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Valorization of oil palm empty fruit bunches into activated carbon: A mini-review

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KEYWORDS

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Waste valorization

ABSTRACT

This paper aimed to comprehensively review the potential valorization of oil palm empty fruit bunches (OPEFBs) into activated carbon and its potential application. Activated carbon is carbon processed through dual phases, including carbonization and activation. Firstly, this process converts biomass into carbon thermally with zero to little oxygen conditions. Next, the carbon needs to be activated to stimulate the formation of pores and reduce impurities. The activated carbon's quality is influenced by the activation process, which can be done physically, chemically, or physiochemically. Activated carbon has an amorphous structure and abundant internal pore structure, thus increasing the surface area. In Indonesia, the quality of active carbon is regulated by Indonesian National Standards or SNI 06-370-1995. The factors influencing the activation step include activator agent type, activator agent concentration, activation ratio and time, etc. Generally, activated carbon can be widely applied to various sectors, such as agriculture (i.e., slow-released fertilizer, fertilizer, etc.), waste treatment (i.e., adsorbent, activator in anaerobic digestion/AD, bioremediation, etc.), gas purification, ceramic membrane, etc. However, further in-depth investigation is required to determine potential scaling-up and commercialization.

Introduction

Oil palm empty fruit bunches (OPEFBs) are generated from palm oil mills (POMs), where fruits are removed from the fresh fruit bunches (FFB) to be used for crude palm oil (CPO) production. The main components of OPEFBs are cellulose (44.2%), hemicellulose (33.5%), and lignin (20.4%) (Kristiani et al., 2015). OPEFB is a non-wood lignocellulosic biomass rich in organic materials with moisture content in the range of 60-70%, hence suitable for bioenergy and bioproducts production (Ajayi et al., 2023; Hidayat et al., 2020; Ramlee et al., 2019; Suhartini et al., 2020; Suhartini et al., 2022a; Suhartini et al., 2023; Suhartini et al., 2022b). Different range of products can be produced from OPEFBs including alternative fuels (i.e., methanol, bioethanol, di-methyl ether, biohydrogen, biodiesel, bio-solid refuse fuels, etc.) and biomaterials (i.e., chemical compounds, fertilizer, etc.) (Burhani and Triwahyuni, 2019; Harahap et al., 2019; Heryadi et al., 2019; Nuryadi et al., 2019; Parbowo et al., 2019; Rahmi et al., 2019; Yoo et al., 2019).

In 2030, it is projected that there will be a production of 54 million tonnes of OPEFBs in Indonesia, considering the mass balance of palm processing where FFB (100%) could contribute to 21% of OPEFBs, 65.5% of fruits and their residues, as well as 13.5% of palm oil mill effluent/POME (Hambali and Rivai, 2017). This projection leads to

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encourages further in-depth research to improve the value-added benefits of the palm oil industry, minimize waste, and make the processes more environmentally sustainable. Furthermore, as an agricultural country, Indonesia has access to a great potential for biomass abundance, such as OPEFBs. However, the processing of bioenergy or bioproducts from biomass resources still needs to be eco-friendly. Therefore, an integrated biorefinery approach is suggested to utilize every component of waste generated during the production process to attain maximum efficiency (Burhani and Triwahyuni, 2019).

The activated carbon is carbon processed through carbonization, followed by the activation process. This process converts biomass into carbon thermally with zero to little oxygen conditions (Heidarinejad et al., 2020). Meanwhile, to get activated carbon, it needs to be "activated" to stimulate the formation of pores and reduce impurities. The quality of activated carbon is influenced by the activation process, which can be conducted either physically, chemically, or physiochemically (Ao et al., 2018; Ayinla et al., 2019; Heidarinejad et al., 2020; Wang et al., 2017). Activated carbon has an amorphous structure, abundant internal pore structure, and extensive surface area (Mistar et al., 2020; Tadda et al., 2016). Indonesia has active carbon standards regulated in SNI 06-370-1995, which include the requirement of activated carbon and its process. In general, activated carbon results from two process stages: carbonization to convert biomass into carbon and activation to increase porosity and surface area (Gayathiri et al., 2022; Raut et al., 2022; Yameen et al., 2023; Zakaria et al., 2023). Prior to these processes, the biomass materials were dried to reduce the water content. The factors influencing the activation process in synthesizing activated carbon include the type of activator agent, the concentration of activator agent, the activation ratio, and the activation time (Amin et al., 2023; Bergna et al., 2022; Kumar et al., 2022; Thithai et al., 2021). The application of activated carbon is mainly in the adsorption process, both for waste adsorption and adsorption of certain substances in the production process (Karić et al., 2022; Tadda et al., 2016; Wang et al., 2021a). In the agricultural sector, activated carbon can be used as a macronutrient carrier in fertilizer, thus obtaining fertilizer with a slow nutrient release rate known as slow-released fertilizer (Arslanoğlu and Tümen, 2021).

