

SUSTAINABLE OIL PALM BIOMASS VALORISATION FOR ACTIVATED CARBON: A REVIEW OF INTEGRATED CARBONISATION- ACTIVATION PATHWAYS

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ABSTRACT

The oil palm industry produces substantial amounts of oil palm biomass (OPB), which remains largely underutilised, with conventional applications limited to electricity generation, composting, and boiler fuel. In light of increasing environmental concerns and the push for sustainable resource management, valorisation of OPB for activated carbon (AC) production has garnered substantial attention, particularly in palm oil-producing regions. This review critically investigated the potential of an integrated carbonisation and activation process for producing high-quality AC from OPB. The findings showed that this innovative approach enhanced AC's physicochemical properties while improving production efficiency. Furthermore, using OPB-derived AC in wastewater treatment and air purification applications highlighted its dual benefits of environmental impact mitigation and value addition. This study comprehensively reviewed technological advancements, challenges and practical implications for optimising OPB utilisation, advancing sustainable pathways for AC production and waste management in the palm oil industry.

Keywords: activated carbon, environmental sustainability, oil palm biomass, one-step carbonisation, waste management.

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INTRODUCTION

Palm oil is one of the most widely consumed vegetable oil globally. Indonesia and Malaysia are the largest producers and exporters, with Malaysia

ranking as the second-largest producer, contributing about 31% of the global supply (Malaysian Palm Oil Certification Council [MPOCC], 2021). Malaysia produces 19–20 million tonnes of crude palm oil (CPO) yearly (Parveez et al., 2024). Processing fresh fruit bunch (FFB) to palm oil at the mills produces various types of oil palm biomass (OPB), including oil palm empty fruit bunch (OPEFB), oil palm mesocarp fibre (OPMF) and oil palm kernel shell (OPKS). Meanwhile, plantation activities produce oil palm fronds (OPF) and oil palm trunks (OPT) as the primary leftover biomass (Figure 1). These biomass materials are left at the plantation or around the mill for natural degradation (Kaniapan et al., 2021). While some OPB materials are utilised for biocompost production, others are burnt in the boiler to generate electricity (Abu Bakar et al., 2023). Considering the abundant availability of OPB in Malaysia, this material can be a good source for activated carbon (AC) production, technically and economically. The oil palm industry could

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generate additional income, reduce the cost of waste management, and simultaneously make the entire operation more environmentally friendly by producing AC from OPB. Nevertheless, the feasibility of the technologies that can be implemented to generate high-quality, high-yield AC at minimal operational expenses is one factor to be considered when converting OPB to AC.

Various types of biomass are used to generate high-quality AC, such as cocoa shells (Fasakin et al., 2024), bamboo fibres (Naifar et al., 2025), coconut shells (Pitthaikannu et al., 2025), rice husk (Liu et al., 2025), sawdust (Sanz-Santos et al., 2025) and OPB (Zakaria et al., 2023). One of the primary factors influencing AC's quality is the carbonisation (initial step) and activation process (subsequent step). In the conventional approach, these processes were typically conducted in two separate chambers. In the first step, the raw material is burnt in limited oxygen at 700°C–800°C to produce carbonised material called biochar (Haeldermans et al., 2020). This process is commonly conducted using a conventional, microwave, or hydrothermal heating method, whereby each poses its advantages and disadvantages over the other. In the second step, the biochar is activated using a physical or chemical activation process (Hoang et al., 2022; Ogungbenro et al., 2020) to enhance the formation

of a porous structure and total surface area (Zakaria et al., 2023). However, these two separate processes are at the expense of materials, facilities, time and resources. Therefore, integration of carbonisation and activation was studied, making the process unique due to the simple reactor design and ease of operation and reducing the operational cost (Abbas & Ahmed, 2016; Osovsky et al., 2011; Ould-Idriss et al., 2011; Rashidi et al., 2014; Velo-Gala et al., 2014).

Various types of OPB have been used for carbonisation and activation technologies under different operating conditions. Although each process has advantages and limitations, the overall performance of the technology in producing good quality AC using a cost-effective process is very important. High-quality AC is determined based on its surface area, pore size and ability to adsorb pollutants. For example, AC's adsorptive capacity for pollutants and contaminants, such as chemical oxygen demand (COD) and biological oxygen demand (BOD), is important in determining the suitability of AC as an efficient and cost-effective solution for industrial wastewater treatment (Mubarak et al., 2023; Qin et al., 2024). AC is not only meant for adsorption purposes (Dziejarski et al., 2023), but also has other applications ranging from air purification to electrode manufacturing, which makes AC production a global demand (Sun et al., 2024).

