhancer, either alone (Tables 10 and 11) or in combination with other amendments such as fertilizer, chemical enrichment, animal manure, and sub-bituminous coal [173,201–216]. Biochar works, especially well in degraded land (acidic soil, ex-mine land, reclaimed land, and peatland), and sandy soil by enhancing water holding capacity [191,205,211,217–222].

5.3. Biochar for carbon sequestration and climate change mitigation

Crop residues are typically left in the field to maintain soil fertility, but this practice induces GHG emissions, especially for materials with a low C/N ratio and a high moisture content [228]. Biochar is a promising alternative for sustaining soil fertility while reducing GHG emissions. Table 12 shows the GHG reduction activity in Indonesia based on the use of soil biochar in rice paddies and maize fields. Biochar can reduce CO_2 emissions because it contains many functional groups that are capable of adsorbing CO_2 and it can decrease the amount of labile carbon by the sorption of organic matter and enzymes onto its surface [229]. However, no significant effect was noted for rice husk biochar mixed with compost in short-term observation [211], and even an increased CO_2 emissions is observed following EFB biochar application to peat soil [230], probably reflecting the increased availability of media as microbial substrates and activation of microbial breakdown [230]. PKS biochar in quartz sand can potentially sequester nearly 0.4 tons of CO_2 per ton of biomass [173]. Rice husk and cacao shell biochar, sometimes combined with either compost or fertilizer, can decrease N_2O and CH_4 emissions [231–234]. The total carbon of OPB biochar is stable and may contribute to carbon storage in oil palm, indicating the potential for a carbon depository [185]. A higher biochar production temperature generally leads to a lower emission of CH_4 and N_2O [217,235].

Biochar can also debilitate methanogenic activity by increasing the CH_4 oxidation activity and soil aeration, thereby limiting methanogenesis [237]. Several long-term tests show that biochar effectively reduces CH_4 emissions by inhibiting the substrate availability for CH_4 production [206,238,239]. In particular, the reduction of CH_4 emissions by biochar has been confirmed in flooded paddy soils, indicating that this could significantly reduce GHG emissions in Indonesia, where paddy farming is very active [206]. However, contradictory results also exist regarding the reduction of CH_4 emissions by biochar [229,238, 240–243]. Soil biochar typically reduces extractable nitrate by promoting adsorptive immobilization of inorganic N, thereby suppressing N_2O release in the agricultural sector [109,206,232,234,238,244]. The positive effect of biochar on crop yield is well known; however, GHG mitigation by biochar should be further verified, particularly in Indonesian soils.

5.4. Biochar for pollution remediation

Biochar can be applied to removal of pollutants from soil and aqueous/gaseous media, taking advantage of its abundant oxygen functional groups and porous structure (high specific surface area). Biochar in soil can minimize heavy metal (Cd, Pb, Zn, Ni, Cu, Hg, and As) contamination on root plants, which might cause human chronic diseases [245]. The heavy metals can be adsorbed on biochar through ion exchange and/or electrostatic interaction [115]. OPB biochar adsorbents for water pollution control systems have been extensively studied, especially for palm oil mill effluent (POME) treatment [115,246,247]. POME that is discharged from palm oil milling contains high biochemical oxygen demand (BOD), chemical oxygen demand (COD), and colored contaminants [248]. POME remediation is mandatory in Indonesia, with an effluent standard (2014) of 100 mg/L and 350 mg/L for BOD and COD, respectively [249]. Table 13 lists OPB biochar applied to POME treatment. The OPB-based adsorbent can remove residual oil, suspended solids, and heavy metals from POME, which is technically different from the conventional ponding system (anaerobic and aerobic treatment) [250]. Biochar can also remove gaseous pollutants like volatile organic compounds (VOCs), NH_3, and H_2S [247]. However, no reports are available for OPB adsorbent in Indonesia.

Biochar pyrolyzed at >500 °C has relatively high specific surface area and well-developed micro-porosity, and therefore is generally more

Table 10

Effect of OPB biochar on crop productivity and soil improvement.