In recent years, the integrated biorefinery in palm oil residues has been increasingly utilized for the adsorption of pollutants, bioenergy production, and soil amendment (Rashidi and Yusup, 2017; Zakaria et al., 2023). This represents a good understanding of how this biomass residual could be further applied to industry applications. However, while a review of the general palm oil residuals has been conducted, more focus on the OPEFBs is still limited. Thus, this review provides the possibility for utilization and highlights the optimization to increase its functionality from OPEFBs along with its national potential in Indonesia.

Methods

This paper reviews various mechanisms available for converting OPEFBs into activated carbon. This review also intends to provide a systematic review of the impact of pre-treatment on the structural changes of the OPEFBs biomass and thereby investigate the potential of any additional economic benefits on current activated carbon production in practice in Indonesia to further utilize OPEFBs as bioproduct sources. The literature reviews were carried out using ScienceDirect, ProQuest, Google Scholar, and Web of Science. The papers were selected based on the publication over the last ten years, from 2014 to 2024. The keywords used include 'oil palm empty fruit bunches', 'activated carbon', 'pyrolysis', 'activated carbon from OPEFBs', 'carbonation', 'carbon activation', etc. This selection aimed to compare various carbonation or activation steps for OPEFBs, seeking the trends and patterns of research for improving activated carbon production from OPEFBs.

Discussion

Palm oil – potential and availability in Indonesia

Oil palm is a non-timber plantation crop widely used to produce CPO (Sakai et al., 2022). This plant has many benefits in the food, cosmetics, textiles, biodiesel, and pharmaceutical sectors (Shigetomi et al., 2020). Oil palm can produce 20 tons of FFB annually (Risdianto et al., 2016). The palm oil industry is one of the largest contributors to Indonesia's foreign exchange and employment. The palm oil sector is developing in 22 provinces in Indonesia, where about 90% of oil palm plantations are located on the islands of Sumatra and Kalimantan (Purba and Sipayung, 2018). Based on data from the Indonesian Statistics Council, in 2020, Riau was the province with the largest CPO production, followed by Central Kalimantan, West Kalimantan, North Sumatra, and East Kalimantan. Oil palm is classified as a tropical plant that is growing rapidly in Southeast Asia. This crop has a minimum crop rotation of 25 years (Luke et al., 2020).

Oil palm can produce a large amount of usable oils to make various products, such as cooking oil, margarine, ice cream, instant noodles, soap, shampoo, detergent, cosmetics, etc. Abundant derivative products and the magnitude of population growth cause the high demand for palm oil plantations (Afrizon, 2017). Since 2014, Indonesia has been ranked the first palm oil producer in the world, followed by Malaysia and Thailand (Suhartini et al., 2022b). Indonesia even accounts for 59.15% of the global palm oil market in 2023, as shown in Table 1.

Palm oil mill – production process and waste generation

POMs produce OPEFBs with the value of 25% (w/w) of FFB (Santi et al., 2019); or about 22% (w/w) of FFB (Hafyan et al., 2020). In Indonesia, CPO is mainly used for food (~ 80%) and non-food (~ 20%). The increase in CPO production is related to the growth of palm oil plantations and waste resulting from POMs (Risdianto et al., 2016). The high number of POMs also impacted the large production of OPEFBs as solid waste. In Indonesia, POMs generate around 22.5% of OPEFBs, 14.3% of oil palm mesocarp fibre (OPMF), 6.7% coconut shell, and 5.4% palm oil waste (Suhartini et al., 2022b). OPEFBs are mainly used as fertilizer or directly disposed to the nearby environment (i.e., returned to the plantation area) ((Hidayat et al., 2020). It is estimated that 1 ton of CPO produced generates 1 ton of OPEFBs (Suhartini et al., 2022b). Therefore, potential OPEFBs in Indonesia reaches 47.00 million tons in 2023. Images of OPEFBs can be seen in Figure 1

Figure 1. Images of OPEFBs obtained from PT. Sawit Arum Madani, Blitar City

Table 1. Production of palm oil in 2014-2023 (in million tons)

Year	Indonesia	Malaysia	Thailand	Global
2014	29.28	19.67	1.85	61.75
2015	31.07	19.66	1.83	58.92
2016	31.49	17.32	1.82	65.34
2017	34.94	19.20	2.60	70.58
2018	42.88	19.52	2.80	74.02
2019	45.86	19.58	2.90	72.27
2020	43.50	17.85	2.96	73.28
2021	42.00	18.15	3.38	72.96
2022	46.00	18.39	3.42	77.56
2023	47.00	19.00	3.45	79.46