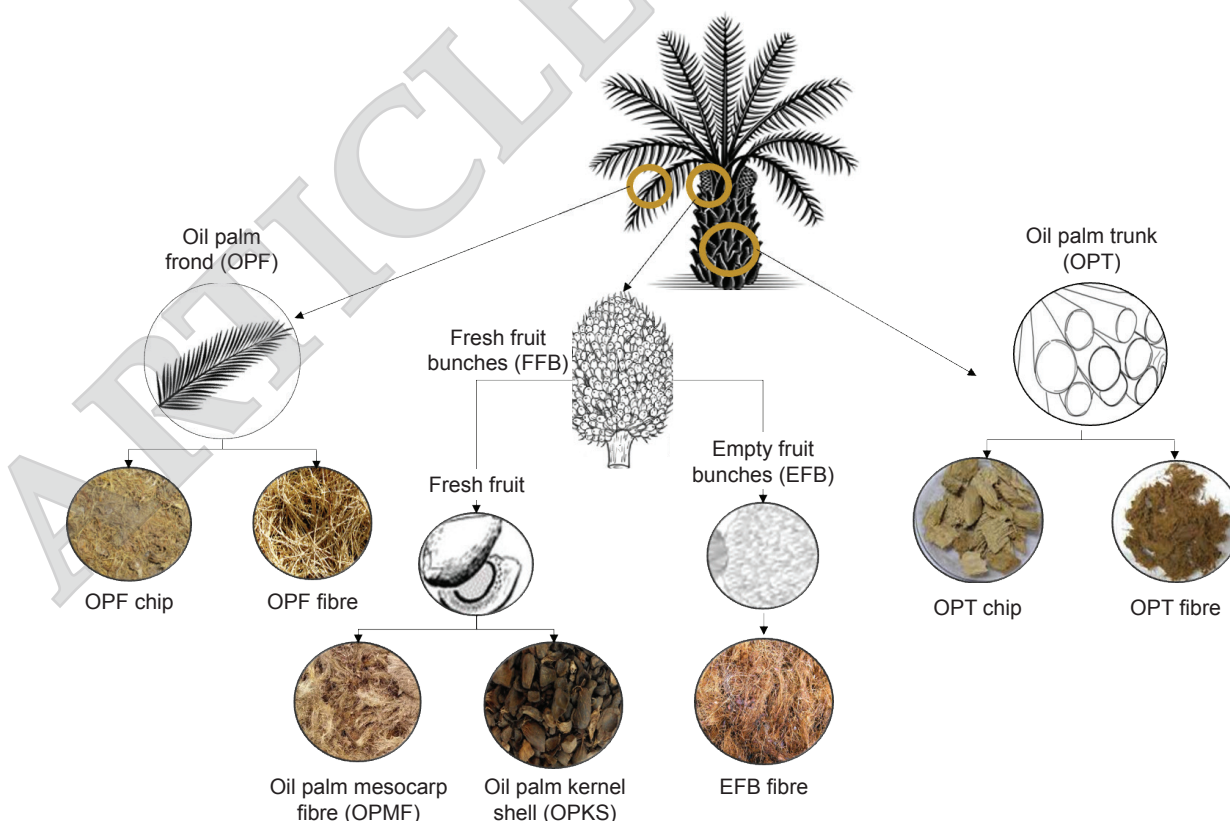


Figure 1. Oil palm biomass and its major by-products.

Given the enormous availability of OPB, a comprehensive evaluation of its suitability for AC production should be reviewed to ensure that the processes used are efficient, environmentally friendly, and economically viable, making the most of this abundant resource. This approach will meet the increasing demand for AC and its pivotal role in various applications, contributing to climate mitigation.

Therefore, this review aims to (i) examine the types, quantities and physicochemical properties of OPB that support its suitability for AC production, (ii) evaluate carbonisation technologies including conventional, microwave and hydrothermal heating, together with activation methods such as chemical activation using KOH or H_3PO_4 and physical activation using CO_2 or steam, with respect to efficiency, scalability and environmental impact and (iii) investigate integrated carbonisation and activation pathways that enhance production efficiency and AC quality. The discussion covers the environmental challenges posed by OPB waste, its availability and characterisation (including EFB, PKS and fibres), technological approaches for AC production with emphasis on integration strategies, and the applications of OPB-derived AC in wastewater treatment, air purification and energy storage. The review concludes with insights into technological advancements, challenges and future research directions to maximise the potential of OPB in AC production while supporting sustainable development goals.