Biochar feedstock (HTT[a], Ht[b], pH)	BET SSA[c] (m^2/g)	Location	Soil type	Biochar application rate	Crop type	Crop response/soil quality changes	Ref.
EFB (400–600 °C, 2–3 h, 8.23)	–	Sumatra, Indonesia	Lead contaminated soil	–	–	SOC, N, P, and K concentrations improved.	[183]
EFB (300–500 °C, 3 h, 10.5)	–	Bangka Belitung, Indonesia	Ex-tin mining soil	20 (t/ha)	Maize	Soil pH and soil nutrients improved, increasing corn yield up to 26%.	[184]
EFB (300–350 °C, -, 7.5)	–	Malaysia	Sandy clay	0; 0.5; 1.0; 1.5% (w/w)	Oil palm (In main nursery stage)	Root growth was enhanced significantly with 1.5% w/w biochar; Ammonium-N leaching decreased up to 21–46%.	[185]
EFB (300–400 °C, -, 8.0)	–	Malaysia	Acid sulfate soil	0; 10; 20; 40 (t/ha)	Rice	Grain yield increased by 141–472%; Soil water pH nearly doubled from 3.5 to 6.	[181]
EFB (300–350 °C, 3 h, -)	12.22	Malaysia	Loamy soil	0; 15; 30 (t/ha)	Maize	Maize growth improved significantly compared to wood and rice husk biochar applications.	[186]
PKS and rice husk (250–350 °C, 3.5 h, 7.1–7.7)	–	Sumatra, Indonesia	Ultisol: Typic Kanhapludults	0; 2.5; 5; 7.5 (t/ha)	Maize	Physicochemical properties of acidic soil improved with 5–7.5 t/h application.	[187]
PKS (405 °C, -, -)	270	Malaysia	Mushroom substrate (sawdust, rice bran, and CaCO$_3$)	0; 1; 2; 3% (w/w)	Oyster mushroom	At 2% biochar application, the mycelium growth accelerated within 21 days and produced the highest mushroom yield (550 g/month).	[188]
PKS (405 °C, 35 min, -)	270	Malaysia	Mushroom substrate (sawdust, rice bran, and lime)	2.5% (w/w)	Oyster mushroom	At optimum pH (6.8–7) after biochar application, medium growth and mushroom yield increased by 91% and 280 g, respectively.	[15]
OPF (300 °C, 3 h, -)	–	Nigeria	Drought nature soil	0; 10; 20; 30; 40 (t/ha)	Oil palm seedling	Plant growth increased up to 10%; Biochar promoted water holding capacity.	[189]

[a] Highest treatment temperature.
[b] Holding time.
[c] Surface area.

Table 11

Other biomass-derived biochars used as soil amendments in Indonesia.

Biochar feedstock (HTT[a], RT[b])	Location	Soil type	Biochar application rate (t/ha)	Crop type	Improvement	Ref.
Shorea sp. (600 °C, 8 h)	Lampung	Topsoil	50% (w/w)	*Paraserianthes falcataria*	Shoot yield, plant growth	[223]
Shorea sp. (600 °C, 14 days)	Lampung	Topsoil	5% (w/w)	*Falcataria moluccana*	Root growth	[224]
Shorea sp. (600 °C, 4 day)	Lampung	Podsolic soil	25	*Falcataria moluccana*	P uptake, plant growth	[200]
Coconut shell (-, -)	Bengkulu	Ultisol	12	Oil palm	Soil pH, SOC, available K	[191]
Coconut shell (400 °C, -)	Central Kalimantan	Peatland	4	Maize	Soil pH, available K, NPK uptake	[220]
Coconut shell (600 °C, -)	Yogyakarta	Inceptisols (ex-brick mine soil)	15	Rice paddy	SOC, rice yield	[219]
Rice husk (-, -)	South Kalimantan	Acid sulfate soil	5	Rice paddy	Soil pH, total N and K content, plant growth, rice yield	[198]
Rice husk (600 °C, -)	West Kalimantan	Acid sulfate soil	10	Rice paddy	SOC, available P, Al^{3+} reduction, soluble Fe, rice biomass	[199]
Bamboo (400–500 °C, 45 min)	West Sumatra	Ultisol	2% (w/w)	Soybean	Soil pH, available P, SOC, CEC, plant growth	[225]
Bamboo (250–350 °C, 2–3.5 h)	Bali	Dryland farming	10	Maize	Plant growth	[197]
Cacao shell (300–450 °C, 3 h)	South Sumatra	Ultisol: Typic Kanhapludults	22.5	Maize	Crop yield, Al^{3+} reduction	[194]
Vitex pinnata (400–500 °C, 30–60 min)	East Kalimantan	Degraded Spodosols	10–15%v	*Anthocepalus cadamba*	Plant growth	[226]
Gliricidia sepium (350 °C, 24 h)	East Nusa Tenggara	Vertisol	5	Maize	Soil bulk density, crop yield	[195]
Cocopeat (400–600 °C, 1 h)	Aceh	Entisol	10	Peanut	Soil pH, C:N ratio, exchangeable K, plant growth, crop yield	[227]
Farmyard manure (240–300 °C, 8–10 h)	East Java	Inceptisols (clay loam)	15	Maize	Crop yield	[192]
Cattle manure (250 °C, 9–10 h)	West Nusa Tenggara	Sandy soils	15	Maize	SOC, crop yield	[196]