Source: (Suhartini et al., 2022b; U.S. Department of Agriculture, 2023)

Table 2. Composition of lignocellulosic biomass from oil palm

Type of biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
OPMF	19.0	15.2	30.5
Oil palm shells	14.7	16.4	53.6
OPEFB	37.3-46.5	25.3-33.8	20.4-32.5
Oil palm frond	33.5	13.9	30.9

Source: Suhartini et al. (2022b)

Table 3. The Indonesian national standard (SNI) for activated carbon (SNI 06-370-1995)

Parameters	SNI values	
	Granular	Powder
Volatile matter at 900 °C (%)	≤ 15	≤ 25
Moisture content (%)	≤ 4.5	≤ 15
Ash content (%)	≤ 2.5	≤ 10
Non-carbon materials	0	0
Fixed carbon (%)	≥ 80	≥ 65
Iodine absorption capacity (mg/g)	≥ 750	≥ 750
Methylene blue absorption capacity (mg/g)	≥ 60	≥ 120
Benzene absorption capacity (%)	≥ 25	-
Density (g/mL)	0.45-0.55	0.30-0.35
Escaped mesh 325 (%)	-	≥ 90
Mesh size (%)	90	-
Hardness (%)	80	-

It has been found that commonly OPEFBs were only left in factories or plantations until the waste decomposed naturally (Ahmad et al., 2019). Meanwhile, the OPEFBs are rich in organic materials such as carbon of 480-490 kg/ton, nitrogen of 6.4-9.8 kg/ton, with a C/N ratio of 50-60 and water content of 60-70% (Nurika et al., 2022). On the other hand, the utilization of OPEFB for boiler combustion is complicated because of the higher moisture content (ca. 60%); hence, drying treatment is necessary. Ahmad et al. (2019) explained that OPEFB can be reprocessed into various bioproducts, such as biofuels, pellets, activated carbon, fiberboard, and other products. Carbon content and the large amount of lignin from OPEFBs allo this biomass to be utilized as activated carbon. In summary, the characteristics of palm oil biomass from cellulose content, hemicellulose, and lignin are shown in Table 2.

Activated carbon

Activated carbon is an effective adsorbent for removing fluid contamination because of its large surface area and adsorption capacity. Activated carbon also has a pore structure on its surface as an adsorption medium (Ronda et al., 2015; Wang et al., 2017; Wirasnita et al., 2014). Acrylic carbon has an amorphous (microcrystalline) structure due to activation treatment, which gives it a large surface area. Activated carbon is made from materials that contain carbon, both organic and inorganic (González-García, 2018; Reza et al., 2020; Yahya et al., 2015). The structure owned by activated carbon causes an increase in surface area up to more than 1,000 m^2/g. Given the particle size matter, activated carbon is in the form of granules, powders, and pellets. However, granules and powders are most commonly used(Jjagwe et al., 2021; Kårelid et al., 2017; Meinel et al., 2014). Activated carbon production is carried out by employing carbonization and activation (i.e., physically, chemically, or physicochemical) (Tadda et al., 2016). The quality of commercially used activated carbon is regulated in SNI 06-370-1995, as shown in Table 3.

Production of activated carbon – a basic principle

The production step in activated carbon can be seen in Figure 2. First, drying aims to reduce the water content of biomass to reach < 15% at 170^{0}C so that carbonization can be effectively operated. Next, carbonization aims to reduce organic material to carbon, carried out at 400^0-700^{0}C. Finally, activation aims to increase the carbon surface area through increasing porosity and pore volume. However, the critical steps in producing activated carbon are generally carbonization and activation.

Carbonization

Carbonization is a process aimed at enriching the carbon content of samples. The principle of carbonization is to remove non-carbon material thermally. Generally, the process temperature is ranging from 400^0-700^{0}C (Lütke et al., 2019; Mopoung and Dejang, 2021; Pallarés et al., 2018; Tomul et al., 2020). The common method used in carbonization is pyrolysis, a thermal treatment under certain conditions a vacuum or a little oxygen, or using an inner gas, such as N_2, Ar, and others (Indayaningsih et al., 2017). Pyrolysis of biomass generally uses a temperature of 300^0 – 1200^0C for a certain time. The pyrolysis process is affected by temperature, residence time, rate of heating, as well as the size and shape of the biomass particles (Januszewicz et al., 2020). The pyrolysis process is generally classified into 3 types based on the heating rate (Aladdin et al., 2023):

- Slow pyrolysis, where the heating rate is less than 50 °C per minute with a relatively low temperature (i.e., 300-600 °C), with the main products being carbon (or char) amounted to ≥ 35% and syngas around 35-40%.
- Fast pyrolysis, where the heating rate is 50-200 °C per second with moderate temperatures (i.e., 500-600 °C), with the main products of bio-oil (50-70%) and syngas (around 30%).
- Flash pyrolysis, where the heating rate is ≥ 200 °C per second with a heating temperature of more than 700 °C, giving the main product of 70-75% bio-oil.