Availability and Characterisation of Oil Palm Biomass

The total production of oils and fats is projected at 260.38 million tonnes, with palm oil accounting for the largest share at 30%, followed by soybean

oil (25%), rapeseed oil (12%) and sunflower oil (9%). This substantial contribution underscores the scale of the palm oil industry, which not only meets global demand for vegetable oils but also generates significant amounts of OPB as a byproduct. OPB is produced throughout the supply chain, from plantation activities such as harvesting FFB and replanting, to milling processes that convert FFB into CPO. Given the magnitude of palm oil production, the valorisation of OPB presents an opportunity to enhance sustainability within the industry while minimising environmental impact.

Annually, Malaysia's plantation activities generate an estimated 60.62 million tonnes of OPF and 13.07 million tonnes of OPT (Parveez et al., 2024). Meanwhile, 6.29 million tonnes of OPMF, 7.21 million tonnes of OPEFB, and 4.34 million tonnes of OPKS are being generated at the mill. In Indonesia, the figures stand at approximately 128.9 million tonnes of OPF and 59.7 million tonnes of OPT/yr (Nabila et al., 2023). OPEFB, OPT and OPF are commonly left on-site around palm oil mills or plantations for natural biodegradation and nutrient recycling. Only recently, this material has been utilised for the large production of other products such as bio-compost, pellets (Pua et al., 2020), nanocellulose (Bakar et al., 2022), microcrystalline cellulose (MCC) (Tan et al., 2020), medium-density fibreboard (MDF) (Ibrahim et al., 2021), biofuel (Chew et al., 2023), biocomposite (Perera et al., 2023), pulp and paper (Yiin et al., 2019), binderless board (Komariah et al., 2019), concrete (Muthusamy et al., 2019) and graphene (Teow et al., 2020), to name a few. Some OPBs, such as OPKS and OPMF, are burned in the boiler for steam and electricity generation for the mill. Nevertheless, a considerable amount of OPB is still underutilised and can be converted into more valuable products (Figure 2).

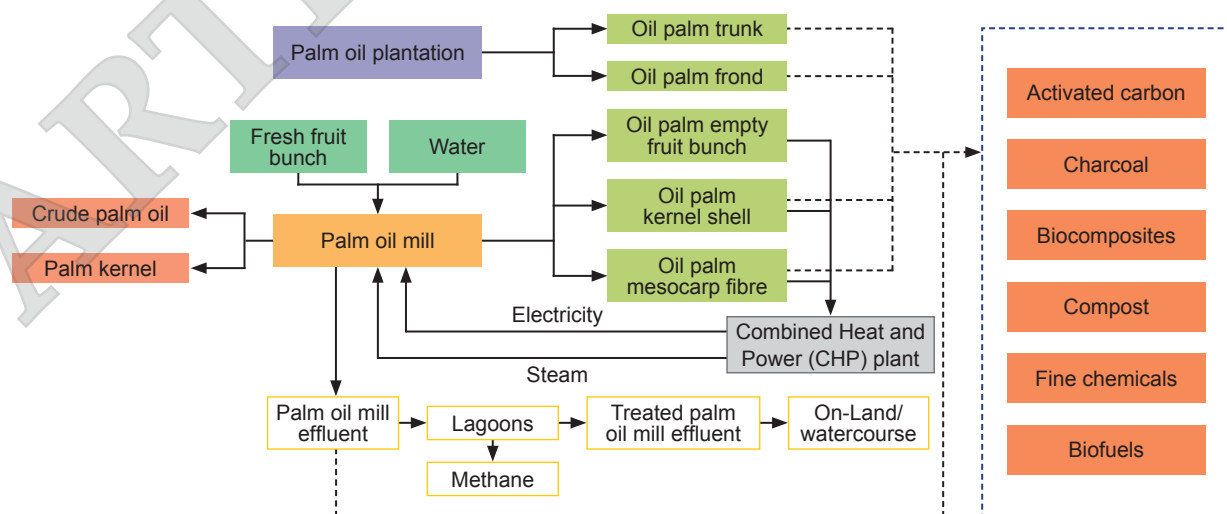


Figure 2. Palm oil biorefinery system showing major by-products and their value-added utilisation pathways (activated carbon, charcoal, biocomposites, compost, fine chemicals and biofuels).

