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Review

Valorization of Indonesian Wood Wastes through Pyrolysis: A Review

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Abstract: The wood processing industry produces a significant amount of wood waste. Biomass valorization through pyrolysis has the potential to increase the added value of wood wastes. Pyrolysis is an important thermochemical process that can produce solid, liquid, and gas products. This paper aims to review the pyrolysis of wood wastes from Indonesia, including teak wood (*Tectona grandis*), meranti (*Shorea* sp.), sengon (*Paraserianthes falcataria* (L) Nielsen), and rubberwood (*Hevea brasiliensis*). The review is based on an in-depth study of reliable literatures, statistical data from government agencies, and direct field observations. The results showed that pyrolysis could be a suitable process to increase the added value of wood waste. Currently, slow pyrolysis is the most feasible for Indonesia, with the main product of charcoal. The efficiency of the slow pyrolysis process can be increased by harvesting also liquid and gaseous products. The use of the main product of pyrolysis in the form of charcoal needs to be developed and diversified. Charcoal is not only used for fuel purposes but also as a potential soil improvement agent.

Keywords: biochar; renewable energy; pyrolysis; sengon; meranti; rubberwood; teakwood wood waste; bio-oil

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1. Introduction

Indonesia is a country endowed with very rich forest resources. Geographically, Indonesia's location on the Equator is advantageous because it has tropical forests with high-quality timber. The primary forest product is wood, which is then used for domestic purposes and is converted into processed wood products for export. Since the 1970s, the wood processing industry has become one of the most important subsectors in Indonesia. In this period, the characteristics of the national timber industry were export-oriented, so that it became the largest foreign exchange source of non-oil and gas and was very significant in the national economy. Despite the decline, in 1997 the production of sawn timber and plywood was still quite large, at 2.6 million and 6.7 million m^3, respectively. Ten years later, in 2007, sawn timber and plywood production were only 525 thousand and 3.4 million m^3. The decline in productivity was also indicated by a decrease in the export volume from 2 million m^3 of sawn timber and 6 million m^3 of plywood in 2000 to 635 thousand m^3 and 2.7 million m^3 in 2007, respectively, for sawn timber and plywood [1].

Currently, Indonesia is one of the world's wood exporters, in 9th position, with a share of 2.9%. In 2017, the wood and wood goods industry was still ranked 7th of primary commodities in non-oil and gas exports with values of USD 4.5 billion and USD 4.4 billion, respectively. Wood products (HS44 code) still provide a share of 2.7% of total non-oil and

gas exports. Indonesian wood product exports have an increasing trend with a fairly high value from USD 4.1 billion in 2015 to USD 4.5 billion in 2018 [2]. The wood industry also provides job opportunities for many people. For example, in Jepara Regency (Central Java) alone, there are at least 15,271 units of industries consisting of 14,091 units (92%) of small enterprises, 871 units (6%) of medium enterprises, and 309 units (2%) of big industries [3]. These industries are bound to involve thousands of workers.

The present condition of the wood industry still shows promising prospects. In 2019, production of logs totaled 48.0 million m^3, and processed timber reached 38.8 million m^3 consisting of sawn timber 2.1 million m^3, plywood 4.2 million m^3, wood chips 31.4 million m^3, and veneer 1.2 million m^3. In addition, there is still pulp of 7.6 million tonnes [4]. The wood industry has special characteristics where the availability of raw materials is very dependent on forest management because it relates to the tempo of the tree renewal process. It takes at least 5–8 years for the wood to be ready for harvesting since planting at the forest area [5]. The wood industry also produces large amounts of waste. Therefore, the efficient use of wood waste will significantly contribute to the wood industry's sustainability. In general, Indonesia is still inefficient in utilizing natural wood resources, especially for natural forests outside Java. Handling wood waste is a problem for various parties, namely (1) the waste producer (forest concessionary entrepreneurs and wood processing industry), (2) the government, and (3) the surrounding community [5]. Therefore, the problem of handling wood waste is the responsibility of the three parties together.

The basic concept of handling waste in general is 3R, which is reduce, reuse and recycle. Waste removal should be the last option. Wood waste can still be processed into other products. Wood, including wood waste, is a multipurpose and renewable resource that may once again be an important energy source [6]. However, biomass is complex and heterogenous that may impede its exploitation up to full potential [7]. There are various treatments or ways to recycle wood waste into value-added products. Pyrolysis is a promising thermochemical valorization method for treating wood waste into other value-added products. The purpose of this paper is to conduct a review of the pyrolysis of wood waste for Indonesia. The discussion will be limited to wood waste that is prominent in Indonesia, including rubberwood, meranti wood, sengon wood, and teak wood.

2. Potential Wood Wastes for Indonesia

The wood industry is divided roughly into two types: the log industry and the processed wood industry. Type of wastes and their quantity resulted from different activities are significantly different. Log is the main product of harvesting activity from various forests, including natural forests managed by concessionaires, land clearing processes, industrial-based forest, and community-based forest. A part of logs is used as raw materials in wood industries and are processed into various products.

2.1. Wood Waste of Forest Harvesting

Harvesting wood from the forest produces logging residue, not only from felled trees but also from surrounding trees that have been damaged during harvesting. Logging waste is classified into four forms: broken stems, stumps, branches and twigs, and fallen trees. The collection and transportation to the utilization location is a big problem because the terrain and road conditions are very heavy so that it is considered nonusable. Prior to 2000, the efficiency of timber harvesting was very low and generated many wastes. Darusman (1988) noted that forest exploitation in a wet tropical forest from a natural forest concession (HPH) in South Kalimantan reached an efficiency of 51.0% of the volume of commercial tree stands. Waste (49%) consisted of residue in the harvesting area of 42.3% (mainly trunks and branches above 10 cm), in the log yard 6.8% (trunks), and in log pond 1.9% (trunks). Meanwhile, forest exploitation waste in an HPH in East Kalimantan reaches 39.9%, consisting of 26.5% (trunks) and 13.4% (branches) [5]. Research in 1985 also showed that forest wood harvesting waste with 10–40 cm diameter was still large. Logging waste of diameter 10–40 cm was 27.9 m^3/ha in Aceh, 28.9 m^3/ha in North Sumatera,

and 52.4 m^3/ha in East Kalimantan. It is worth noting that wood waste of 10–40 cm diameter and >4 m length was in the highest proportion of 62.7% (Aceh), 58.5% (North Sumatra), and 47.5% (East Kalimantan) [8]. Forest wood waste with a diameter of 10–40 cm has the potential to become industrial raw materials. Research in a North Kalimantan HPH showed that from the volume of logs cut 22.5 m^3/tree, equivalent to 8.7 m^3/ha, wood waste (branches and twigs) with a diameter of 10–30 cm reaches 9.46 m^3/tree or 3.64 m^3/ha (41.7%). In addition, the surrounding wood that is not harvested produces a waste volume of 1.9 m^3/ha. Meanwhile, selected logging in a concession in West Papua obtained the volume of harvested wood 13.16 m^3/tree (8.2 m^3/ha), resulting in 5.1 m^3/tree or 3.2 m^3/ha plus 1.8 m^3/ha of waste from surrounding damaged trees [9].

Until 2013, logging waste was still quite significant. Data collected from forest companies reveals that logging residue was 33.8% and 30.1% in West Sumatera and Central Kalimantan. The wastes consist of the stump, stem without branch, top stem, and branch. Furthermore, it was also revealed that the wood wastes volume 2.7–7.9 m^3/tree or 21.2–69.6 m^3/ha in Central Kalimantan and 3.7–5.5 m^3/tree or 17.4–48.7 m^3/ha in West Sumatera. The waste was mainly found in the harvesting plot, namely 97% in both locations [10].

From the above figures, it can be seen that the wood waste during forest exploitation activities is still very large so that new methods of harvesting forest wood are required to improve its efficiency. This led to the adoption of the RIL (Reduced Impact Logging) harvesting method. A study in two concession areas of forest management in Wasior and Nabire Districts (West Papua Province) compared Reduced Impact Logging (RIL) and conventional techniques. Results showed that the RIL technique produces slightly better performance with wood utilization 4.0 m^3 out of clear bole 4.6 m^3 and wood waste of 0.5 m^3 (in the harvesting site) and 0.1 m^3 (in the landing point), which equivalent to the recovery rate of 87.8% and residual factor of 12.3%. Wood utilization in conventional technique was 4.6 m^3 out of 5.3 m^3 clear bole and waste of 0.7 m^3 (in the harvesting site) and very little in the landing point), meaning a recovery rate of 86.2% and residual factor of 13.8%. In general, most of the logging waste was in the form of defective wood (65.1%), broken wood (23.3%), and timber waste (11.6%) with good potential [11]. The advantages of the RIL method were also reported in the Indonesian Selective Cutting and Planting (TPTI) system, where wood waste was 11.1 m^3/ha with the RIL harvesting method and 16.3 m^3/ha using the conventional logging method [12].

Many other studies on residual factors and utilization factors have also been carried out in natural forests. Sianturi et al. (1984) showed that the factor of timber utilization in Pulau Laut natural forest was 80% [13]. The low waste is caused by the calculation method where the whole tree method considers only clear bole wood (up to the first branch). A study conducted in Central Kalimantan, East Kalimantan, and Jambi revealed that the logging waste ranges from 16.3% to 24.6% of the clear bole volume. The logging waste is on average of 22.2%, consisting of 9% defected wood and 12.2% trimming waste and stumps [14].

Improved forest management and logging techniques can increase logging efficiency and reduce logging waste. Research in Perseroan Terbatas (PT) Roda Mas Timber, a forest concession in Kalimantan, showed logging residue of 1.4 m^3/tree with 0.4 m^3/tree (25.6%) in good quality. The logging efficiency was reported as 91.4% on average, with an average logging waste of 1.4 m^3/tree [15]. It was also shown that the topography did not significantly influence the exploitation factor. Another study in PT Kemakmuran Berkah Timber (South Kalimantan) concession reported that exploitation factor was 93% on flat terrain (0–8°), and 92% on other terrain topography (sloping (9–15°), rather steep, (16–25°), and steep (26–40°)) [16].

Table 1 summarises the efficiency and residues of wood harvesting using improved methods. We can take an assumption for wood waste resulted from logging activity as 20% of the total harvested volume. With a round wood production of 48.0 million m^3, the wood waste in Indonesia will reach a total of no less than 12 million m^3. This is a huge

potential. Therefore, making the best possible use of it will support the sustainability of the wood industries as well as forest. It is worth noting that sustainable forest management is essential to guarantee the sustainability of the wood processing industry [17].

Table 1. Wood harvesting efficiency using the improved method in Indonesia (in %).

Location	Efficiency	Total Waste	Remarks
West Papua (improved method)	86.2%	13.8%	Defect wood (65.1%), broken wood (23.3%), and timber waste (11.6%)
Central Kalimantan, East Kalimantan, and Jambi (improved method)	77.8%	22.2%	Meranti wood. Waste is an average value and no significant difference in the three areas. The waste consists of 9% defected wood and 12.2% trimming and stumps.
Java	79.6	20.4	Teakwood. Residues consist of the broken stem, short dimension, branch and twig, stump, and irregular wood shape
Kalimantan	91.4%	8.6	Logging residue 1.4 m^3/tree with 0.4 m^3/tree (25.6%) is of good quality

There are four species of wood special to Indonesia, namely jati or teak wood (*Tectona grandis*), meranti (*Shorea* sp.), sengon (*Paraserianthes falcataria* (L) Nielsen), and rubberwood (*Hevea brasiliensis*). Table 2 shows the characteristic of those woods important to pyrolysis.

Table 2. Characteristic of wood specific to Indonesia (meranti, teak, rubberwood, sengon).

Wood Properties	Unit	Meranti	Teakwood	Rubberwood	Sengon
Physical properties:					
Air-dry density	g/cm^3	0.85	0.66	0.60	0.46
Specific grafity		0.48	0.66	0.59	0.38
Chemical properties:					
Hemicellulose	%	26.0	17.0	18.3	25.9
Cellulose	%	40.3	34.0	34.6	51.9
Lignin	%	38.2	30.0	25.5	22.2
Heating value (HHV)	MJ/kg	19.6	20.2	19.4	17.8
Ash	%TS	1.2	2.10	2.4	1.59
Fixed carbon	%TS	22.7	12.69	16.8	n.a
Volatile solid	%TS	78.61	80.29	74.4	90.01
C	%	42.10	51.6	45.5	52.5
H	%	7.88	6.0	5.8	6.0
O	%	49.75	42.2	39.68	42.3
N	%	0.24	0.26	0.20	0.2
S	%	0.03	0.01	0.02	n.a

Note: References: Meranti [18–22]; Teak: [22–28]; Ruberwood: [20,29,30]; Sengon: [31–34].

Meranti (*Shorea* sp.) is popular wood in the trade in Indonesia or even Southeast Asia. Generally, meranti wood is used as material for building construction and furniture, such as roof frames, parquet floors, stair railings, doors, windows, and even floor mats. Studies on meranti logging in three provinces (West Sumatra, West Kalimantan, and South Kalimantan) show that the average recovery factor is 0.8%, and no significant difference in the three provinces [35].