Hu and Gholizadeh (2019) and Choi et al. (2018) stated that there are at least 4 stages in the pyrolysis process. The first stage occurs at a temperature of 40-200^0C where the evaporation of the water in the material occurs. The following stage is at a temperature of 200-280^0C where the decomposition occurs transforming hemicellulose into volatile components, syngas, tar, carbon, and bio-oil. Then, at a temperature of 280-350^0C, the cellulose decomposition occurs into syngas, bio-oil, and carbon. The fourth stage is at a temperature of 280-500^0C or more decomposition occurs lignin into carbon and bio-oil. The pyrolysis apparatus and thermal decomposition diagram with pyrolysis can be seen in Figure 3. The equation for the reaction of carbon formation through the pyrolysis process is as follows (Basu, 2018):

$$C_6H_{10}O_5 \rightarrow 3.74C + 2.65H_2O + 1.08CH_4 \text{ ....(1)}$$

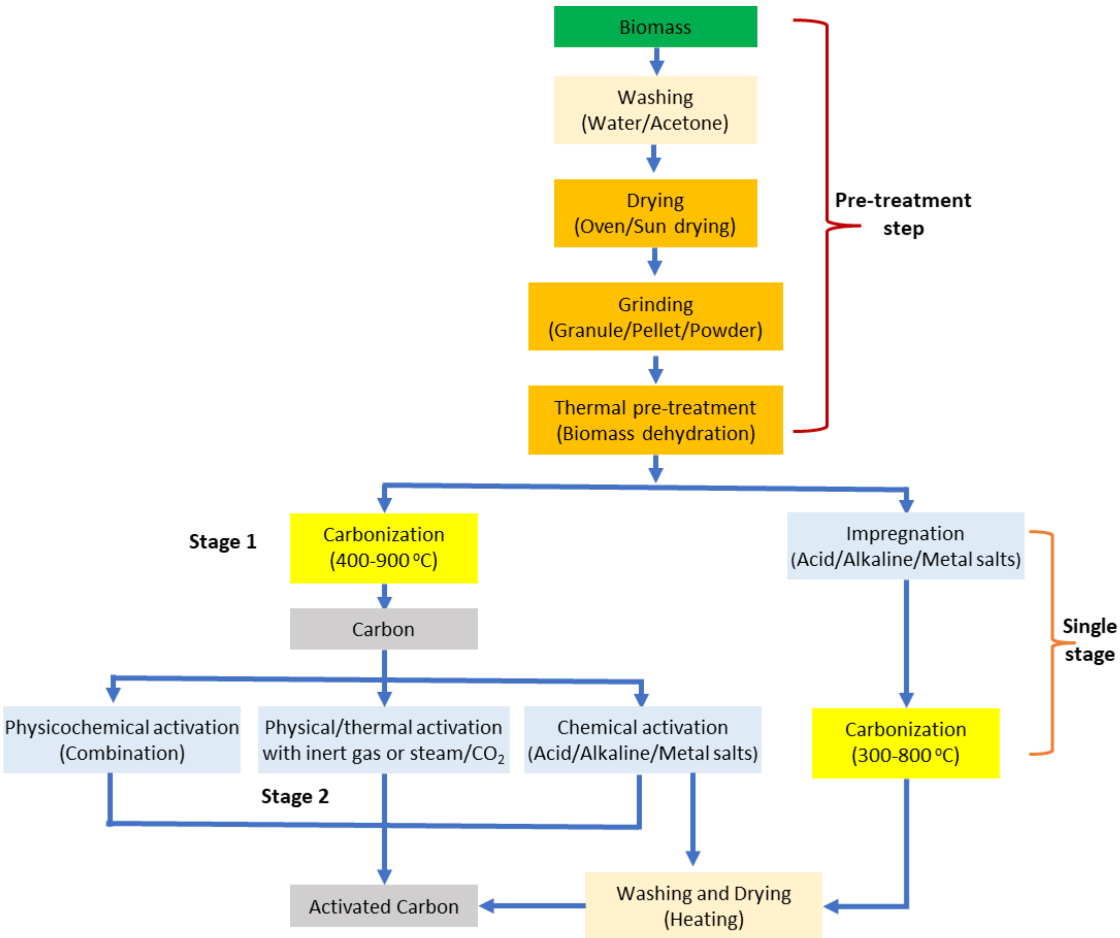

Figure 2. Manufacturing of activated carbon (modified from Ayinla et al. (2019); Tadda et al. (2016); and Heidarinejad et al. (2020))