[a] Highest treatment temperature.
[b] Residence time.

Table 12

Biochar mitigates GHG emissions in Indonesia.

Biochar feedstock (HTT[a], Ht[b], pH)	Location	Soil type	Biochar application rate	Crop type	GHG reduction	Ref.
EFB (250–300 °C, 8 h, 10.0)	Central Kalimantan	Peat soil	2.5 (t/h) + 2.5 (t/h) of compost	–	In short-term observation (90 days), CH_4 emissions dropped by up to 300%, but CO_2 and N_2O emissions increased by up to 126% and 125%, respectively.	[230]
Rice husk (-, -, -)	South Kalimantan	Acid sulfate soil	1% (w/w)	Rice paddy	CH_4 emissions decreased by up to 53.2% with the addition of biochar and compost (1:1).	[231]
Rice husk (600 °C, -, -)	Central Java	Sandy loam and clay soil	0; 5; 10 (t/ha) Compost: biochar (4:1)	Rice paddy	No significant CO_2 flux occurred in the short-term bio-compost application.	[211]
Cacao shell (-, -, 9.7) Rice husk (-, -, 9.0)	Lampung	Kanhapludults (Ultisols)	0; 15 (t/ha)	Rice paddy	Total N_2O emissions decreased by 26% and 21% for cacao shell and rice husk biochar, respectively, during upland rice planting.	[232]
NR[c]	Central Java	Aeric Endoaquents	3 (t/ha) Urea: biochar (4:1)	Maize	Global warming potential (GWP) decreased by up to 12.5%.	[233]
Rice husk and cacao shell (250–350 °C, 3.5 h, 8.4 and 9.8)	Lampung	Acidic, sandy loam Acrisols (Ultisols)	0; 1; 2; 5; 10% (w/w)	–	Net NO and N_2O decreased. At >2% cocoa shell biochar addition, denitrification rates dramatically increased and improved N_2 production.	[234]
NR[c]	Central Java	Aeric Endoaquepts	3 (t/ha) Manure: biochar (4:1)	Rice paddy	In 6 planting seasons, GWP declined by 17%.	[236]
OPB biochar application in other countries						
PKS (731 °C, -, -)	Malaysia	Quartz sand	NPK: Biochar (1:3)	–	The carbon sequestration potential of PKS biochar was estimated at 0.398 tons of CO_2 per ton of biochar. PKS biochar can be used as a slow-release fertilizer.	[173]
PKS (400–550 °C, -, 8.0)	Japan	Clay loam	0; 10; 20; 40 (t/ha)	Broccoli	No significant change in GHG emissions but the soil nutrients significantly increased at 40 t/ha biochar application.	[228]

[a] Highest treatment temperature.
[b] Holding time.
[c] Not reported.

Table 13

OPB biochar as adsorbents for POME (wastewater) treatment in palm oil.

Biochar feedstock	Treatment condition	BET SSA (m^2/g)	Adsorbate	Initial concentration (mg/L)	Adsorption performance	Ref.
EFB	CO_2 pyrolysis at 800 °C for 30 min	937	BOD[a]; COD[b]	154; 3238	Using a 9% w/v biochar dosage, the BOD of POME decreased by up to 98% during the first 24 h of treatment.	[251]
PKS	Doped with Zeolite and Fe(II)	NR	COD and color	NR	At 4 g/L dose of biochar removed 67.2% of the COD and 83.1% of the color in 30 min.	[248]
PKS	Doped with Fe(II)	611.8	COD and color	492	At 9.9 g/L within 3.4 h, the optimum removal of COD was 85% and nearly 100% for color.	[252]
OPF	Steam pyrolysis at 500 °C for 2 h, and pulverized	457.7	COD and color	224	At 30 g/L, COD decreased to 41.6 mg/g and color decreased from 344 to 15 Pt–Co.	[253]
OPT	Gasification at 500–950 °C	95.9	COD and color	2850	During a 12-h adsorption, the highest COD removal was 49.5%.	[254]