Teakwood is the mainstay of wood for the production of furniture and carvings, and is appreciated worldwide. Teakwood forests in Indonesia cover about 1.77 million ha, mainly in Java. Teakwood forests are managed by Perum Perhutani, a state-owned company, which is able to supply only 403,432 m^3 of this wood, while the demand for teak reaches 1.5–2.2 million m^3 [24]. Currently, the availability of teak in Indonesia is dominated by small diameter woods (<30 cm), and about 80% of the teakwood comes from community forests of 6 years old or even less [36]. Thinned wood of more than 10 cm diameter

is even used for carpentry [37]. Research on teakwood harvesting concluded that the recovery utilization factor in an average of 79.6% and residual factor of 20.4%. The wood residues constitute the broken stem, short dimension, branch and twig, stump, and irregular wood shape. Most of the wood waste from teakwood harvesting is utilized by the local community for fuels [38].

Sengon is a remarkably fast-growing species native to the eastern island of Indonesia. In good growing conditions, sengon trees of 3–5 years old in the Perhutani area (Kediri, East Java) had an average diameter of 11.3–18.7 cm and an average height of 11.7–20.5 m [39]. Sengon distribution area in Indonesia is quite wide, starting from Sumatra, Java, Bali, Flores, and Maluku [40]. Sengon is a significant multipurpose tree for timber materials, packing cases, and furniture [31]. It is also used for light construction (ceilings, panels, interiors, furniture, and cabinets), feedstock for plywood and particleboard, and pulp for making paper.

Rubberwood is produced from plantations. In 2019 rubber plantations were 3.68 million ha consisting of smallholder 3.25 million ha (88.3%) and large plantations 437.4 ha (12.7%) [4]. The productive age of rubber trees is 25–30 years so that roughly 4% or around 147,200 ha/y of the plantations have to be rejuvenized [41,42]. Rubberwood can be explored as veneer material, sawn timber, MDF (Medium Density Fibreboard), active biochars, as well as fuels in brick and roof tile industries [43,44]. Rubberwood logs volume of 1–1.5 m cuts is estimated to 40 m^3/ha from smallholdings and 75 m^3/ha from estate plantations [43]. Rubberwood with a diameter greater than 5 cm is 87.7% (used for industrial raw materials), and that less than 5 cm accounts for 12.3% (used for fuel) [45]. Rubberwood is good fuel due to its high calorific value of 17.90 MJ/kg.

2.2. Wood Waste from Wood Processing Industry

Some examples of processed wood include sawn timber, plywood, wood chips, and veneers. The wood processing industry also Included the woodworking, furniture, and woodcraft industry. Processes in the wood sawmill generally involve stages of break down sawing, resawing, edging, and trimming [46].

Waste from the processing wood industry includes pieces (woodcuts), blocks, damaged wood, and sawdust. In 1989, the Ministry of Forestry estimated the amount of waste in sawn timber production to be 50%, consisting of 15% sawdust, 25% cut, and 10% cut edge [26]. Research in a sawmill industry in East Kalimantan showed that a total wood waste of 42% was produced during wood processing. The waste consists of bark, offcut slabs, cross cuts, shavings, and sawdust [46]. The wastes from sawmill industries in Java still reaches 49.3% to 50.1% consisting of 23.5–24.1% slabs, 13.5–14.2% sawdust, and 12.0–14.2% cutting edge [5]. Other research at four wood sawmills in South Kalimantan revealed that the sawmill industry produced waste of 40.48% of the volume of wood processed, consisting of offcut slabs (22.3%), wood chips (9.4%), and sawdust (8.8%). Based on the processing stages, waste in the form of the slab was resulted from break down sawing 5.5%, resawing 8.2%, and edging 8.6%. Sawdust was wasted from all sawing stages, namely, break down 1.6%, resawing 2.8%, edging 2.9%, and trimming 1.5%. Waste in the form of wood chips (9.4%) was produced from trimming only [47].

The waste generated from sawmilling of matoa wood (*Pometia* spp.) at PT Inhutani II Manokwari (Papua) was 47.6%, consisting of 5.5% in the form of sawdust, 35.6% of slabs, and 6.5% of large pieces. Meanwhile, sawmill waste of ironwood (*Instia* sp.) in the upstream wood processing industriy PT Prabu Alaska unit I in Fakfak (Papua) was 33.8% consisting of 4.1% sawdust, 29.0% big slabs, and 0.4% cut edge [46]. Another study at five sawmill enterprises in Jepara (Central Java) showed that the types of wood include teak (*Tectona grandis*), mahogany (*Swietenia* sp.), trembesi (*Samanea saman*), and mango (*Mangifera* sp.). The results also show that the yield or sawing recovery from sawmills reached 70–80%. This figure is relatively high because the sawing pattern applied is one-sided, and the resulting sawn timber did not experience side alignment or re-sawing into square boards. Compared to the regulations issued by the government, sawmills in Jepara

are efficient [48]. Another factor is the fact that wood resources in Java, especially teak, are getting increasingly difficult to obtain, so there is pressure to make use of the wood as maximum as possible.

The characteristics and types of raw materials seem to influence the type and amount of wood wastes. The type and percentage of waste produced by sawmills using log raw materials will differ from those that use sawn timber (square blocks). For example, the waste produced by a Wood Industry, Jayapura Regency (Papua) that used flitches, consisting of shaving, powder (sawdust), slabs (slab), and cut ends (cross cuts); respectively, 16.0% (sawdust), 13.5% (shaving), 11.6% (slabs), and 1.1% cross cuts [46].

Plywood industry is another wood processing which also produces significant wastes. In short, plywood processing resulted from activities such as log cutting, log stripping (peeling) for veneers, preparing veneers, structuring veneer, cutting edges of the plywood, and sanding the plywood. The waste from four plywood industries in South Kalimantan was on average of 54.8% by volume of used wood. Details of the wastes consisted of log pieces (3.7%), log peel remnants (18.3%), wet veneers (8.5%), shrinkage (3.7%), dry veneers (9.6%), reduction in thickness (dry veneers) (1.9%), cut edges of plywood (3.9%), sawdust (2.2%) and plywood dust (3.1%). Utilization of these two types of waste includes fuel, blockboard core, blockboard, particleboard, core veneer joints, or plywood back veneers [47].

Table 3 summarises the performance of wood industries. We can confidently assume that waste from sawmills is no less than 40% of the volume of wood processed, and plywood waste is in an average of 50% of the processed materials. With the production of sawn timber of 2.1 million m^3 and plywood 4.2 million m^3 [4], the potential of wood waste in Indonesia is 5.6 million m^3, consisted of 1.4 million m^3 from sawmills and 4.2 million m^3 from the plywood industry.

Table 3. The efficiency of Wood Industries in Indonesia.

Industry	Efficiency	Waste	Remarks
Sawn timber	50.0%	50.0%	15% sawdust, 25% cut, 10% cut edge
Sawmill, Jayapura	57.8%	42.2%	Sawdust 16.0%, shaving 13.5%, slabs 11.6%, and cross cuts 1.1%.
Sawmill, Java	49.9–50.7%	49.3–50.1%	Slabs 23.5–24.1%, sawdust 13.5–14.2%, and cutting edge 12.0–14.2%.
Sawmill, South Kalimantan	49.9–50.7%	40.8%	Slabs (22.3%), wood chips (9.4%), and sawdust (8.8%).
Plywood, South Kalimantan	54.8%	45.2%	Log pieces (3.7%), log peel (18.3%), wet veneers (12.2%), dry veneers (11.5%), plywood cut edges (3.9%), sawdust (2.2%), and plywood dust (3.1%).
Sawmill, PT Inhutani II Manokwari (Papua)	52.4%	47.6%	Matoa wood (*Pometia* spp.). The waste consists of sawdust 5.5%, slabs 35.6%, and large pieces 6.5%.
Sawmill, IPKH PT Prabu Alaska, Fakfak (Papua)	66.2%	33.8%	Besi wood (*Instia* sp.). The waste consists of sawdust 4.1%, big slabs 29.0%, and cut edge 0.4%.
Sawmill, Jepara (Central Java)	70–80%	20–30%	Teakwood, mahogany (*Swietenia* sp.), trembesi (*Samanea saman*), and mango (*Mangifera* sp.).

3. Wood Wastes Pyrolysis

Pyrolysis, rooted from the Greek words "pyr" meaning "fire" and "lysis" meaning "breakdown" or "disintegration", is an endothermic thermochemical decomposition of organic matter into different useful products [49]. Most papers describe pyrolysis as a process with an inert atmosphere in the absence of oxygen [50–54]. However, limited oxygen is allowed as long as it does not facilitate gasification to a substantial level [55,56]. From a thermal point of view, the pyrolysis process can be divided into four steps: drying, initial stage, intermediate stage, and final stage [20,55]. It should be noted that this description applies only to the pyrolysis of biomass. Drying occurs up to temperature 105 °C, in which the moisture is evaporated and is followed by an initial stage up to 225–325 °C where hemicellulose decomposes. The intermediate stage is the heart of pyrolysis, taking place at temperatures of 325–375 °C, where cellulose decomposes to produce bio-oil, and biomass

particles decompose into biochar, condensable and non-condensable gases. The final phase occurs at 250–500 °C where lignin, the hardest component to decompose, degrades into phenols and phenol derivatives [57]. Pyrolysis gases are released, and a char layer is formed. In general, pyrolysis reaction can be presented as the following, Equation (1):

$$\text{Biomass} + \text{heat} \rightarrow \text{char} + \text{liquid} + \text{gas} + \text{steam} \quad (1)$$

Pyrolysis is an old conversion technology for biomass. Originally, pyrolysis was a low heating rate process identical to carbonization with solid fuel charcoal as the main product. Now, pyrolysis has developed into a versatile technology with the ability to produce a variety of products. Solid, liquid, and gaseous products can be produced depending on pyrolysis conditions. Depending on the residence time and heating rate, pyrolysis can be classified into slow, intermediate, and fast pyrolysis. Slow pyrolysis is usually intended to obtain solid products of biochar or charcoal, whereas fast pyrolysis is to obtain more liquid products. Fast pyrolysis is described by high heating rates and very short residence times (<2 s) and followed by rapid condensation [58]. Table 4 provides a description of these types and product distribution of pyrolysis.

Table 4. Type of pyrolysis and corresponding product composition [7,49,59–61].

Parameter	Slow	Intermediate	Fast
Temperature	400–500 °C	~500 °C	300–1000 °C
Heating rate	1 °C/s	1–1000 °C/s	>1000 °C/s
Residence time	10–2000 min	5–30 s	1–2 s
Pressure	1 atm	1 atm	1 atm
Particle size	5–50 mm	-	<1
Biochar yield	35%	25%	12–25%
Bio-oil	25–30%	40–50%	60–75%
Gas	25–35%	25%	13–20%
Carbon in biochar	50–95%	66–74%	64–90%

The fraction of products is affected by several factors such as the type, particle size, and composition of biomass, and process conditions such as heating rate, temperature, and residence time. The liquid yield is optimized at fast pyrolysis conditions when the heating rate around 1000 °C/s and pyrolysis temperature at around 500 °C. Under this condition, biomass pyrolysis is expected to produce 60–70 wt.% bio-oil, 15–25 wt.% biochar, and 10–15 wt.% gas [62]. Fast pyrolysis is considered as a technology capable of producing high-value liquid products for direct substitutes of fossil fuels or is further processed into chemicals. Products with high value, such as chemicals and fertilizers, are interesting opportunities but very challenging [62].

Pyrolysis of wood wastes has been reported for many wood residues. Pyrolysis of meranti sawdust in temperature range of 450–600 °C produced a maximum bio-oil of 33.7 wt.% at 600 °C. Biochar yield decrease from 39% at temperature 450 °C to 24.4% at 650 °C, while non-condensable gas increased from 37.9% at 450 °C to 45% at 650 °C [20]. Another work on pyrolysis of meranti sawdust by Mazlan et al. (2015) used particle size of 0.15–0.5 mm, temperature 450–550 °C, and residence time 10 minutes. Results showed that biochar yield decreased with temperature from 38.7% at temperature 450 °C to 28.7% at 550 °C. On the other side, bio-oil and gas products increased from 24% and 37.6% to 30% and 41.6%, respectively, at the temperature of 450 °C and 550 °C [63]. Bio-oil yield from pyrolysis of meranti sawdust can be increased by using nitrogen gas. Azura et al. (2017) reported pyrolysis red meranti sawdust using particle size of 0.3–3.0 mm, residence time 40–100 min, N_2 flow rate 5–30 L/min, and temperature 350–600 °C. The highest bio-oil yield of about 63.2 wt.% is gained using feed particle of 0.3 mm at the temperature of 450 °C, 25 L/min of N_2 stream, and 60 min of retention time. In addition, within the particle size range of 0.3–3.0 mm, there is no appreciable difference in bio-oil yield due to particle size [21].

Teakwood sawdust can be made into activated charcoal with satisfactory quality. The yield of teakwood charcoal is 28.6%. The charcoal is characterized by a moisture content of 11.3% (wet basis), ash content of 7.7% (dry basis), volatile matter of 11.3% (dry basis), and fixed carbon of 81.0 [64]. Ratnani et al. (2019) recently also reported that activated carbon obtained from teakwood waste satisfies the quality of national standard SNI 0258-79. It was also revealed that teakwood pyrolyzed at 750 °C produced the most satisfying activated carbon characterized by 1.0% water content, 15.1% volatile matter, 2.3% ash, and 82.5% fixed carbon [65]. Another study used teak tree sawdust (TTSD) with particle sizes of 0.5–1.0 mm pyrolyzed at 450 °C in a fixed bed pyrolyzer. The bio-oil yield of 33.3 wt.% was collected with a calorific value of 23.41 MJ/kg, higher than its parent biomass [66]. It is unusual because bio-oil's calorific value is usually lower than the parent biomass [53]. Rahmat et al. (2014) reported that pyrolysis of teakwood waste at 450 °C resulted in a product composition of 22.2% biochar and 53.0% liquid consisting of 49.3% wood vinegar, 3.3% tar, and 0.4% bio-oil [67].