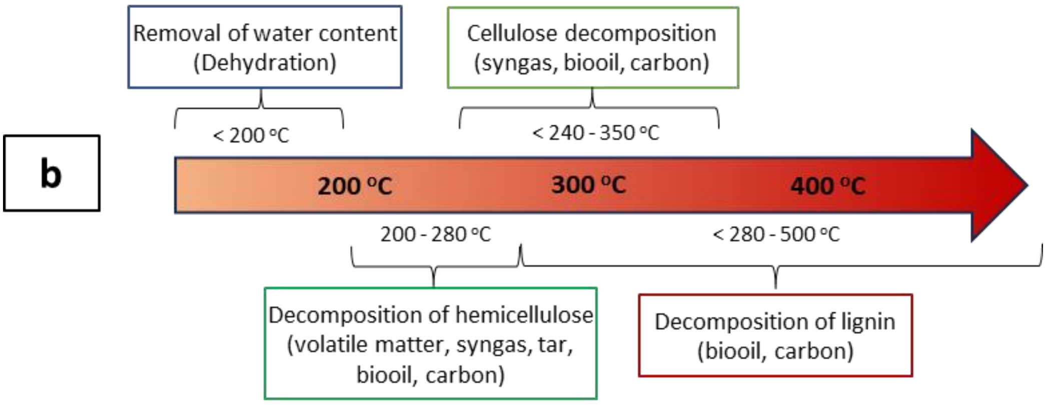

Figure 3. (a) Pyrolysis apparatus (own documentation) and (b) Thermal decomposition diagram with pyrolysis (modified from Hu and Gholizadeh (2019))

Activation

Activation aims to increase the pore volume and porosity of activated carbon (Heidarinejad et al., 2020; Tadda et al., 2016). The carbon activation can be carried out physically, chemically, and combined.

a) Physical activation

As the common synthesis methods, physical activation (also known as thermal activation) is a two-step process consisting of carbonization and followed by the reaction of controlled gasification between carbonized material with the activation agent or oxidizing gas (i.e., water vapor, CO_2, H_2O, N_2, or any mixed of these gas) at elevated temperature (i.e., 800 - 1,100 °C) (Pallarés et al., 2018; Yahya et al., 2015). This reaction will form the complex heterogeneous surface on the treated carbon. This method does not depend on chemical agents and offers several advantages, including low production cost, less environmental impact, and no impurities production (Zhou et al., 2018; Zhou et al., 2021). The higher specific area of activated carbon is affected by the carbonized material production and a deeper specific area is found after being activated (Colomba et al., 2022). A higher pore structure on activated carbon is also identified after the pressurized physical activation. The carbonized material was heated at 700-900 °C with a flow of pure CO_2 (150-200 cm^3/min) under the pressure of 0.1 or 1.0 MPa for atmospheric (Yi et al., 2021). Sharif et al. (2018) investigated the effects of microwave and conventional on sesame seed shells that coupled with $ZnCl_2$ (act as chemical agents) as the two-step pretreatment. The activation has shown a significant impact on the pore diameter and its volume. In the same oxidizing agent, Zaini et al. (2021) studied and utilized CO_2 and steam on fibre-based activated carbon, resulting in higher microporous than in control experiments. Other properties (i.e., wettability and electrochemical) related to the activated carbon's utilization of charge storage (supercapacitor) have also shown improvement with this activation method. Thus, the specific surface area increased by 3.3 times after activation and enlarged its pore volume up to 4 times.

b) Chemical activation

Chemical activation was done by soaking the carbon in chemical solutions such as $ZnCl_2$, organic acids (i.e., H_2SO_4 and H_3PO_4), hydroxides (i.e., KOH and NaOH), carbonate salts, and chlorides under a nitrogen atmosphere (Amin et al., 2023; Gao et al., 2020; Kumar et al., 2022; Nayak et al., 2017; Özsin et al., 2019; Sevilla et al., 2021). Mixing with the precursors resulted in dehydration and oxidation, leading to improved pore volume and surface area (Kumar et al., 2022). This process allows many quantities of pores to form. Parameters affecting the properties of activated carbon under this activation include the temperature of activation, precursor material, the ratio between chemical compound and the precursor, and the mixing method (Gul et al., 2022). The weakness of this activation is the potential for corrosion and detrimental environmental impact, therefore washing is required to remove activation residue (Ao et al., 2018). These issues could be solved by using green chemical materials to reduce their environmental impact (Sevilla et al., 2021).