[a] Biochemical oxygen demand.
[b] Chemical oxygen demand.

suitable for adsorptive removal of hydrophobic organic pollutants. On the other hand, low temperature biochar containing abundant oxygen functional groups is more effective for ionic and/or polar pollutants [115]. Physical and chemical activation of OPB biochar can improve the adsorption performance.

5.5. Agro-economic and environmental benefit of biochar in Indonesia

Due to soil degradation and low crop productivity, a developing country requires more agricultural land to meet its food demands [255]. The establishment of new rice fields in Java, Sulawesi, and Eastern Indonesia is expected to meet the estimated needs of approximately 11 million ha rice fields in 2050 [256]. However, as qualified fields are lacking, suboptimal soil (acid and dryland soil) has been targeted for this expansion [143]. Fertile agricultural land has organic nutrient contents of over 3% [257]. A significant portion of Indonesian dryland is classified as acid soil (107 M ha) consisting of ultisols (42%), inceptisols (41%), oxisols (14%), entisols (3.8%), and spodosols (2.1%); the rest is

peat soil (15 M ha) [182,258]. Upgrading low-quality acid soil and peatland is inherently challenging, since these soils contain considerable organic acid and have low fertility and low CEC [194,221].

The rice productivity in Indonesia is still low, with one of the main reasons being the improper use of fertilizer and consequent imbalance in the soil nutrients [259]. Urea, subsidized by the government, is currently the most widely used fertilizer in Indonesia [260]. Chemical fertilizer like urea can improve productivity in the short term but it ultimately degrades the soil [261]. In particular, the excess nitrogen lowers the pH and kills soil bacteria. Leached fertilizer can also contaminate drinking water [260].

Excessive use of *N*-fertilizer is common in various crops, even though it increases production costs. For example, 300–600 kg urea/ha is used for rice in Java, 500–700 kg urea/ha for corn in N. Sumatra, and 350–1000 kg urea/ha for vegetable crops in Java [177]. Urea in the soil induces N_2O emissions [262]. Indonesia is ranked fifth in the world for GHG emissions in the agricultural sector, releasing around 200 Mt CO_2eq (2018) [263]. Forestland clearing further aggravates the

situation [264]. Agriculture, forestry, and other land use (AFOLU) contributed 60% of the total GHG emissions in Indonesia (2018) [263]. Indonesia now faces the challenge of securing crop productivity while minimizing GHG emissions [177]. Indonesia's updated NDC (COP26) indicates a strategy of sustainable agriculture and plantations by implementing climate-adaptive technology [143]. Agricultural communities are encouraged to adopt more advanced eco-friendly technology to increase agricultural yields [265].

In Indonesia, the agricultural sector contributes around 10% of the national gross domestic product (GDP), with food crops and plantations accounting for 3% and 7%, respectively [266,267]. The livelihood of 25 million farm households depends on agriculture [268]. Soil enhancement can meet rising food demands while reducing deforestation [264]. Biochar, particularly from OPB, is emerging as one of the most practical options for achieving both goals. It can minimize the use of chemical fertilizers by preventing nutrient leaching and providing a liming effect, which is critical in Indonesia, where most agricultural soil is acidic [269]. Small- and medium-scale farmers can produce biochar at a relatively low price (approximately 100 USD/t) using traditional kilns and semi-continuous kilns like the box, dome, and drum kilns [270, 271]. The cost is less than half the price of the dolomite (liming agent, 250–500 USD/t) commonly used in Indonesia [194]. Therefore, soil amendment by biochar, which is critical in this case, is a promising way to ameliorate the damaged soil [272]. Biochar can also enhance microbial activity, water, and nutrient holding, and the diffusion in the soil. Application of OPB biochar to oil palm fields, especially for oil palm seedling production, could be the best-case scenario regarding the economy and sustainability [185]. By contrast, the conversion of rainforests and peatlands to oil palm monoculture results in substantial soil carbon loss (174 tons C/ha in Sumatra), and this can be offset by biochar [273,274].