Pyrolysis of rubberwood waste is triggered, among others, by the fact that rubberwood is one of the important plantation crops in South East Asia, including Indonesia, Malaysia, and Thailand. Lim and Egashira (2005) reported pyrolysis of rubberwood waste, where the liquid product of 52 wt.% was collected from pyrolysis at above 430 °C, gas product of around 26 wt.% after 600 °C, and biochar of 24 wt.% at above 530 °C [68]. Another study by Mazlan et al. (2015) used rubberwood sawdust of 0.15–0.50 mm (particle size) and pyrolysis temperatures range of 450–650 °C. The bio-oil product increased with temperature and achieved the highest yield of 33.0 wt.% at 550 °C. In addition, biochar yield decrease from around 38.7% at 450 °C to 26% at 600 °C, whereas non-condensable gas increased from 36% at 450 °C to 46.2% at 600 °C [20]. As presented in Table 2, the bio-oil product has a low calorific value because of its high oxygen and water content. The oxygen element in the bio-oil can be reduced by applying torrefaction before the pyrolysis process. Chen et al. (2018) revealed that torrefaction pretreatment to rubberwood sawdust prior to the pyrolysis process resulted not only in more uniform bio-oil but also in reducing oxygen content in the bio-oil [17]. Preliminary evaluation on slow pyrolysis of rubberwood to produce wood vinegar or bio-oil was reported by Ratanapisitet al. (2009). The highest yield of wood vinegar of 27.4% was achieved at a temperature of 550 °C and a heating rate of 1.4 °C/min. The liquid product has pH of about 2.9–3.8 and specific gravity of 1.01–1.03, depending on the process conditions [69]. Rubberwood of 7.5–20 cm diameter and 40 cm length was pyrolyzed using a brick dome-type kiln to produce quality charcoal with a calorific value of 27.5 MJ/kg [70].

Sengon wood pyrolysis was reported by Wibowo et al. (2013) at pyrolysis temperature of 350–500 °C and residence time of 30 and 60 min. The results showed that the charcoal yield decreased from 30.3% at 350 °C to 23.3% at 500 °C. On the other hand, the liquid product increased from 44.3% at 350 °C to 51.7% at 500 °C. At the same temperature range, the product gas also increased from 30.8% to 33.0% [71]. Activated charcoal from sengon wood waste has a high surface area, especially from pyrolysis at elevated temperatures. Hendrawan et al. (2019) reported that the surface area of the activated carbon produced from pyrolysis of sengon wood increased with temperatures from 380.8 to 1000 m^2/g, respectively, at temperatures of 400 to 600 °C [72]. Nugrahaningtyas et al. (2019) compared bio-oil production from four wood waste cut into pieces with a volume size of 1–3 cm^3 and pyrolysis temperature of 300 °C. The bio-oil yield is 33.0%, 35.8%, 37.0%, and 38.8%, respectively, from bangkirai, coconut, sengon, and meranti [73].

Table 5 summarizes properties of the pyrolysis products (biochar and bio-oil) resulted from wood wastes of meranti, teakwood, rubberwood, and sengon wood.

Table 5. Characteristics of biochar and bio-oil of meranti, teakwood, rubberwood, and sengon wood produced from pyrolysis.

Parameter	Meranti		Teak		Rubber		Sengon	
	B.oil	**B.char**	**B.oil**	**B.char**	**B.oil**	**B.char**	**B.oil**	**B.char**
Proximate								
Moisture (wt.%)	n.a	2.9	13.8	2.12	n.a	2.9	n.a	n.a
Ash (%DS)	n.a	3.0	n.a	10.89	n.a	4.9	n.a	n.a
Volatile matter (%)	n.a	42.5	n.a	17.88	n.a	50.6	n.a	n.a
Fixed carbon (%)	n.a	51.6	n.a	69.11	n.a	41.6	n.a	n.a
Elemental analysis								
C	15.7	84.9	65.08	75.51	15.7	77.2	n.a	72.4
H	8.2	2.3	7.19	3.17	8.2	2.6	n.a	5.1
O	76.0	12.4	26.84	20.09	69.2	15.2	n.a	21.9
N	0.1	0.4	0.89	1.23	0.1	0.4	n.a	0.1
Calorific value (MJ/kg)	6.7	28.5	23.41	27.51	7.4	29.1	n.a	24.55

References: [63,74–76].

4. Application of Pyrolysis Products

4.1. Biochar

So far, charcoal produced through the pyrolysis process has been used primarily as a fuel in metal casting, blacksmithing, filters, and grilling food to give it a distinctive taste like satay. This relates to the high calorific value of biochar of about 29 MJ/kg (Table 2), which is considerably higher than that of biomass or bio-oil. This relates to the declining of H/C and O/C element ratios. For example, Gupta et al. (2019) reported the H/C atomic ratio of teakwood is 1.4, and its biochar has H/C of 0.7 at pyrolysis temperature 400 °C and decreased to 0.3 at 700 °C, whereas the O/C ratio decreased from 0.7 (raw teakwood) to 0.2 (biochar, 400 °C) and further decreased to 0.1 (biochar, 700 °C). At the same time, relative energy increased from 17.7 MJ/kg (raw) to 27.2 MJ/kg (biochar 400 °C) and 28.9 MJ/kg (biochar 700 °C) [75]. However, charcoal has broader and more value-added potential, such as materials for soil amendment, activated carbon, electrode materials, and graphene. It is worth noting that biochars produced by slow pyrolysis have lower surface area than those produced by flash pyrolysis or gasification [77].

4.1.1. Soil Amendment

The utilization of biochar to improve soil quality is among the accepted soil conservation technologies to maintain or increase land productivity. Biochar is a carbon-rich (carbon ~85%) product with a highly stable composition and does not degrade. The organic part of biochar has a great carbon content, and the inorganic part comprises minerals such as calcium (Ca), magnesium (Mg), potassium (K), as well as inorganic carbonates, depend on the biomass type [78]. Biochar is identified as a superb soil amendment having the possibility to revolt the environmental management concepts [79]. The utilization of biochar for soil amendment provides beneficial effects on soil and significantly improves crop growth [80]. Other benefits of biochar to soil involve increasing plant yield and reducing nutrient loss [81]. Application of biochar influences soil properties, both physical (bulk density, porosity) and chemical (pH, electrical conductivity, capacity of cation exchange, nutrient levels), and biological properties (microorganism population structures). Biochar also offers chances to stockpile carbon (C) in the soil much longer than the raw feedstock. Biochar also influences the microbial community in soil by offering habitats and finally converting nutrients into ready-available forms for plants [82].

Sánchez-Monedero et al. (2019) reported the effects of biochar and compost application across the different cropping systems in Europe. All amendment materials are suitable to enhance organic C in the soil. Compared to the control treatment, the increase in organic C is 11%, 36%, and 20% for compost, biochar, and biochar-compost blend, respectively [83]. Conversely, Alotaibi (2016) confirms that the positive effects of biochar

are more pronounced in a mixture with fertilizer than that of biochar alone [84]. Chan (2007) conducted a pot trial to study the effect of green waste biochar on the soil quality of Alfisol soil and radish production. Interaction of nitrogen fertilizer and biochar resulted in a higher yield, indicating the function of biochar in increasing N fertilizer efficiency for the plant. With N fertilizer, the dry matter of radish yield increases from 95% to 266% in the zero biochar (control) and soils with 100 t/ha biochar addition [85]. Biederman (2013) analyzed huge separated studies from hundreds of published papers and revealed that application of biochar into soils increases aboveground biomass, crop productivity, soil microbial, rhizobia nodulation, phosphorus (P), potassium (K), total nitrogen (N), and total carbon (C) in the soil, as well as K content in plant tissues. The pH of soil also inclines after the application of biochar. Therefore, biochar's application is an answer because biochar enhances soil fertility, stimulates crop development, improves plant production, and decreases contaminations [86].

4.1.2. Other Encouraging Applications

Charcoal or biochar produced from wood wastes pyrolysis has high potential applications in other areas. Recently, Jain et al. (2017) reported a greatly mesoporous activated carbon resulted from the hydrothermal carbonization process of teakwood sawdust as an encouraging material in electronics. The carbon, processed using benzene tetracarboxylic acid and followed by physicochemical activation, has a high surface area of 2108 m^2/g. This activated carbon is promising as an electrode in the fabrication of Li-ion capacitor with high energy. The material delivers an excellent energy density of around 111 Wh/kg when it couples with LiC_6 [87].

Another promising application for wood waste carbon is a precursor for graphene, as a support material for fuel cell catalysts working at low-temperature such as Polymer exchange membrane fuel cells (PEMFC). Graphene from biomass carbon has a unique morphological plane structure with high surface area, high conductivity, and defective sites. Therefore, it has potential to be used as a support material for fuel cell catalysts working at low-temperature like Polymer exchange membrane fuel cells (PEMFC) [88]. Very recently, Sudarsono et al. (2020) reported that graphene powder prepared through microwave-assisted carbonization of sengon wood revealed a high performance as support for iron-based oxygen reduction catalyst (Fe-N/C) in the acidic medium [89]. The mesoporous structure of reduced graphene oxide (RGO) prepared from sengon wood pyrolysis is comparable to graphite RGO and even increases the stability by 8% and better methanol tolerance when compared to a benchmark noble metal-based on platinum (Pt/C) catalyst. Non-precious metal salts, especially iron (Fe), with polymeric nitrogen precursors (Fe-N/C), have gained the most attention owing to their facile synthesis, low cost, environmental friendliness, and good performance as an ORR catalyst. Non-precious catalyst supported on reduced graphene oxide (RGO) derived from sengon wood shows promising performance for fuel cell application [90]. Fe-based electrocatalyst with stabilized graphitic N-bond supported by sengon wood-derived RGO (Fe-N/RGO) shows excellent performance for ORR (oxygen reduction reaction) in the acidic medium [91]. Fe-N/C catalyst also exhibits high ORR activities similar to or even superior to a benchmark Pt/C catalyst in alkaline media.

4.2. Bio-Oil

There are several names for the liquid product of pyrolysis, namely bio-oil, liquid smoke, pyrolysis oil, bio-crude, and wood vinegar. Bio-oil, a black and tarry liquid with a sharp aroma, is composed of complex hydrocarbon compounds with hundreds of oxygenated species, high moisture content, and low pH (~2). Table 6 provides properties of bio-oil produced from pinewood pyrolysis in comparison with mineral oils such as light fuel oil (LFO), heavy fuel oil (HFO), and #2 diesel fuel. As we will see, the bio-oil can be improved through different methods into a more desirable product. Bio-oil can be

explored for many applications from fuel, chemical, and growth regulators as well as an insect pest repellent.

Table 6. Properties of bio-oil and diesel fuel.

Property	Unit	Pine [92,93]	#2 Diesel [59,94]	HFO [92,95]	LFO [92,96]
Density	kg/L	1.21	0.83	0.9–1.02	0.89
HHV	MJ/kg	16.9	50.02	40	43.02
Viscosity	cSt	17	2.39	140–380	6
Pour point	°C	−36	−6	>15	−15
Coke residue	wt.%	16	0.19	12.2	9
Flash point	°C	53	60	>65	60
Water	wt.%	23.9	-	<7	0.025
C	dwt.%	40.6	86	85	86.0
H	dwt.%	7.6	11.1	11	13.6
O	dwt.%	51.7	0	1.0	0
N	dwt.%	<0.1	1	0.3	0.2
S	dwt.%	0.01	0.80	1	<0.18
Cl	dwt.%	0.006	-	-	-
Ash	wt.%	0.03	-	0.1	0.01
K and Na	ppm	34	-	-	<0.02

4.2.1. Fuels

Bio-oil produced from biomass pyrolysis is prospective as a competitive fuel to replace mineral oil. Research on this subject has been started long before. Compared to diesel oil, in general bio-oil shows a higher density, lower calorific value, and higher viscosity. However, a medium to large or low-speed engines require less stringent on fuel properties. Combustion experiments have revealed that bio-oil burns effectively in standard boilers and furnaces with performance close to those with mineral oil.

The use of pyrolysis oil to substitute heavy fuel oil (HFO) has been demonstrated. Boilers using HFO are generally larger and stronger than those of light fuel oil (LFO) boilers. Therefore, pyrolysis oil is more suitable for boiler fuel, but it has to meet acceptable emission, economic feasibility, and stable quality standards [59]. Several works have been conducted on bio-oil utilization to substitute HFO in boiler units. For example, Oasma et al. (2001) reported the utilization of bio-oil using a 4 MW nominal capacity boiler. The test furnace was cylindric with an inner diameter of 2.4 m and a length of 5.2 m. Different pyrolysis oils were produced from hardwood and pine with water content 19.3–35.7%, viscosity 6–42 cSt, calorific value 11.2–17.5 MJ/kg, solid residue 0.03–1.86%. In order to improve the homogeneity and increase the combustibility of the oils, methanol was added (10 wt.%) during the experiment. The result showed that bio-oils burnt fairly well in conventional furnaces and boilers. The fire is greater and combustion takes a lengthier time than that of fossil oils. Furthermore, even though the particle content is higher, in general, the emissions resulted from the combustion of bio-oil are better than that of heavy fuel oil [97].