Mariah et al. (2023) investigated the potential of waste tea as activated carbon using sulfuric acid as the chemical activation for removing heavy metals and its properties have the same potential with the commercial-grade activated carbon. Illingworth et al. (2022) observed that the KOH activation on activated carbon fibre matting material had increased the micropores at low temperatures, and under high temperatures, its pore widening took place. The same behavior was observable in the study of activated carbon from corn stigmata fibre material (Mbarki et al., 2022). An approach to environmental analysis should have been made; a life cycle assessment (LCA) study may be needed to estimate the impact of chemical utilization on ecological footprints. A comparative study could also be an option since the laboratory- and industrial-scale have different material and tools requirements (Amin et al., 2023). KOH is one of the activating agents used for carbon and is quite popular because the price is cheaper than that of other activator agents. In addition, KOH can also produce a large surface area, distribution of finer pores (micropores), less corrosive, and minor in negative impact to the environment (Heidarinejad et al., 2020). Increased KOH activation ratio could improve the quality of activated carbon because it can reduce metal minerals (ash) activated carbon (Borghei et al., 2021). Chemical activation with KOH provides the structure-activated carbon with a large surface area and pore volume (Januszewicz et al., 2020), so that it has the potential to be used for the adsorption of pollutants (i.e., As, Pb, and Cd) (Jin et al., 2014; Li et al., 2020a; Li et al., 2020b).

The large surface area is due to the tendency of KOH activating agents to form micropores than other activating agents, such as $ZnCl_2$, which tends to forming mesopores (Bergna et al., 2022). Indicators used to identify the pore formed are iodine and methylene blue adsorption capacity. Iodine adsorption occurs more in micropores (Mopoung and Dejang, 2021; Shrestha et al., 2019), while the adsorption of methylene blue occurs more in mesoporous (Jawad and Abdulhameed, 2020; Jawad et al., 2019; Mopoung and Dejang, 2021). Jin et al. (2014) explained some advantages of carbon activation with KOH such as increased surface area and volume total pores, modified carbon functional groups, and increased adsorption of As metal contaminants on waste. Heidarinejad et al. (2020) reported that a chemical reaction occured in the carbon activation with KOH is following the equation given below:

$$6KOH + 2C \dashrightarrow 2K^+ + 3H_2 + 2K_2CO_3 \text{............} (2)$$

Various studies have highlighted the use of KOH activation solutions to make activated carbon. For example, Huang et al. (2019) made active carbon from garlic skins with KOH activation for CO_2 adsorption. Activated carbon production was carried out in a double stage with carbonization at 400^0C for 1 hour. Chemical activation process using a carbon:KOH ratio (1:2), then heated at temperatures of 600, 700, and 800 ^oC for 1 hour. It was reported that at an activation temperature of 600 ^oC the best results were obtained with a surface area of 947 m^2/g. CO_2 absorption at 0 ^oC is 6.2 mmol/g, and at 25 ^oC of 4.2 mmol/g. Wang et al. (2021b) studied chitosan-based activated carbon with KOH activation for CO_2 absorption. Activated carbon is made at a temperature of 300 ^oC for 4 hours, then activated with a carbon:KOH ratio (1:1). Chemical activation is carried out again thermally at a temperature of 600-800 ^oC for one hour. Thermal activation at 800 ^oC produces a larger surface area (2,547 m^2/g) than the temperature of 600 ^oC (1,249 m^2/g). However, at 600 ^oC obatined better CO_2 absorption at 4.41 mmol/g.

Jin et al. (2014) investigated the potential of active carbon from solid waste urban areas that are pyrolyzed using temperatures of 400, 500, and

600 ^{o}C with N_2 gas. The activation was done using 500 mL of 2M KOH 2M KOH added to 2 g of activated carbon) and then stirred for 1 hour without physical activation. The research results obtained activated carbon with a large surface area and a large pore volume. The As adsorption capacity reached 30.98 mg/g at pyrolysis treatment 500 ^{o}C. Zhang et al. (2022) researched the manufacture of activated carbon for supercapacitors with KOH activation made from corncobs. The research was carried out using two stages of carbonization at 400 ^{o}C for 1 hour and activation using KOH with a ratio of charcoal:KOH activator (1:2, 1:3, and 1:4). The, the carbon was activated with a furnace in a nitrogen atmosphere at 600, 650, 700, and 750 ^{o}C for 0.5, 1, and 2 hours. The best activation ratio was 1:3, with the pore size spread over the range of 0.5-2.5 nm.