Biochar is recognized as one of negative emission technologies (NETs) by the Intergovernmental Panel on Climate Change (IPCC). Economic benefits can be obtained through the ETS and clean development mechanism (CDM), based on the carbon storage amount, which is expected to increase significantly (estimated to be 0.3–2 $GtCO_2eq/yr$ in 2050) [275,276]. Carbon removal by biochar is the most practical tool available to developing countries like Indonesia because it is technically easy and economical [222]. The agronomic benefits of biochar

are far more significant in Indonesia, located in a tropical area, than in other higher latitude countries due to the abundance of raw materials and potentially huge agricultural market [277].

6. Life cycle assessment of oil palm biomass for solid biofuel and biochar

The environmental impact of the upgraded OPB as solid fuel and biochar has been discussed based on the life cycle assessment (LCA), which is an analytical methodology considering the life cycle of a product or process [278]. ISO 14,040 and ISO 14,044 specify four key stages of LCA: 1) aim and scope definition; 2) life cycle inventory analysis; 3) environmental impact assessment; and 4) life cycle interpretation [279–281]. Three phases are generally applied for the upgrading of lignocellulosic biomass as the LCA boundary in the cradle-to-grave system: 1) biomass cultivation and transportation, 2) production at the plant site and further enhancement of the primary product when necessary, and 3) demolition and recycling of the plant [279,282]. The LCA boundary of OPB solid fuel and biochar can be written similarly, as shown in Fig. 10.

Phase 1 (biomass cultivation) indicates that the land use change is highly influential on the GHG emissions [283]. The energy input in planting and collecting in stage 1 is significant as well as in the other stages, and it needs to be electrified by renewable energy to decrease the CO_2 emissions [284,285]. The by-products (biooil and biogas) produced in phase 2 should be properly recycled in stage 3, which would also decrease the emissions. The reduction of water consumption and waste disposal will lead to a lower carbon footprint during the life cycle of the palm oil industry [286]. Less CO_2 emissions combined with the circular economy will secure a sustainable palm oil industry.

The LCA study on the utilization of upgraded OPB as solid biofuel and biochar in Indonesia is very limited. Therefore, the LCA of closely related palm-based biooil and biodiesel systems is briefly reviewed [278, 280,283,287–289]. The production of biooil from EFB by fast pyrolysis was estimated to emit 586 kg of CO_2eq for every kg/h of EFB used, mostly contributed by the drying step (assuming a 55% moisture content) [288]. Stichnothe et al. reported that the composted FFB residue (110 kg CO_2eq/t) can reduce the CO_2 emissions by > 350 kg CO_2eq per one t of FFB, compared to the abandoned one (460 kg CO_2eq/t) [290].
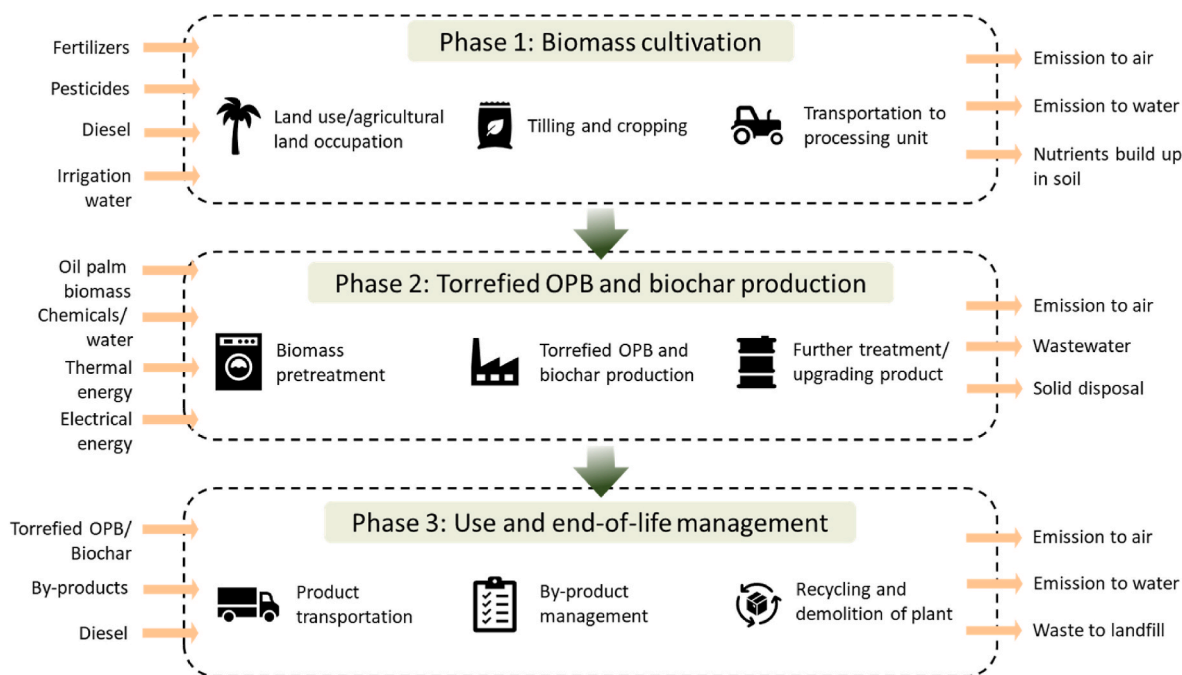