Some studies, however, recognize important challenges for bio-oil due to its characteristics. High water content in the bio-oils resulted in a negative effect on combustion. This means that more energy is demanded for the ignition of bio-oils than mineral oils, resulting in ignition difficulties. High water content also causes low calorific values of bio-oil in the range of only 40% to 50% of that for mineral oils. Furthermore, bio-oil is also corrosive for metals in general due to its organic acid content [92]. Bertoli et al. (2001) confirmed that wood bio-oil is hardly be used as a straight fuel in diesel motor without blends [98]. The composition of bio-oils is also non-uniform for different biomass feedstock, making it a low quality fuel need to be upgraded [99]. With all its disadvantages, bio-oil from fast pyrolysis of wood is estimated to be the promising candidate for replacing HFO in industrial or district heating boilers [100].

Solantausta et al. (1993) investigated the use of pyrolysis oil as a fuel in a single-cylinder Petter AVB 500-cm^3 diesel engine run at a speed of 2000 rpm and 50% load. It was revealed that ethanol is required as pilot fuel to help ignition because bio-oil solely did not ignite readily in a conventional diesel engine. After warming up using diesel fuel, the engine was switched to ethanol, and then to 12 min running on bio-oil; switched back to ethanol, and switched over to bio-oil, etc. Even though pyrolysis oil is difficult to ignite, it burnt easily when combustion happens, indicating that bio-oil can be an appropriate fuel for engines with pilot-ignition [101]. Diebold and Bridgwater (1997) cited that filtered pyrolysis oil successfully works with 18 cylinders, 1.4 MW, low-speed diesel engine, with a thermal efficiency of 45% and no corrosion problems. They also summarized that raw pyrolysis liquid had been successfully tested for more than 10 h of continuous operation using a modified 250-kWe dual-fuel engine with and without dilution with alcohol [53]. Shihadeh and Hochgreb (2000) also found that pyrolysis oils indicate equal thermal efficiency to that of diesel fuel. However, pyrolysis oils result in long ignition delays and significantly lower cylinder pressure rise rates as compared with #2 diesel fuel [102]. Chiaramonti et al. [96] concluded that diesel engines are very promising to generate power using pyrolysis oil, but gas turbine plants are the most technically advanced mode. Some difficulties are still identified correspond to the utilization of straight bio-oils for fuel of diesel engines that need to be solved, such as combustion delay, carbon deposition, and corrosion. The use of bio-oil as a fuel source can also be performed through the steam reforming process to produce hydrogen gas. Hydrogen gas is a promising fuel source in the future [103]. The steam reforming process is carried out with the help of metal-based catalysts such as Ni, La, Co, Cu, Cr, Pt, etc. Further description of this process is added in the next Table 5.

4.2.2. Chemicals

Pyrolysis oil contains so many compounds that can be employed as plant regulators in the agriculture field. The application of wood vinegar as a plant growth regulator at a concentration of 50 mL/L effectively increased papaya stem diameter during nursery [67]. Utilization of wood vinegar as pest control at 5 mL mixing with 200 g maize can effectively decrease the number of maize weevil and reduce maize damage during storage [67]. Bio-oil, with molecular weight of 300–1000 g/mol, contains molecular fractions of hemicellulose, cellulose, and lignin polymers escaping the pyrolysis atmosphere [53,104]. The compounds in bio-oil are classified into five broad categories, namely: hydroxy aldehydes, hydroxy ketones, sugars and dehydrosugars, carboxylic acids, and phenolic compounds [55]. Table 7 provides a short description of those routes to upgrade bio-oil into chemicals.

Table 7. Summary of the promising route to upgrade pyrolysis oil to produce chemicals.

Chemicals	Description
Physical methods:	
Emulsion	Produce homogenous emulsions by using the proper emulsifier. Diesel fuel and biodiesel or their mixtures can significantly improve fuel properties of bio-oil and the resulted emulsion work in diesel engines with lower emissions [105]. An optimal emulsion of oil palm biomass-based bio-oil and diesel fuel is achieved with a pH of 3.29, mass density of 0.86 g/cm^3, and calorific value of 42.19 MJ/kg [106]. High energy consumption is one of the disadvantages of this method [107].
Filtration	Improve bio-oil quality (viscosity, solids content, ash content, alkali content, and acidity) by using granular filters. The bio-oil yield decreases with increasing granular size, mass flow rate, and number of filtration runs. The bio-oil quality (solids content, ash content, initial viscosity, viscosity change, and aging rate) is enhanced by the hot vapor granular filtration [108]. During filtration, 10–30% of bio-oil yield is lost due to filter plugging [109].
Solvent addition	Reduce bio-oil viscosity and improve its stability using a solvent. Methanol is found to be an effective additive to improve bio-oil viscosity, stability, and heating value [110], as well as its storability [111].

Table 7. *Cont.*

Chemicals	Description
Distillation	Distillation is a common method of physical refining of bio-oil. The process separates different products. McVey et al. (2020) reported a continuous flash distillation to fractionate BTX (Benzene, Toluene, xylene) from partially deoxygenated bio-oil. For a flow rate of 2 mL/min, the extraction efficiency varies from 16.21% at a temperature of 120 °C to 50.81% at a temperature of 140 °C [112].
Chemical methods:	
Aqueous phase reforming	Due to the high water content in the bio-oil, aqueous phase reforming (APR) is an optimistic choice to produce H_2 and alkane from biomass. Vispute and Huber (2010) reported APR with a 1 wt.% Pt/Al_2O_3 catalyst at 265 °C of the hydrogenated bio-oil to produce hydrogen with a selectivity of 60% [113].
Mild cracking	To avoid severe catalyst deactivation as occurred with deep cracking of bio-oil, mild cracking is proposed with the objective to reduce coke and gas formation by partially removing oxygen from the bio-oil [114]. Bio-oil macromolecules are cracked into smaller molecules with the presence of catalysts. The common catalyst is zeolite, but ZnO is found to be a promising catalyst resulting more stable liquid better than the non-catalytic bio-oil [115].
Esterification	The process removes acids and produces esters by reacting bio-oil and alcohols with the presence of catalysts. Methanol is commonly used for esterification due to its high reactivity and less expensive. HZSM-5 and aluminum silicate are among the preferred catalysts for bio-oil esterification [107].
Catalytic methods:	
Hydrogenation	The aim of hydrogenation is to improve bio-oil quality and stability by reducing reactive compounds, such as organic acids and aldehydes [116]. Hydrogenation is performed with a hydrogen atmosphere at high pressure and temperature. During hydrogenation, O in the bio-oil is removed in the form of H_2O or CO_2, producing high-quality oil products [95]. After upgrading, bio-oil has a higher pH value, water content, and H element, while the viscosity decreases [117]. Catalyst deactivation is a problem due to coke formation [118].
Hydrodeoxygenation	Hydrodeoxygenation (HDO) is a promising method to upgrade bio-oil into high-quality fuels comparable to conventional fossil fuels [119]. During the HDO process, the O element in oxygenated chemical groups is removed under high hydrogen pressure (507–4200 psi) and temperature between 300 and 400 °C [120]. The common catalysts for this process are Ni-Mo or Co-Mo catalysts.
Catalytic cracking	Bio-oil macromolecules are cracked into smaller molecules with the presence of catalysts. Schmitt et al. (2018) reported the effectivity of Ni-based catalyst working at 325 °C and 80 bar with 42% of the oxygen removal [121]. Traditional catalytic cracking is performed by thermally treating bio-oil in a tubular fixed bed reactor under hydrogen flow at a higher temperature with high pressure. Recent development combines catalytic pyrolysis and catalytic cracking as a superior technology to improve the yield and the quality of bio-oil. The common catalyst in this reaction is zeolite, while the bottleneck for sustainable application of catalysts is the coke deposition of this catalyst [107].
Steam reforming	The process reacts bio-oil with high-temperature steam with the purposes of steam reforming process is to produce syngas (H_2 and CO) [122,123]. Pan et al. (2006) reported that catalytic steam reforming of the bio-oil over a metal-doped catalyst of C12A7-Mg in the fixed-bed continuous flow reactor obtain hydrogen yield of 80% at 750 °C and the maximum carbon conversion close to 95% under the optimal condition [124]. Catalyst deactivation by coke deposition is a serious problem for the sustainable application of this process [107].

Pyrolysis oil is an auspicious material that can be used for chemicals synthesis through biorefinery processes. High-value specialty chemicals such as hydroxyacetaldehyde, levoglucosan, organic acids, and food flavors can be obtained [53]. Routes to upgrade bio-oil for producing value-added chemicals can be classified into physical (emulsion, filtration, solvent addition, distillation), chemical (aqueous phase separation, mild cracking, esterification), and catalytic methods (catalytic cracking, steam reforming, hydrogenation, hydrodeoxygenation) [125,126].

4.3. Gas

Pyrolysis is a thermochemical process in which biomass is heated up in the absence of, or limited, oxygen. With no oxygen, the biomass is not combusted, but hemicellulose, cellulose, and lignin decomposed into charcoal and primary gases. Most of the gases produced during pyrolysis can be condensed into a liquid (bio-oil), but there are some permanent gases such as CO_2, CO, H_2, CH_4, and other light hydrocarbons. The low heating value (LHV) of primary gases is typically 11 MJ/Nm^3. Some of the organic vapors are

cracked to secondary gases that increase LHV up to (20 MJ/Nm^3) [53]. Depending on the pyrolysis conditions, the gas products may achieve 25–35% of the biomass in slow pyrolysis and 13–20% in fast pyrolysis. The major components of the pyrolysis gas are H_2, CH_4, CO, CO_2, light hydrocarbons (ethane (C_2H_6), ethylene (C_2H_4), propane (C_3H_8), propylene (C_3H_6), and butane (C_4H_{10}). Larger hydrocarbons such as hexane (C_6H_{14}) or benzene (C_6H_6) may also exist [60]. The pyrolysis gases can be explored as a synthesis gas, which through Fischer–Tropsch synthesis can produce transportation fuels such as gasoline or diesel fuel [127]. However, it requires extensive reforming and shifting reaction to produce the desired gas composition. Therefore, the gas is commonly used as fuel to generate electricity or heat [128,129], which can provide the necessary energy to drive the reaction during the pyrolysis process. Another application is for fuel in gas engines [130,131].

5. Pyrolysis in Indonesia: State-of-the-Art

The pyrolysis of wood waste and other biomass residues in Indonesia actually has a bright prospect. Unfortunately, the pyrolysis process uses ancient technology, namely slow pyrolysis or carbonization, with the main objective of producing charcoal. In principle, the biomass is heated slowly in the absence of oxygen to a relatively low temperature (~400 °C) over an extended period of time, which in ancient times ran for several days to maximize the char formation. Furnaces or kilns are made with simple technology. Our field observations get information about several types of kilns or furnaces used by small and medium industries, including the box, dome, and drum kiln. Abidin et al. (2018) reported an average yield of 20.3% by weight from traditional charcoal production with ranges between 17.60% and 23.12% [132].

5.1. Box Furnace

The box pyrolyzer is a method of making charcoal that has a large enough volume. However, the processing time for this furnace is relatively long, and the larger the furnace volume, the longer charcoal processing takes place. This furnace is more efficient for burning raw materials with clear dimensions such as wood. The furnace design in the form of a box or square makes it easy to stack wood and adjusts to the volume of wood to be charred [133]. The box furnace is made of brick and clay construction with a thickness of ±30 cm and the inside dimensions of 2 m so that the volume capacity of this furnace is 8 m^3 (Figure 1a). On the roof of the furnace, there is a window functioning as a facility for initiating combustion and for introducing additional feedstock. This furnace also has three small holes on the sides of the stove body (right, back, and left), and each hole has a vertical position of ±50 cm. In addition, there is a hole in the middle of the furnace door. The small hole in the furnace is useful as a place to control oxygen and to control the temperature of the pyrolysis. Temperature control is important because it can affect the shrinkage of raw materials and heating value [134]. The higher the temperature, the higher the shrinkage and calorific value.

5.2. Dome Furnace

The dome furnace (Figure 1b) has the largest volume. Therefore, this type of furnace is commonly used for charcoal production on a commercial scale. However, the processing time for this stove is relatively longer than that of other types. The main function of this type of furnace is for the charring process. This furnace is among the permanent stoves. The dome furnace is also made of brick and clay construction. The dome furnace is divided into two parts; namely, the body and the dome. The dome furnace has a thickness of ±30 cm, a dimension of 3.8 m of height (2 m of stove height and 1.8 m of dome height), and a radius of 2 m, with a volume of 41.7 m^3. On the left and right of the dome, there are two windows of 2.4 m^2 each, serving as a place for initial combustion as well as a pathway to enter additional raw biomass. As in the box furnace, there are three locations at the body of the furnace (right, back, and left) for small holes. Each location has three holes (top, middle, and bottom) with a vertical distance of ±50 cm. In addition, there is a hole in the

middle of the furnace door. This furnace is equipped with a condenser system to collect the liquid products. The condenser system consists of a chimney that connects to the furnace via a U-shaped pipe, two drums for condensation, and a hose for releasing liquid smoke. There is also a small cooling pond with water for the condensation process. Nurhayati (1995) [70] reported performance of dome kiln of 1.4 m^3 capacity made from red bricks spaced using the mould of clay and sand. A charcoal yield of 26.9% was achieved using rubberwood feedstock with a kiln efficiency of 39.2% and a production rate of 1.6 kg/h.

(**a**) (**b**)

Figure 1. (**a**) Box furnace and (**b**) dome furnace. The red star symbol at (**b**) is the condenser system.