As aforementioned, carbon activation aims to increase the carbon surface area in a way that increases porosity and pore volume (Ao et al., 2018; Ayinla et al., 2019; Heidarinejad et al., 2020; Rashidi and Yusup, 2017). Chemical activation is carried out by immersing the carbon in the activator solution to remove organic or inorganic impurities (Ayinla et al., 2019). Chemical activation also affects the environment but can be handled through neutralizing filter residues or agent activators, and can use the reflux method (Bergna et al., 2022; Bergna et al., 2018). Nayak et al. (2017) and Gao et al. (2020) explained several factors that affect the chemical activation of activated carbon, including the type of activator agents, activator concentration, activation ratio, and activation time. The activator agent needs to be adjusted to the type of activated carbon material used because it affects the process of removing material in the material. The concentration of the activator will affect the resulting adsorption value. Higher concentration can increase the adsorption value, but too high concentration will damage the carbon pores. The activation ratio between the material and the activator solution affects the process of carbon impurity cleaning. A higher activator ratio will maximize the cleaning process, but giving too much activator solution high levels can damage the pore structure of activated carbon. Activation time impacts washing carbon impurities and opens the pore structure of activated carbon.

c) Physicochemical activation

This activation combines chemical and physical activation processes, which promotes a better carbon in terms of pores, texture, and characteristics. However, this method is more complex process and requires large costs (Ao et al., 2018). Table 4 shows several studies conducted using different activation methods and their activated carbon yield.

Applications of activated carbon

Activated carbon can be effectively utilized in various industrial sectors, such as petroleum, fertilizer, nuclear, pharmaceuticals, cosmetics, to textiles. Activated carbon is mainly used for the adsorption of dissolved substances in a solution because of its wide area and large surface. This process can use activated carbon in the form of powder, pellets, or granules. In these cases, activated charcoal can be used as optimal pollutant reduction for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and pH (Tadda et al., 2016). Due to its ability to adsorb dissolved substances, activated carbon is also used in the production of drinking water. In modern water treatment plants, activated carbon is combined with the ozonation to obtain quality water (Jjagwe et al., 2021). Activated carbon is also considered effective as a biogas purifier. This is because the nature of activated carbon is capable of adsorbing CO_2 gas in biogas installations (Durán et al., 2018; Rainone et al., 2021; Reza et al., 2020).

The activated carbon adsorption process for landfill leachate treatment can reduce COD levels by up to 68.4% (Bashir et al., 2015). Activated carbon adsorption can also be carried out to reduce organic pollutants in polluted river water, decreasing COD concentration by 69.80%, color by 78.7%, and turbidity by 66.7% (Sidik et al., 2022). Apart from waste adsorption, activated carbon can also improve the carotene adsorption in palm oil (Ulfah et al., 2019). The large adsorption capacity of activated carbon is used as a macronutrient carrier for fertilizer. In addition, the release of macronutrients into the soil lasts longer; therefore, it can be used for a slow-release fertilizer (Arslanoğlu and Tümen, 2021). Several potential applications of activated carbon from oil palm biomass are shown in Table 5.

Table 4. Comparison of biomass applied act as activated carbon with their properties

Biomass	Activation agent	Operational condition	Specific surface area (m^2/g)	Adsorption capacity (mg/g)	Yield (%)	Ref.
		Chemical activation				
Coconut leaflets	H_3PO_4 $ZnCl_2$ KOH	- Impregnated (1:1) for 24 h then followed by oven-dried at 105±5ºC - Activated in a tubular fixed bed reactor at 600ºC with 10^0C/min for 1 h (fixed flowrate of N_2 for 150 mL/min)	857-1,353 793-1,148 472-964	- - -	32.37-33.27 32.83-33.68 28.98-29.60	(Kumar et al., 2022)
Waste tea	H_2SO_4	- Impregnated with 5-30% of H_2SO_4 concentration for 24 h (under room temperature). - The AC was then neutralized with 2% $NaHCO_3$ to pH of 6.5-7.5	-	1.5757-9.6493 (for methylene blue) 0.0000-0.1073 (for cadmium ions)	-	(Mariah et al., 2023)
Tabah bamboo	H_3PO_4	- Impregnation ratio of 1.5:1 (%wt) - Mixing with magnetic steer under 300 rpm for 2 h, at 200ºC - Held for 5 h and washed with distilled water	245-398	18.870-48.743	-	(Negara et al., 2020)
Corn cob	H_3PO_4	- Corn cob is pretreated under torrefaction - The pretreated corn cob (30g) impregnated with H_3PO_4 (27-83%) in a 500 mL beaker for 24 h at room temperature	719.66-1,092.31	-	79.30	(Mbarki et al., 2022)
- Pine sawdust - Rose seed - Cornel seed	$ZnCl_2$	- Impregnation between $ZnCl_2$ (5; 7.5; 10; 15; and 20g) in 150 mL of distilled water with 10 g of carbonized material for 2 h under temperature of 85ºC - Impregnated material heated on 300-800ºC (10ºC/min heating rate) for 1 h - Cleaned with 3M HCl solution (90ºC, 30 min)	4.47-1,824.71 18.41-1,264.63	179.79-299.94 122.68-296.99 155.00-298.55	38.51-53.41 38.13-52.30 40.76-59.25	(Açıkyıldız et al., 2014)
		Physical activation				
Barley straw	CO_2 and steam	- Carbonization is carried out with Nitrogen - Activation with CO_2 and steam using quartz tubular reactor	789	-	~88	(Pallarés et al., 2018)
Hazelnut shells	CO_2 and H_2O	- A self-constructed thermogravimetric apparatus is utilized and performed the activation with control temperature growth	921-992 (at 25ºC)	0.425 cm^3/g	-	(Kwiatkowski and Broniek, 2017)
Cherry stones	CO_2	- Performed with flow of CO_2 (0.25 L/min) for 30 min at 800ºC	361-367	0.21-0.22 cm^3/g	86.4-97.1	(Nowicki et al., 2015)