Fig. 10. Generalized system boundary for a life cycle assessment (LCA) analysis of torrefied OPB and biochar production. Adapted from Ref. [279].

The LCA in large-scale mills also revealed that EFB composting reduced CO_2 emissions by 75% [286]. The CO_2 emissions can be reduced by 44% by not burning OPB [286]. The production of 1 t of EFB biochar can reduce the emissions of up to 102 CO_2eq/t of EFB used, compared to EFB use as an organic fertilizer [291]. The co-firing LCA of torrefied domestic woody biomass with coal was reported to be the best option in the Netherlands, reducing roughly 12% of CO_2 emissions [292]. Besides, the torrefied cornstalks for the heat generation resulted in a net negative emission of 175.8 kg CO_2eq/t of feedstock [284]. A techno-economic analysis of OPB biochar for soil enhancement resulted in a 67% and 43% return on investment (ROI) when applied to sugarcane and irrigated cotton fields, respectively, where the negative carbon footprints were estimated to be 691 kg/t of biochar as the soil enhancer and 286 kg/t as a replacement of the fertilizer [291]. According to the multiple studies under the various LCA variables, biochar as the soil amendment provided a significant benefit throughout the life cycle, especially by contributing to a carbon-neutral society by reducing the carbon up to 933 kg CO_2eq/t of feedstock [285,293,294]. In addition, other biochar applications, such as activated carbon substitutes, are also promising.

7. Conclusion and outlook

Palm tree plantations account for 14.7 million ha in Indonesia. About 90% of the outcome from both the milling and plantation process is biomass waste (OPB), over 200 million tons annually. These wastes are usually discarded, landfilled, or burned improperly, causing environmental problems such as GHG emissions, groundwater pollution, and release of PM_{10}. The recycling of OPB is expected to contribute to sustainable and economical palm oil production; therefore, it is strongly promoted by the Indonesian government. General information about OPB in Indonesia (availability, properties, and governmental policy) and upgrading of OPB via thermochemical processes (torrefaction and pyrolysis) are reviewed as strategies for recycling the residues to mitigate environmental damage. Palm oil mill wastes (EFB, PKS, and MF) and plantation wastes (OPF and OPT) can be upgraded via torrefaction, which is the most efficient process for converting OPB into high-quality solid fuel. Significant demands for biomass fuel, including OPB, exist in the co-firing sector, and this can be done with minimal modification, making it the most feasible option economically for sustainable electricity production. However, the slagging and fouling issues associated with OPB fuel should be investigated further. The pyrolysis of OPB produces biochar for soil amendment (crop productivity) and carbon storage. Biochar, particularly from OPB, is the most economical option for achieving carbon removal in Indonesia and is readily applicable technically. OPB biochar can also be utilized as an adsorbent for removing pollutants from soil and aqueous/gaseous media. LCA studies indicate that upgrading OPB to solid fuel and biochar provides a significant environmental benefit. Utilization of OPB via torrefaction and pyrolysis meshes well with Indonesia's goal to accomplish sustainable economic development, especially in the oil palm plantation sector, and NZE by 2060 in Indonesia.

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.

Data availability

Data will be made available on request.

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