5.3. Kiln Furnace

Kiln furnace is a mobile furnace that is easy to move, though it has a fairly large volume. This furnace is made of flat iron with a thickness of 0.5 cm. The inner dimensions of the drum furnace include a height of 0.9 m and a radius of 1.2 m so that the volume of this furnace is 3.1 m^3. The kiln furnace has four small holes located each at the bottom, middle, and top of the drum. Thus, the total of small holes contained in this drum furnace is 12 holes. The distance between the small holes (vertical) is 30 cm. The function of the small hole in the drum is to control oxygen and combustion temperature. In addition to a small hole, this furnace is equipped with a lid serving to minimize the amount of oxygen. During the pyrolysis process, the lid of the furnace should be tightly set up such that wood feedstock is not burnt to ash. Syahrinudin et al. (2018) stated that the pyrolyze wood using a closed drum produces perfect and brittle charcoal without ash. The kiln furnace can be seen in Figure 2.

5.4. Drum Furnace

The drum furnace, portrayed in Figure 3, is commonly used in small-scale charcoal producers. The use of drums as a method of making charcoal is widely used by business actors because it is cheap, easy, practical, and can be easily moved (Mardiyanto and Purnomo, 2016). In addition, the combustion process in the drum furnace is relatively faster. However, the drum furnace has a small volume compared to the other furnaces. On one side, this provides a flexible option to compensate with the low volume of biomass. On the other side, tens of drum furnaces are required to pyrolyze larger charcoal capacity.

Figure 2. Kiln furnace.

(**a**) (**b**)

Figure 3. (**a**) Drum furnaces and (**b**) roasting kiln.

The inner dimensions of the drum furnace include a height of 0.9 m and a radius of 0.3 m so that the volume of each furnace is 0.3 m^3. This type of furnace has four small holes located at the bottom, middle, and top of the drum. Thus, the total of small holes contained in this drum furnace is 12 holes. The distance between the small holes (vertical) is ±20 cm. The main function of the holes is to control oxygen and control the combustion temperature. Lowering the temperature process favors the greater charcoal yield (Soolany and Fadly, 2020). This furnace is equipped with a drum lid. Charcoal producers sometimes equipped the drum furnace with a roasting box (Figure 3b) made of 0.5 cm thick iron sheet functioning to dry moist charcoal. The box has a dimension of 4 m long, 3 m wide, and 0.5 m high, making a volume capacity of 6 m^3. This roasting box has four ears to ease its removal. Pyrolysis using drum kilns produces charcoal with a better heating value. For example, Salim (2016) reported the heating value of teak charcoal produced by pyrolysis using a

drum kiln to be 29.9 MJ/kg [135]. The value is higher than the calorific value of ulin wood charcoal (29.4 MJ/kg) and api-api wood charcoal (28.3 MJ/kg) pyrolyzed by burying in the earth [136]. Evaluated from its specific gravity, in fact, teakwood has a lower value (0.7) than those of ulin wood (1.0) or api-api wood (0.8–1.0). Normally wood with high specific gravity will have a higher heating value, too [135]. It is worth noting that the pyrolysis process produces three types of products; namely, biochar, bio-oil, and non-condensable gas. In the pyrolysis process, all three products should be harvested and utilized. The gas product can be directly combusted to produce heat used in the pyrolysis process so that a more efficient pyrolysis system will be created.

6. Market Potential for Charcoal

Charcoal has been used since ancient times for a variety of purposes, but by far its most important use has been as a fuel in the metallurgical industry and in the preparation of various grilled dishes. In modern times, charcoal is widely used for outdoor cooking (grill and barbecue). The domestic market for biochar has much potential. Charcoal is also required to fulfill the local market. The utilization of charcoal in Indonesia is mainly for fuel. The demand for charcoal fuel is estimated to be 191,000 ton in urban areas and around 251,000 ton in the village and suburban areas [137]. Therefore, the domestic market for charcoal is important. Many food stalls require charcoal to cook traditional dishes such as satay, grilled chicken, grilled fish, grilled meat, roasted corn, and specialty boiled noodles, which have to be cooked using wood charcoal to get a distinctive taste. With the increase in the prosperity of the people, food stalls of this kind grow and scatter in various cities and regions so that they require a considerable amount of charcoal. A study by Yandri (2013) revealed that most big restaurants serve grilled dishes prepared using charcoal [138]. As for cooking fuel for traditional food, charcoal is generally sold in small and simple packages (around 250–500 g in a plastic bag) with prices ranging from IDR 4000–5000/kg or USD 0.29–0.36/kg for wood charcoal and IDR 8000–10,000/kg or USD 0.58–0.72/kg for coconut shell charcoal. This means the domestic price for charcoal should be attractive for small and medium enterprises because it is comparable to the export price with destination to Malaysia and China.

Biochar is a value-added product from wood waste that is expected to become one of the mainstay commodities. This can be seen from the export of wood charcoal (including hard bark charcoal or shell charcoal) with HS code 4402, which increased from USD 185.3 million in 2015 to USD 240.5 million in 2017 [2]. The export value further increased to USD 280.1 million in 2019. Indonesia is currently the largest charcoal exporting country in the world with a share of 22.3%, export volume reaching 527 million tons, and a value of USD 280.1 million [139]. The number of countries for charcoal export destinations from Indonesia is close to a hundred, especially from Asia, Europe, and Africa. Table 8 presents the top 10 export destination countries for Indonesian charcoal. The average export value is USD 0.66/kg with the lowest of USD 0.24/kg for Malaysia destination and the highest USD 1/kg for Netherlands and Brazil. The type of charcoal is assumed to greatly determine the price or value of charcoal.

Table 8. Top ten countries for Indonesia's charcoal export destination (2019).

No.	Negara Tujuan	Volume (ton)	Value (Million USD)	Value (USD/kg)
1.	Saudi Arabia	86,718	47.3	0.55
2.	Korea, Republic	46,376	24.6	0.53
3.	Iraq	22,628	20.2	0.89
4.	China	56,482	17.5	0.31
5.	Japan	27,835	17.2	0.62
6.	Lebanon	12,326	10.7	0.87
7.	Malaysia	44,550	10.6	0.24
8.	Netherlands	10,389	10.5	1.01
9.	Turkey	18,170	10.4	0.57
10.	Brazil	8757	9.1	1.04
11.	Others	192,900	102.0	0.53
	TOTAL	527,131	280.1	0.66

References: [137].

Biochar market surveys reported by various agencies provide very intriguing information. For example, Zion Market Research reported a global biochar market value of approximately USD 260.0 million in 2014. The market size is expected to increase to USD 585.0 million by 2020. The market is expected to grow at a compound annual growth rate (CAGR) of around 14.5% between 2015 and 2020 [140]. In addition, Acumen Research and Consulting estimated the CAGR of the global biochar market of 17% between 2014–2023 [141]. IMARC Group recently reported a biochar market size value of USD 484 million globally in 2019 and is predicted to grow strongly in the next five years [142]. A survey by Grand View Research, Inc. estimated a worldwide biochar market size of USD 3.1 billion by 2025, with a CAGR expectation of 13.2% [143].

7. Prospect and Constraint for Charcoal Industries

Conversion of carbon to biochar can be one way to harmonize between people and the environment because biochar is related not only to energy but also agriculture, environment, and development [144]. Therefore, biochar is promising and prospective for industry. In addition, the technology to produce charcoal is easy and simple. Charcoal can be produced by heating wood in a simple kiln. This fact is an interesting opportunity for small and medium enterprises in the agro-industry. So far, community-based forestries are still limited to harvesting or selling the wood. It is actually a good opportunity to develop community plantation forests to provide raw materials for charcoal production. Another prospect for the charcoal industry can be inferred from the increasing demand for export. For example, the export value for charcoal increases by 16.5% in the period of 2015 to 2019 [139].

It is important to note that biochar utilization has shifted from fuel to other applications, particularly for land and crops. A survey by Worldbank with 452 respondents stated that the use of biochar as fuel was followed by only 9.5%, while the application for land and crops was followed by 79.4% [145]. Biochar is beneficial for infertile and degraded soil such as acidic soil [146], ex mine-land [147,148], and peatland [149]. This is a very good prospect considering the large amount of unproductive land in Indonesia that can be repaired using biochar, such as dry land in East Nusa Tenggara [150], acidic soil in Sumatera, Kalimantan, and Papua [151,152], and ex mineral mining land on Bangka Island [153].

Some constraints, however, need to be addressed. First of all, the wood wastes exist in remote areas. Therefore, wood wastes conversion into biochar is feasible for the forest management enterprises (FMEs) that manage a relatively large production forest area with a significant amount of wood waste biomass. The FMEs are classified into Natural Forest Concession or *Hak Pengusahaan Hutan* (HPH) and Plantation Forest Concession or *Hutan Tanaman Industri* (HTI). Generally, the main product extracted by HPH and HTI is the log.

For HPH, they have to provide payment of Reforestation Fee or *Dana Reboisasi* (DR) and Provision of Forest Resources or *Provisi Sumber Daya Hutan* (PSDH) not only for the log (main stem) but also small diameter log or KBK (Kayu Bulat Kecil), which includes wood wastes (such as branches) that they harvested. The DR amount varies based on wood types and location. For example, the DR for meranti KBK is USD 4/m^3, whereas the PSDH for meranti KBK is 10%/m^3 of the standard log price. This PSDH rate also applies to other KBK such as fuelwood, teakwood stump, and alcoves. For PFCs, there is no DR fee, but they have to pay PSDH for KBK at a rate of 6%/m^3 of the standard log price. The rate is also applied for sengon and rubberwood. The DR fee for other KBK is 2 for both fuelwoods (per staple meter) and USD 0.5/piece smaller branch (up to 12 cm diameter) [154].

Another problem is related to the decrease in wood wastes feedstock for charcoal production. This results from the competing use of wood wastes such as for compost or mulch. According to a survey by International Biochar Initiative (IBI), feedstock for biochar production is still dominated by woody biomass sources. The survey found that 87% of the 200 respondents chose to use woody biomass to produce charcoal [155]. In this case, charcoal industries should not have their feedstock depend on just one type but should vary with multiple feedstocks [145]. Another important challenge is that the production of exported charcoal in Indonesia is generally conducted by small and medium enterprises using various techniques and processes. Therefore, the quality of the charcoal produced also varies and results in low biochar prices, only USD 0.66/kg (Table 6). This price is much lower than the average wholesale price at USD 2.06/kg and the retail price at USD 3.08/kg for pure biochar, as obtained from a survey conducted by IBI in 2014 [155].

Higher quality biochar can be produced by fast pyrolysis. However, in Indonesia, it is still in the research and development stage. No industrial stage of fast pyrolysis is reported in work. High technology equipment is one of the obstacles for fast pyrolysis. Another obstacle is that the main product of fast pyrolysis is bio-oil, while the market demand for bio-oil is not yet visible. Technological constraints along lack of financial access are identified in the IBI survey as the main barriers for the industries to expand [155].

8. Conclusions

Indonesia has a huge potential of wood wastes that are still not optimally utilized. Pyrolysis is a promising method to improve wood wastes by producing three different products, namely biochar, bio-oil, and pyrolysis gas. In slow pyrolysis, the composition of the three products is almost equivalent. The liquid portion increases significantly in fast pyrolysis. Biochar is used mainly for fuel. Other interesting applications of biochar include soil amendment, black carbon, and graphene for fuel cell. Bio-oil is applied for fuel and many high-value chemicals. Up to now, the applied pyrolysis technology in Indonesia is still dominated by slow pyrolysis, with biochar as the main product.