Biomass	Activation agent	Operational condition	Specific surface area (m^2/g)	Adsorption capacity (mg/g)	Yield (%)	Ref.
Palm tree fronds	CO_2	- Performed at tube furnace (spesific temperature, 700; 750; 800; 850; 900; 950; 1,000 ºK)	385-1,094	0.1663-0.4382 cm^3/g	8.5-28.42	(Shoaib and Al-Swaidan, 2015)
Olive stones	Steam	- A 2 g of carbonized material is place in fixed bed reactor with stainless steel and performed at 750ºC under 70% H_2O in N_2 during 360 min, with a total gas flow rate equal to 10 NL/h.	807	131	-	(Ghouma et al., 2015)

Table 5. Comparison of various application of activated carbon from oil palm biomass

Biomass	Manufacturing of activated carbon	Particle size	Application	Performance	Ref
Pressed-shredded OPEFB	- Carbonization (700 °C, 2 h, N_2 flow rate of 258 mL/min) - Chemical activation with KOH (impregnation ratio of 1:0.5, KOH: carbon)	≤250 µm	Glycerol decolorization	- glycerol purity enhanced by 98.2% - decolorization efficiency was 89.4%	(Ahmad Farid et al., 2021)
OPEFB fibre	- Carbonization (400 °C, 3 h, 2 bar pressure, limited oxygen) - Chemical activation with KOH (impregnation ratio of 1:3, KOH: carbon)	Micro-sized nanoparticle (<100 nm)	Heavy metal removal	Cu, Pb, and Fe could be removed by 84%	(Zubaidah et al., 2021)
OPEFB	Single-step pyrolysis: - Carbonizatio (800 °C, 3 h, heating rate 10 °C/min) - Nitrogen doping with addition of urea - Chemical activation with KOH (impregnation ratio of 1:3, KOH: carbon)	n.a.	CO_2 adsorption	The highest CO_2 adsorption capacity was 15.02 % wt	(Kurniawan et al., 2019)
OPEFB	n.a.	n.a.	Making of ceramic membrane	Addition of activated carbon and iron powder to make ceramic membrane improved its quality, giving 92.03, 97.08, 99.67, 84.56, and 87.10% rejection of Fe, Mn, Zn, NH_3–N, and PO_4	(Sisnayati et al., 2023)
OPEFB	- hydrothermal carbonization (using $CaCl_2$ activator) - impregantion with urea (nitrogen) - CO_2 gas activation (pyrolysis at 800 °C)	n.a.	Making of high-performance supercapacitor	Used of activated carbon enhanced the performance of supercapacitor, as shown by 100% of Coulombic efficiency and 98.7% of capacitance retention	(Rustamaji et al., 2023; Rustamaji et al., 2022)

Conclusions

As observed by the review analysis, the following aspects must be considered to improve the currently available technologies for OPEFB-based-activated carbon. First, ensure that activated carbon derived from OPEFB fulfills the requirements based on national and international requirements and is appropriately utilized for commercialization (scaling-up). Second, providing the green synthesis approach to production using activation materials that do not negatively impact the environment, i.e., reduce emissions and toxic second waste, should be put on more focus. Finally, regarding agricultural applications, the activated carbon could also be utilized further to adsorb several emissions (i.e., N_2O, CH_4, and CO_2) and odor (i.e., NH_3), which need further optimization as soil utilization or composting. This green prospect also offers carbon sequestration. However, further in-depth investigation is crucial for better efficacy of converting biomass materials into activated carbon and scaling up (or commercialization).

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Declarations

Conflict of interests The authors declare no competing interests.

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