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References

1. Alviya, I. Efficiency and Productivity of Indonesian Wood Processing in the Period 2004–2007 with Non Parametric Approach Data Envelopment Analysis (In Bahasa Indonesia). *J. Penelit. Sos. Dan Ekon. Kehutan.* **2011**, *8*, 122–138. [CrossRef]
2. Deputi Bidang Koordinasi Perniagaan dan Industri. Rapat Koordinasi Pembahasan Industri Hasil Kayu 2019. Available online: http://asmindo.or.id/wp-content/uploads/2019/02/190220-Industri-Kayu_Rev4-1.pdf (accessed on 31 December 2020).
3. Roda, J.-M.; Cadène, P.; Guizol, P.; Santoso, L.; Fauzan, A.U. *Atlas of Wooden Furniture Industry in Jepara, Indonesia*; Center for International Forestry Research: Bogor, Indonesia, 2007; ISBN 978-979-1412-13-1.
4. Badan Pusat Statistik. *Statistical Yearbook of Indonesia 2020*; Badan Pusat Statistik: Jakarta, Indonesia, 2020.
5. Darusman, D. *Aspek Ekonomi Industri Pemanfaatan Limbah Kayu*; Fakultas Kehutanan; IPB Bogor: Bogor, Indonesia, 1988; pp. 11–29.
6. Diaz, L.F.; Golueke, C.G. *Biomass Conversion Processes for Energy and Fuels*; Sofer, S.S., Zaborsky, O.R., Eds.; Springer: Boston, MA, USA, 1981; ISBN 978-1-4757-0303-0.
7. De Wild, P.; Reith, H.; Heeres, E. Biomass Pyrolysis for Chemicals. *Biofuels* **2011**, *2*, 185–208. [CrossRef]
8. Simarmata, S.R.; Dulsalam, D. Volume and Classifiaation of Logging Waste at Several Forest Companies in Sumatera and Kalimantan (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **1985**, *2*, 17–19.
9. Budiaman, A.; Mubarak, F.M.; Lismaya, W. Logging Residues of Low Harvest Intensity in Indonesian Forest Concession (in Bahasa Indonesia). *JIPI* **2020**, *25*, 145–151. [CrossRef]
10. Matangaran, J.R.; Partiani, T.; Purnamasari, D.R. Exploitation Factor and Quantification of Wood Waste in Order to Improve Efficiency of Natural Forest Harvesting (in Bahasa Indonesia). *J. Bumi Lestari* **2013**, *13*, 384–393.
11. Soenarno, S.; Endom, W.; Suhartana, S. The Study on Utilization and Waste Factor of Timber Harvesting at Natural Forest, West Papua (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **2018**, *36*, 67–84. [CrossRef]
12. Muhdi, M.; Elias, E.; Murdiyarso, D.; Matangaran, J.R. Wood Waste Caused by Reduced Impact Logging in Indonesian Selective Cutting and Planting System, North Borneo, Indonesia. *Int. J. Sci. Basic Appl. Res.* **2016**, *30*, 86–92.
13. Sianturi, A.; Soerianegara, I.; Suparto, R.S.; Manan, S. Exploitation Factor in the Pulau Laut Depterocarp Forest (in Bahasa Indonesia). *Jumal Penelit. Has. Hutan* **1984**, *1*, 1–10. [CrossRef]
14. Simarmata, S.R.; Dulsalam, D. The Exploitation Factor for *Shorea* spp. in Jambi, Central Kalimantan and East Kalimantan (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **1985**, *2*, 10–12. [CrossRef]
15. Soenarno, S. Logging Efficiency and Quality of Logging Waste in a Tropical Mountainous Forest: Case Study in the Licency Natural Forest Concessionary of PT. Roda Mas Timber Kalimantan (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **2014**, *32*, 45–61. [CrossRef]
16. Soenarno, S.; Dulsalam, D.; Endom, W. Exploitation Factor in Limited Production Forest in Licenced Natural Forest PT Kemakmuran Berkah Timber (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **2013**, *31*, 151–160. [CrossRef]
17. Chen, W.-H.; Wang, C.-W.; Kumar, G.; Rousset, P.; Hsieh, T.-H. Effect of Torrefaction Pretreatment on the Pyrolysis of Rubber Wood Sawdust Analyzed by Py-GC/MS. *Bioresour. Technol.* **2018**, *259*, 469–473. [CrossRef] [PubMed]
18. The Wood Database. Balau. Available online: https://www.wood-database.com/balau/ (accessed on 6 January 2021).
19. Ahmad, Z.S.; Munaim, M.S.A.; Said, F.M. *Characterization of Meranti Wood Sawdust and Removal of Lignin Content Using Pre-Treatment Process*; Universiti Malaysia Pahang: Pahang, Malaysia, 2016; pp. 598–606.
20. Mazlan, M.A.F.; Uemura, Y.; Osman, N.B.; Yusup, S. Fast Pyrolysis of Hardwood Residues Using a Fixed Bed Drop-Type Pyrolyzer. *Energy Convers. Manag.* **2015**, *98*, 208–214. [CrossRef]
21. Azura, N.W.; Zularisam, A.W.; Norsita, S.; Nasrullah, M.; Kamaruzaman, N.W. Effect of Fast Pyrolysis Operating Conditions on Product Yield of Red Meranti Sawdust. *Int. Res. J. Eng. Technol. (Irjet)* **2017**, *4*, 607–611.
22. Rani, A.; Singh, J.; Singh, T. An Experimental Characterization of Physical Properties of Timber Woods. *Nanotechnology* **2017**, *1*, 41–45. [CrossRef]
23. The Wood Database. Teak. Available online: https://www.wood-database.com/teak/ (accessed on 6 January 2021).
24. Hidayati, F.; Fajrin, I.T.; Ridho, M.R.; Nugroho, W.D.; Marsoem, S.N.; Na'iem, M. Sifat Fisika Dan Mekanika Kayu Jati Unggul "Mega" Dan Kayu Jati Konvensional Yang Di Tanam Di Hutan Pendidikan, Wanagama, Gunungkidul, Yogyakarta. *J. Ilmu Kehutan.* **2016**, *10*, 98. [CrossRef]
25. Basri, E.; Wahyudi, I. Wood Basic Properties of Jati Plus Perhutani from Different Ages and Their Relationships to Drying Properties and Qualities (in Bahasa). *J. Penelit. Has. Hutan* **2013**, *31*, 93–102. [CrossRef]
26. Balogun, A.O.; Lasode, O.A.; McDonald, A.G. Devolatilisation Kinetics and Pyrolytic Analyses of *Tectona grandis* (Teak). *Bioresour. Technol.* **2014**, *156*, 57–62. [CrossRef]
27. Peng, H.; Li, Y.; Chen, G.; Li, Y. Co-Combustion Interactions between Teak Sawdust and Sewage Sludge with Additives. *BioResources* **2019**, *14*, 1466–1481.
28. Kartikawati, A.; Wahyudi, I.; Pari, G.; Karlinasari, L. Color and Dimensional Stability of Fast Growing Teakwood by Mild Pyrolysis and Combination Process. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *935*, 012014. [CrossRef]
29. The Wood Database. Rubberwood. Available online: https://www.wood-database.com/rubberwood/ (accessed on 6 January 2021).
30. Sultan, S.H.; Palamanit, A.; Techato, K.; Amin, M.; Ahmed, K.; Asadullah, A. Syngas Production from Rubberwood Biomass in Downdraft Gasifier Combined with Wet Scrubbing: Investigation of Tar and Solid Residue. *JSM* **2020**, *49*, 1729–1743. [CrossRef]

31. Hartati, S.; Sudarmonowati, E.; Fatriasari, W.; Hermiati, E.; Dwianto, W.; Kaida, R.; Baba, K.; Hayashi, T. Wood Characteristic of Superior Sengon Collection and Prospect of Wood Properties Improvement through Genetic Engineering. *Wood Res. J.* **2010**, *1*, 103–105.
32. Saputro, D.D.; Widayat, W. Karakterisasi Limbah Pengolahan Kayu Sengon Sebagai Bahan Bakar Altrnatif. *Sainteknol J. Sain Dan Teknol.* **2016**, *14*, 21–29.
33. Listyanto, T. Wood Quality of *Paraserianthes falcataria* L. Nielsen Syn Wood from Three Year Rotation of Harvesting for Construction Application. *Wood Res.* **2018**, *63*, 497–504.
34. The Wood Database. Batai. Available online: https://www.wood-database.com/batai/ (accessed on 6 January 2021).
35. Dulsalam, D. Logging Recovery of Meranti in West Sumatera, West Kalimantan and South Kalimantan (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **1988**, *5*, 47–49. [CrossRef]
36. Wahyudi, I.; Sinaga, D.K.D.; Muhran, M.; Jasni, L.B. Spacing Effect on Tree Growth and Several Physical-Mechanical Properties of Faster-Grown Teak Wood (in Bahasa Indonesia). *J. Ilmu Pertan. Indones.* **2014**, *19*, 204–210.
37. Pramono, A.A.; Fauzi, M.A.; Widyani, N.; Heriansyah, I.; Roshetko, J.M. *Pengelolaan Hutan Jati Rakyat-Panduan Lapangan Untuk Petani*; Center for International Forestry Research (CIFOR): Bogor, Indonesia, 2010; ISBN 978-602-8693-19-6.
38. Matangaran, J.R.; Anggoro, R. Teak Harvesting Waste at Banyuwangi East Java. *Perennial* **2012**, *8*, 88–92. [CrossRef]
39. Kurinobu, S.; Prehatin, D.; Mohanmad, N.; Matsune, K.; Chigira, O. A Provisional Growth Model with a Size–Density Relationship for a Plantation of *Paraserianthes falcataria* Derived from Measurements Taken over 2 Years in Pare, Indonesia. *J. For. Res.* **2007**, *12*, 230–236. [CrossRef]
40. Krisnawati, H.; Varis, E.; Kallio, M.; Kanninen, M. *Paraserianthes falcataria (L.) Nielsen: Ekologi, Silvikultur Dan Produktivitas*; CIFOR: Bogor, Indonesia, 2011; ISBN 978-602-8693-52-3.
41. Hytönen, J.; Nurmi, J.; Kaakkurivaara, N.; Kaakkurivaara, T. Rubber Tree (*Hevea brasiliensis*) Biomass, Nutrient Content, and Heating Values in Southern Thailand. *Forests* **2019**, *10*, 638. [CrossRef]
42. Ratnasingam, J.; Ramasamy, G.; Tau Wai, L.; Senin, A.L.; Muttiah, N. The Prospects of Rubberwood Biomass Energy Production in Malaysia. *BioResources* **2015**, *10*, 2526–2548. [CrossRef]
43. Agustina, D.S.; Syarifa, L.F.; Nancy, C. A Study on Institutions and Partnership in Rubberwood Marketing in South Sumatera Province (in Bahasa Indonesia). *J. Penelit. Karet* **2013**, *31*, 54–67. [CrossRef]
44. Simanjuntak, J.P.; Lisyanto; Daryanto, E.; Tambunan, B.H. Producer Gas Production of Indonesian Biomass in Fixed-Bed Downdraft Gasifier as an Alternative Fuels for Internal Combustion Engines. *J. Phys. Conf. Ser.* **2018**, *970*, 012019. [CrossRef]
45. Balsiger, J.; Bahdon, J.; Whiteman, A. *The Utilization, Processing and Demand for Rubberwood as a Source of Wood Supply*; Asia-Pacific Forestry Sector Outlook Study; FAO Forestry Policy and Planning Division: Rome, Italy, 2000.
46. Wahyudi, W. *Dasar-Dasar Penggergajian Kayu*, 1st ed.; Pohon Cahaya: Yogyakarta, Indonesia, 2013.
47. Purwanto, D. The Analysis of Variety of Wood Waste Material from Wood Industry in South Borneo. *J. Ris. Ind. Has. Hutan* **2009**, *1*, 14–20. [CrossRef]
48. Malik, J.; Hopewell, G.P. Sawing Recovery of Several Sawmills in Jepara. *J. Penelit. Kehutan* **2011**, *29*, 331–342. [CrossRef]
49. Kantarelis, E.; Yang, W.; Blasiak, W. Biomass pyrolysis for energy and fuel production. In *Technologies for Converting Biomass to Useful Energy*; Dahlquist, E., Ed.; CRC Press: Boca Raton, FL, USA, 2013; pp. 245–277.
50. Koufopanosi, C.A.; Maschio, G.; Lucchesit, A. Kinetic Modelling of the Pyrolysis of Biomass and Biomass Components. *Can. J. Chem. Eng.* **1989**, *67*, 75–84. [CrossRef]
51. Demirbaş, A.; Arin, G. An Overview of Biomass Pyrolysis. *Energy Sources* **2002**, *24*, 471–482. [CrossRef]
52. Bridgwater, A.V. Biomass Fast Pyrolysis. *Therm. Sci.* **2004**, *8*, 21–49. [CrossRef]
53. Diebold, J.P.; Bridgwater, A.V. Overview of fast pyrolysis of biomass for the production of liquid fuels. In *Developments in Thermochemical Biomass Conversion*; Bridgwater, A.V., Boocock, D.G.B., Eds.; Springer Science + Business Media: Dordrecht, The Netherlands, 1997; Volume 1, pp. 5–25. ISBN 978-94-010-7196-3.
54. Venderbosch, R.H.; Prins, W. Fast pyrolysis. In *Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power*; Brown, R.C., Ed.; John Wiley & Sons, Ltd.: Chichester, UK, 2011; pp. 124–156. ISBN 978-0-470-72111-7.
55. Basu, P. *Biomass Gasification and Pyrolysis: Practical Design and Theory*; Academic Press: Burlington, MA, USA, 2010; ISBN 978-0-12-374988-8.
56. Mohan, D.; Pittman, C.U.; Steele, P.H. Pyrolysis of Wood/Biomass for Bio-Oil: A Critical Review. *Energy Fuels* **2006**, *20*, 848–889. [CrossRef]
57. Shafizadeh, F.; Chin, P.P.S. Thermal Deterioration of Wood. In *Wood Technology: Chemical Aspects*; Goldstein, I.S., Ed.; ACS Symposium Series; American Chemical Society: Washington, DC, USA, 1977; Volume 43, pp. 57–81. ISBN 978-0-8412-0373-0.
58. Balonek, C.M. Autothermal Oxidative Pyrolysis of Biomass Feedstocks over Noble Metal Catalysts to Liquid Products. Ph.D. Thesis, University of Minnesota, Minnesota, MN, USA, 2011.
59. Jahirul, M.; Rasul, M.; Chowdhury, A.; Ashwath, N. Biofuels Production through Biomass Pyrolysis—A Technological Review. *Energies* **2012**, *5*, 4952–5001. [CrossRef]
60. Xu, L.; Jiang, L.; Zhang, H.; Fang, Z.; Smith, R.L. Introduction to Pyrolysis as a Thermo-Chemical Conversion Technology. In *Production of Biofuels and Chemicals with Pyrolysis*; Fang, Z., Smith, R.L., Jr., Xu, L., Eds.; Biofuels and Biorefineries; Springer: Singapore, 2020; Volume 10, pp. 3–30. ISBN 9789811527319.

61. Kumarathilaka, P.; Mayakaduwa, S.; Herath, I.; Vithanage, M. Biochar. In *Biochar: Production, Characterization, and Applications*; Uchimiya, S.M., Chang, S.X., Bolan, N., Eds.; CRC Press: Boca Raton, FL, USA, 2016; pp. 18–42. ISBN 978-1-4822-4230-0.
62. Bridgwater, A.V.; Meier, D.; Radlein, D. An Overview of Fast Pyrolysis of Biomass. *Org. Geochem.* **1999**, *30*, 1479–1493. [CrossRef]
63. Mazlan, M.A.F.; Uemura, Y.; Osman, N.B.; Yusup, S. Characterizations of Bio-Char from Fast Pyrolysis of Meranti Wood Sawdust. *J. Phys. Conf. Ser.* **2015**, *622*, 012054. [CrossRef]
64. Komarayati, S.; Gusmailina, G.; Hendra, D. Manufacturing Activated Charcoal from Teakwood Sawdust (in Bahasa Indonesia). *Bul. Penelit. Has. Hutan* **1997**, *15*, 94–100.
65. Ratnani, R.D.; Purbacaraka, F.H.; Hartati, I.; Syafaat, I. Actived Carbon from Teak Wood, Jackfruit Wood, and Mango Wood Pyrolysis Process. *J. Phys. Conf. Ser.* **2019**, *1217*, 012055. [CrossRef]
66. Bardalai, M.; Mahanta, D.K. Characterisation of Pyrolysis Oil Derived from Teak Tree Saw Dust and Rice Husk. *J. Eng. Sci. Technol.* **2018**, *13*, 242–253.
67. Rahmat, B.; Pangesti, D.; Natawijaya, D.; Sufyadi, D. Generation of Wood-Waste Vinegar and Its Effectiveness as Plant Growth Regulator and Pest Insect Repellant. *BioResources* **2014**, *9*, 6350–6360. [CrossRef]
68. Lim, K.G.; Egashira, R. Pyrolysis and Characterization of the Products for Recycle of Rubberwood Residues. Master's Thesis, Tokyo Institute of Technology, Tokyo, Japan, 2004.
69. Ratanapisit, J.; Apiraksakul, S.; Rerngnarong, A.; Chungsiriporn, J.; Bunyakarn, C. Preliminary Evaluation of Production and Characterization of Wood Vinegar from Rubberwood. *Songklanakarin J. Sci. Technol.* **2009**, *31*, 343–349.
70. Nurhayati, T. Charcoal Production of Rubber Wood (*Hevea brasilliensis*) in Dome Kiln of S-93 Model (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **1995**, *13*, 37–44. [CrossRef]
71. Wibowo, S. Characteristics of Bio-Oil from Sengon (*Paraserianthes falcataria* L. Nielsen) Sawdust by Slow Pyrolysis Process (in Bahasa Indonesia). *J. Penelit. Has. Hutan* **2013**, *31*, 258–270. [CrossRef]
72. Hendrawan, Y.; Sajidah, N.; Umam, C.; Fauzy, M.R.; Wibisono, Y.; Hawa, L.C. Effect of Carbonization Temperature Variations and Activator Agent Types on Activated Carbon Characteristics of Sengon Wood Waste (*Paraserianthes falcataria* (L.) Nielsen). *IOP Conf. Ser. Earth Envrion. Sci.* **2019**, *239*, 012006. [CrossRef]
73. Nugrahaningtyas, K.D.; Prasetyorini, E. Local Wood's Bio-Oil Upgrading Using Non-Sulfided (Co, Mo)/USY Catalyst. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *578*, 012012. [CrossRef]
74. Mazlan, M.A.F.; Uemura, Y.; Yusup, S. Fast Pyrolysis of Rubber Wood Sawdust via a Fluidized Bed Pyrolyzer: The Effect of Fluidization Gas Velocity. *Sindh Univ. Res. J. (Sci. Ser.)* **2016**, *48*, 9–16.
75. Gupta, G.K.; Gupta, P.K.; Mondal, M.K. Experimental Process Parameters Optimization and In-Depth Product Characterizations for Teak Sawdust Pyrolysis. *Waste Manag.* **2019**, *87*, 499–511. [CrossRef]
76. Putra, H.; Damanhuri, E.; Dewi, K.; Pasek, A.D. Production of Coal-Like Solid Fuel from *Albizia chinensis* Sawdust Via Wet Torrefaction Process. *J. Ecol. Eng.* **2020**, *21*, 183–190. [CrossRef]
77. Fryda, L.; Visser, R. Biochar for Soil Improvement: Evaluation of Biochar from Gasification and Slow Pyrolysis. *Agriculture* **2015**, *5*, 1076–1115. [CrossRef]
78. Rajapaksha, A.U.; Mohan, D.; Igalavithana, A.D.; Lee, S.S.; Ok, Y.S. Definitions and Fundamentals of Biochar. In *Biochar: Production, Characterization, and Applications*; Ok, Y.S., Uchimiya, S.M., Chang, S.X., Bolan, N., Eds.; Urbanization, Industrialization, and the Environment; CRC Press: Boca Raton, FL, USA, 2016; pp. 4–16. ISBN 978-1-4822-4230-0.
79. Lehmann, J.; Joseph, S. (Eds.) *Biochar for Environmental Management: Science and Technology*; Earthscan: London, UK; Sterling, VA, USA, 2009; ISBN 978-1-84407-658-1.
80. Suthar, R.; Wang, C.; Nunes, M.; Chen, J.; Sargent, S.; Bucklin, R.; Gao, B. Bamboo Biochar Pyrolyzed at Low Temperature Improves Tomato Plant Growth and Fruit Quality. *Agriculture* **2018**, *8*, 153. [CrossRef]
81. Biederman, L.A.; Harpole, W.S. Biochar and Its Effects on Plant Productivity and Nutrient Cycling: A Meta-Analysis. *GCB Bioenergy* **2013**, *5*, 202–214. [CrossRef]
82. Sheng, Y.; Zhu, L. Biochar Alters Microbial Community and Carbon Sequestration Potential across Different Soil PH. *Sci. Total Environ.* **2018**, *622–623*, 1391–1399. [CrossRef] [PubMed]
83. Sánchez-Monedero, M.A.; Cayuela, M.L.; Sánchez-García, M.; Vandecasteele, B.; D'Hose, T.; López, G.; Martínez-Gaitán, C.; Kuikman, P.J.; Sinicco, T.; Mondini, C. Agronomic Evaluation of Biochar, Compost and Biochar-Blended Compost across Different Cropping Systems: Perspective from the European Project FERTIPLUS. *Agronomy* **2019**, *9*, 225. [CrossRef]
84. Alotaibi, K.; Schoenau, J. Application of Two Bioenergy Byproducts with Contrasting Carbon Availability to a Prairie Soil: Three-Year Crop Response and Changes in Soil Biological and Chemical Properties. *Agronomy* **2016**, *6*, 13. [CrossRef]
85. Chan, K.Y.; Van Zwieten, L.; Meszaros, I.; Downie, A.; Joseph, S. Agronomic Values of Greenwaste Biochar as a Soil Amendment. *Soil Res.* **2007**, *45*, 629. [CrossRef]
86. Ding, Y.; Liu, Y.; Liu, S.; Li, Z.; Tan, X.; Huang, X.; Zeng, G.; Zhou, L.; Zheng, B. Biochar to Improve Soil Fertility. A Review. *Agron. Sustain. Dev.* **2016**, *36*, 36. [CrossRef]
87. Jain, A.; Jayaraman, S.; Ulaganathan, M.; Balasubramanian, R.; Aravindan, V.; Srinivasan, M.P.; Madhavi, S. Highly Mesoporous Carbon from Teak Wood Sawdust as Prospective Electrode for the Construction of High Energy Li-Ion Capacitors. *Electrochim. Acta* **2017**, *228*, 131–138. [CrossRef]
88. Antolini, E. Graphene as a New Carbon Support for Low-Temperature Fuel Cell Catalysts. *Appl. Catal. B Environ.* **2012**, *123–124*, 52–68. [CrossRef]

89. Sudarsono, W.; Wong, W.Y.; Loh, K.S.; Majlan, E.H.; Syarif, N.; Kok, K.Y.; Yunus, R.M.; Lim, K.L. High Performance Iron-Based Oxygen Reduction Catalyst Supported on Sengon Wood-Derived Reduced Graphene Oxide in Acidic Medium. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *463*, 012060. [CrossRef]
90. Sudarsono, W.; Wong, W.Y.; Loh, K.S.; Majlan, E.H.; Syarif, N.; Kok, K.; Yunus, R.M.; Lim, K.L. Noble-free Oxygen Reduction Reaction Catalyst Supported on Sengon Wood (*Paraserianthes falcataria* L.) Derived Reduced Graphene Oxide for Fuel Cell Application. *Int. J. Energy Res.* **2020**, *44*, 1761–1774. [CrossRef]
91. Sudarsono, W.; Wong, W.Y.; Loh, K.S.; Majlan, E.H.; Syarif, N.; Kok, K.-Y.; Yunus, R.M.; Lim, K.L.; Hamada, I. Sengon Wood-Derived RGO Supported Fe-Based Electrocatalyst with Stabilized Graphitic N-Bond for Oxygen Reduction Reaction in Acidic Medium. *Int. J. Hydrogen Energy* **2020**, *45*, 23237–23253. [CrossRef]
92. Oasmaa, A.; Czernik, S. Fuel Oil Quality of Biomass Pyrolysis Oils: State of the Art for the End Users. *Energy Fuels* **1999**, *13*, 914–921. [CrossRef]
93. Oasmaa, A.; Solantausta, Y.; Arpiainen, V.; Kuoppala, E.; Sipilä, K. Fast Pyrolysis Bio-Oils from Wood and Agricultural Residues. *Energy Fuels* **2010**, *24*, 1380–1388. [CrossRef]
94. Parray, R.A.; Bhattacharya, T.K. Fuel Properties of Ethanol-Diesel Blends for Use as Engine Fuel. *Int. J. Sci. Res.* **2015**, *4*, 2443–2446.
95. Zhang, Q.; Chang, J.; Wang, T.; Xu, Y. Review of Biomass Pyrolysis Oil Properties and Upgrading Research. *Energy Convers. Manag.* **2007**, *48*, 87–92. [CrossRef]
96. Chiaramonti, D.; Oasmaa, A.; Solantausta, Y. Power Generation Using Fast Pyrolysis Liquids from Biomass. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1056–1086. [CrossRef]
97. Oasmaa, A.; Kytö, M.; Sipilä, K. Pyrolysis Oil Combustion Tests in an Industrial Boiler. In *Progress in Thermochemical Biomass Conversion*; Blackwell Science: Oxford, UK, 2001; Volume 2, pp. 1468–1481.
98. Bertoli, C.; Calabria, R.; D'Alessio, J.; Giacomo, N.D.; Lazzaro, M.; Massoli, P.; Moccia, V. Diesel Engines Fueled by Wood Pyrolysis Oil: Feasibility and Perspectives. In Proceedings of the 5th International Conference Internal Combustion Engines, Naples, Italy, 23–27 September 2001; p. 41.
99. Bridgwater, A.V. Review of Fast Pyrolysis of Biomass and Product Upgrading. *Biomass Bioenergy* **2012**, *38*, 68–94. [CrossRef]
100. Lehto, J.; Oasmaa, A.; Solantausta, Y.; Kytö, M.; Chiaramonti, D. *Fuel Oil Quality and Combustion of Fast Pyrolysis Bio-Oils*; VTT: Espoo, Finland, 2013; ISBN 978-951-38-7930-3.
101. Solantausta, Y.; Nylund, N.-O.; Westerholm, M.; Koljonen, T.; Oasmaa, A. Wood-Pyrolysis Oil as Fuel in a Diesel-Power Plant. *Bioresour. Technol.* **1993**, *46*, 177–188. [CrossRef]
102. Shihadeh, A.; Hochgreb, S. Diesel Engine Combustion of Biomass Pyrolysis Oils. *Energy Fuels* **2000**, *14*, 260–274. [CrossRef]
103. Haryanto, A.; Fernando, S.; Murali, N.; Adhikari, S. Current Status of Hydrogen Production Techniques by Steam Reforming of Ethanol: A Review. *Energy Fuels* **2005**, *19*, 2098–2106. [CrossRef]
104. Iliopoulou, E.F.; Triantafyllidis, K.S.; Lappas, A.A. Overview of Catalytic Upgrading of Biomass Pyrolysis Vapors toward the Production of Fuels and High-Value Chemicals. *Wires Energy Environ.* **2019**, *8*, e322. [CrossRef]
105. Leng, L.; Li, H.; Yuan, X.; Zhou, W.; Huang, H. Bio-Oil Upgrading by Emulsification/Microemulsification: A Review. *Energy* **2018**, *161*, 214–232. [CrossRef]
106. Chong, Y.Y.; Thangalazhy-Gopakumar, S.; Ng, H.K.; Ganesan, P.B.; Gan, S.; Lee, L.Y.; Manickavel, V.S.A.R.; Ong, C.M.; Al Hinai, H.S. Emulsification of Bio-Oil and Diesel. *Chem. Eng. Trans.* **2017**, *56*, 1801–1806. [CrossRef]
107. Zhang, S.; Yang, X.; Zhang, H.; Chu, C.; Zheng, K.; Ju, M.; Liu, L. Liquefaction of Biomass and Upgrading of Bio-Oil: A Review. *Molecules* **2019**, *24*, 2250. [CrossRef]
108. Paenpong, C.; Inthidech, S.; Pattiya, A. Effect of Filter Media Size, Mass Flow Rate and Filtration Stage Number in a Moving-Bed Granular Filter on the Yield and Properties of Bio-Oil from Fast Pyrolysis of Biomass. *Bioresour. Technol.* **2013**, *139*, 34–42. [CrossRef]
109. Krutof, A.; Hawboldt, K.A. Upgrading of Biomass Sourced Pyrolysis Oil Review: Focus on Co-Pyrolysis and Vapour Upgrading during Pyrolysis. *Biomass Convers. Biorefin.* **2018**, *8*, 775–787. [CrossRef]
110. Pidtasang, B.; Udomsap, P.; Sukkasi, S.; Chollacoop, N.; Pattiya, A. Influence of Alcohol Addition on Properties of Bio-Oil Produced from Fast Pyrolysis of Eucalyptus Bark in a Free-Fall Reactor. *J. Ind. Eng. Chem.* **2013**, *19*, 1851–1857. [CrossRef]
111. Mei, Y.; Chai, M.; Shen, C.; Liu, B.; Liu, R. Effect of Methanol Addition on Properties and Aging Reaction Mechanism of Bio-Oil during Storage. *Fuel* **2019**, *244*, 499–507. [CrossRef]
112. McVey, M.; Elkasabi, Y.; Ciolkosz, D. Separation of BTX Chemicals from Biomass Pyrolysis Oils via Continuous Flash Distillation. *Biomass Convers. Biorefin.* **2020**, *10*, 15–23. [CrossRef]
113. Vispute, T.P.; Huber, G.W. Production of Hydrogen, Alkanes and Polyols by Aqueous Phase Processing of Wood-Derived Pyrolysis Oils. *Green Chem.* **2009**, *11*, 1433. [CrossRef]
114. Liao, H.T.; Ye, X.N.; Lu, Q.; Dong, C.Q. Overview of Bio-Oil Upgrading via Catalytic Cracking. *AMR* **2013**, *827*, 25–29. [CrossRef]
115. Nokkosmäki, M.I.; Kuoppala, E.T.; Leppämäki, E.A.; Krause, A.O.I. Catalytic Conversion of Biomass Pyrolysis Vapours with Zinc Oxide. *J. Anal. Appl. Pyrolysis* **2000**, *55*, 119–131. [CrossRef]
116. Venderbosch, R.H.; Heeres, H.J. Pyrolysis Oil Stabilisation by Catalytic Hydrotreatment. In *Biofuel's Engineering Process Technology*; Dos Santos Bernardes, M.A., Ed.; InTech: London, UK, 2011; ISBN 978-953-307-480-1.
117. Zhang, X.; Wang, T.; Ma, L.; Zhang, Q.; Jiang, T. Hydrotreatment of Bio-Oil over Ni-Based Catalyst. *Bioresour. Technol.* **2013**, *127*, 306–311. [CrossRef] [PubMed]

118. Zhang, A.; Tang, J.; Lie, J.; He, Y.; Xiao, Z. Study on the Preparation of Biohydrocarbon Fuel by Catalytic Hydrogenation of *Swida wilsoniana* Pyrolysis Products. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 3569125. [CrossRef]
119. Li, X.; Chen, G.; Liu, C.; Ma, W.; Yan, B.; Zhang, J. Hydrodeoxygenation of Lignin-Derived Bio-Oil Using Molecular Sieves Supported Metal Catalysts: A Critical Review. *Renew. Sustain. Energy Rev.* **2017**, *71*, 296–308. [CrossRef]
120. Sanna, A.; Vispute, T.P.; Huber, G.W. Hydrodeoxygenation of the Aqueous Fraction of Bio-Oil with Ru/C and Pt/C Catalysts. *Appl. Catal. B Environ.* **2015**, *165*, 446–456. [CrossRef]
121. Schmitt, C.C.; Raffelt, K.; Zimina, A.; Krause, B.; Otto, T.; Rapp, M.; Grunwaldt, J.-D.; Dahmen, N. Hydrotreatment of Fast Pyrolysis Bio-Oil Fractions Over Nickel-Based Catalyst. *Top. Catal.* **2018**, *61*, 1769–1782. [CrossRef]
122. Wu, C.; Huang, Q.; Sui, M.; Yan, Y.; Wang, F. Hydrogen Production via Catalytic Steam Reforming of Fast Pyrolysis Bio-Oil in a Two-Stage Fixed Bed Reactor System. *Fuel Process. Technol.* **2008**, *89*, 1306–1316. [CrossRef]
123. Lan, P.; Xu, Q.; Zhou, M.; Lan, L.; Zhang, S.; Yan, Y. Catalytic Steam Reforming of Fast Pyrolysis Bio-Oil in Fixed Bed and Fluidized Bed Reactors. *Chem. Eng. Technol.* **2010**, *33*, 2021–2028. [CrossRef]
124. Pan, Y.; Wang, Z.; Kan, T.; Zhu, X.; Li, Q. Hydrogen Production by Catalytic Steam Reforming of Bio-Oil, Naphtha and CH_4 over C12A7-Mg Catalyst. *Chin. J. Chem. Phys.* **2006**, *19*, 190–192. [CrossRef]
125. Pawar, A.; Panwar, N.L.; Salvi, B.L. Comprehensive Review on Pyrolytic Oil Production, Upgrading and Its Utilization. *J. Mater. Cycles Waste Manag.* **2020**, *22*, 1712–1722. [CrossRef]
126. Yang, H.; Yao, J.; Chen, G.; Ma, W.; Yan, B.; Qi, Y. Overview of Upgrading of Pyrolysis Oil of Biomass. *Energy Procedia* **2014**, *61*, 1306–1309. [CrossRef]
127. Siedlecki, M.; De Jong, W.; Verkooijen, A.H.M. Fluidized Bed Gasification as a Mature And Reliable Technology for the Production of Bio-Syngas and Applied in the Production of Liquid Transportation Fuels—A Review. *Energies* **2011**, *4*, 389–434. [CrossRef]
128. Baratieri, M.; Baggio, P.; Bosio, B.; Grigiante, M.; Longo, G.A. The Use of Biomass Syngas in IC Engines and CCGT Plants: A Comparative Analysis. *Appl. Therm. Eng.* **2009**, *29*, 3309–3318. [CrossRef]
129. Zhang, D.; Zhu, M.; Zhang, Z.; Wu, J. Combined Heat and Power (CHP) Generation Using Gas Engines Fueled with Pyrolysis Gases. In *Handbook of Clean Energy Systems*; Yan, J., Ed.; John Wiley & Sons, Ltd: Chichester, UK, 2015; pp. 1–17. ISBN 978-1-118-99197-8.
130. Hagos, F.Y.; Aziz, A.R.A.; Sulaiman, S.A. Trends of Syngas as a Fuel in Internal Combustion Engines. *Adv. Mech. Eng.* **2014**, *6*, 401587. [CrossRef]
131. Hossain, A.K.; Davies, P.A. Pyrolysis Liquids and Gases as Alternative Fuels in Internal Combustion Engines—A Review. *Renew. Sustain. Energy Rev.* **2013**, *21*, 165–189. [CrossRef]
132. Abidin, Z.; Jauhari, A.; Afriza, M.H. Potential Assessment and Development Concession Charcoal Wood in the Ranggang Luar Village, Takisung Sub District, Tanah Laut, South Kalimantan (in Bahasa Indonesia). *J. Hutan Trop.* **2018**, *6*, 108–115. [CrossRef]
133. Sulistyo, J.; Marsoem, S.N.; Kholik, A.; Wibowo, M.N. Proses Pengarangan Dari Tungku/Dapur Pengarang Konvensional Dan Permanen Di Wonosari, Gunungkidul. In *Proceedings of the Proseding Seminar Nasional Masyarakat Peneliti Kayu Indonesia XX*; MAPEKI (Masyarakat Peneliti Kayu Indonesia): Bali, Indonesia, 2017; pp. 206–216.
134. Tirono, M.; Sabit, A. Efek Suhu Pada Proses Pengarangan Terhadap Nilai Kalor Arang Tempurung Kelapa (Coconut Shell Carchoal). *J. Neutrino* **2011**, *3*, 143–152.
135. Salim, R. The Quality and Characteristics of Teak (*Tectona grandis*) Charcoal Made by Mixed Carbonisation in Drum Kiln (in Bahasa Indonesia). *J. Ris. Ind. Has. Hutan* **2016**, *8*, 53–64. [CrossRef]
136. Iskandar, H.; Santosa, K.D. *Panduan Singkat Cara Pembuatan Arang Kayu Alternatif Pemanfaatan Limbah Kayu Oleh Masyarakat*; CIFOR (Center for International Forestry Research): Bogor, Indonesia, 2005; ISBN 979-3361-85-9.
137. Rochmayanto, Y. The Potency of Stump of *Acacia crassicarpa* and Economic Utilization as the Raw Materials Charcoal Resources. *J. Penelit. Hutan Tanam.* **2012**, *9*, 9–18. [CrossRef]
138. Yandri, P. Consumer Preferences for Coconut Shell Charcoal in Suburban Indonesia. *Int. Res. J. Bus. Stud.* **2013**, *VI*, 121–132. [CrossRef]
139. World Integrated Trade Solution, (WITS). Indonesia Wood; Charcoal (Including Shell or Nut Charcoal), Whether or Not Agglomerated Exports by Country in 2019. Available online: https://wits.worldbank.org/trade/comtrade/en/country/IDN/year/2019/tradeflow/Exports/partner/ALL/product/440200 (accessed on 11 February 2021).
140. Zion Market Research. Global Biochar Market Size Expected to Reach $585.0 Million by 2020. Available online: http://www.globenewswire.com/news-release/2017/06/06/1008630/0/en/Global-Biochar-Market-Size-Expected-to-Reach-585-0-Million-by-2020.html (accessed on 24 February 2021).
141. Acumen Research and Consulting. USD 15 Mn Biochar Market Size Expected to Reach between 2014–2023 Says Acumen Research and Consulting Experts. Available online: http://www.globenewswire.com/news-release/2017/11/29/1210264/0/en/USD-15-Mn-Biochar-Market-Size-Expected-to-Reach-between-2014-2023-Says-Acumen-Research-and-Consulting-Experts.html (accessed on 24 February 2021).
142. IMARC Group. Biochar Market Size, Share, Price Trends and Forecast 2020–2025. Available online: https://www.imarcgroup.com/biochar-market (accessed on 24 February 2021).
143. Grand View Research Biochar Market Size Worth $3.1 Billion By 2025, CAGR: 13.2%. Available online: https://www.grandviewresearch.com/press-release/global-biochar-market (accessed on 24 February 2021).
144. Chen, W.; Meng, J.; Han, X.; Lan, Y.; Zhang, W. Past, Present, and Future of Biochar. *Biochar* **2019**, *1*, 75–87. [CrossRef]

145. Scholz, S.B.; Sembres, T.; Roberts, K.; Whitman, T.; Wilson, K.; Lehmann, J. *Biochar Systems for Smallholders in Developing Countries: Leveraging Current Knowledge and Exploring Future Potential for Climate-Smart Agriculture*; The World Bank: Washington, DC, USA, 2014; ISBN 978-0-8213-9525-7.
146. Wu, S.; Zhang, Y.; Tan, Q.; Sun, X.; Wei, W.; Hu, C. Biochar Is Superior to Lime in Improving Acidic Soil Properties and Fruit Quality of Satsuma Mandarin. *Sci. Total Environ.* **2020**, *714*, 136722. [CrossRef] [PubMed]
147. Ippolito, J.A.; Cui, L.; Novak, J.M.; Johnson, M.G. Biochar for Mine-Land Reclamation. In *Biochar from Biomass and Waste*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 75–90. ISBN 978-0-12-811729-3.
148. Liu, J. The Application of Biochar as a Soil Amendment in Land Reclamation. Master's Thesis, University of Alberta, Alberta, AB, Canada, 2015.
149. Maftu'ah, E.; Nursyamsi, D. Effect of Biochar on Peat Soil Fertility and NPK Uptake by Corn. *Agrivita J. Agric. Sci.* **2019**, *41*, 64–73. [CrossRef]
150. Norwegian Geotechnical Institute. *Biochar on Acidic Agricultural Lands in Indonesia and Malaysia*; Norwegian Research Council: Oslo, Norway, 2014.
151. Berek, A.K. The Potential of Biochar as an Acid Soil Amendment to Support Indonesian Food and Energy Security—A Review. *Pertanika J. Trop. Agric. Sci.* **2019**, *42*, 745–759.
152. Juhrian, J.; Yusran, F.H.; Wahdah, R.; Priatmadi, B.J. The Effect of Biochar, Lime, and Compost on The Properties of Acid Sulphate Soil. *J. Wetl. Environ. Manag.* **2020**, *8*, 129–140. [CrossRef]
153. Sukarman, S.; Gani, R.A.; Asmarhansyah, A. Tin Mining Process and Its Effects on Soils in Bangka Belitung Islands Province, Indonesia. *Sains Tanah J. Soil Sci. Agroclimatol.* **2020**, *17*, 180. [CrossRef]
154. President of The Republic of Indonesia. *Regulation of The Government of Indonesia No.12/2014 on the Types and Rates of Non-Tax State Revenues Applicable at the Indonesia Ministry of Forestry*; Minister of Justice and Human Rights, The Republic of Indonesia: Jakarta, Indonesia, 2014.
155. Jirka, S.; Tomlinson, T. *State of the Biochar Industry 2014: A Survey of Commercial Activity in the Biochar Sector*; International Biochar Initiative (IBI): New York, NY, USA, 2015; p. 77.