The primary reason OPB is suitable as a starting material for AC is mainly due to its lignocellulosic-type content. The OPB consists mainly of cellulose, hemicellulose and lignin at approximately 22%–70%, 9%–41% and 13%–47%, respectively, depending on the type of OPB (Table 1) (Loh, 2017; Onoja et al., 2019). The chemical composition of OPB is an important consideration for AC production. Hemicellulose can be degraded at 250°C–300°C during carbonisation. Higher temperature is required to degrade cellulose, i.e., 350°C–400°C, while lignin, a more robust polymer, can be degraded above 400°C. These components are decomposed into combustible gases at ascending temperature (Gorbounov et al., 2024).

Typically, biomass with high moisture has a higher heating value (HHV), resulting in low AC quality. An additional drying step is required to reduce the moisture content to avoid ignition and combustion problems during carbonisation. Thus, biomass must be sun-dried to reduce its moisture content to <15% before carbonisation (Yusoff et al., 2019). High moisture content in biomass leads to higher energy and time consumed for drying, leading to increased operational costs. High volatile matter content can cause the formation of tar in AC production, which is difficult to remove during the carbonisation and activation process. This situation occurs especially when the carbonisation and activation are at low temperatures and short treatment times, as well as when the moisture content in the biomass is high.

Another factor that can affect the HHV is the ash content. Ash content of >8% in biomass will reduce the HHV (Demirbas, 2002). This is because ash is considered an impurity in AC that can reduce the adsorption efficiency of pollutants onto the AC

surface and clog its pores. Depending on the type of biomass, the ash content should be <5% to produce good quality AC.

Among the different OPB types, OPKS is particularly promising for AC production due to its relatively low ash content (2.2%–10.5%), which minimises pore blockage, and its high lignin content (45.0%–47.0%), which enhances fixed carbon yield and pore development during activation. The OPEFB, despite its higher moisture content, contains a relatively high cellulose fraction (34.0%–40.0%) that supports pore formation, and it is also the most abundantly available biomass at palm oil mills, making it highly attractive for large-scale utilisation. In contrast, OPF and OPT have higher ash and moisture levels, which limit their suitability for high-quality AC production. Therefore, OPKS and OPEFB stand out as the most favourable precursors for OPB-derived AC when both physicochemical properties and practical availability are considered (Table 1) (Nahrul Hayawin et al., 2017, 2018).

TECHNOLOGIES FOR ACTIVATED CARBON (AC) PRODUCTION

Conventional Heating Technology

Table 2 provides a comprehensive overview of biochar produced from various OPB using conventional heating technology. Different types of oil palm biomass, including OPEFB, OPF and OPT, were subjected to distinct reactor types, carbonisation temperatures, durations, resulting biochar yields and HHV. Through a set brick system at 600°C for 12 hr, 10%–11% biochar, with an HHV range of 23–25 MJ/kg was produced (Idris et al., 2015b). OPEFB

TABLE 1. PHYSICAL AND CHEMICAL PROPERTIES OF VARIOUS OIL PALM BIOMASS

Properties	OPMF	OPKS	OPEFB	OPF	OPT
Moisture content (%)	37.2–42.0	11.0–21.4	57.2–67.0	60.0	67.0–78.0
Proximate analysis (wt.%)					
Ash	6.6–10.2	2.2–10.5	3.0–7.3	2.2–4.3	2.3–10.3
Volatile matter	68.8–73.7	69.2–86.5	70.5–83.9	NA	61.3–75.2
Fixed carbon	12.6–18.8	6.5–20.5	8.6–17.0	NA	10.0–2.8
Ultimate analysis (wt.%)					
Carbon (C)	43.2–46.6	41.3–67.5	40.9–49.1	41.5	41.9
Hydrogen (H)	5.2–5.6	4.5–8.4	5.4–7.3	4.5	5.9
Nitrogen (N)	1.5–1.7	0.08–1.60	0.01–1.50	2.5	3.7
Sulphur (S)	0.1	0.09–0.30	0.1–0.6	0.3	0.3
Oxygen (O)	39.5–49.8	22.1–53.0	40.2–51.7	50.9	43.2
HHV (MJ/kg)	19.0–19.6	16.3–20.1	16.8–19.4	NA	14.4–17.5
Chemical composition (wt.%)					
Cellulose	24.3–29.2	20.1–29.3	34.0–40.0	31.2–40.8	22.1–44.8
Hemicellulose	19.2–24.3	21.4–23.8	15.2–22.4	23.0–38.0	12.7–29.2
Lignin	23.1–29.2	45.5–47.3	25.1–29.5	18.4–32.5	18.9–36.8

Note: OPMF - oil palm mesocarp fibre; OPKS - oil palm kernel shell; OPEFB - oil palm empty fruit bunch; OPF - oil palm frond; OPT - oil palm trunk; HHV - higher heating value.

Source: Akhlisah et al. (2021); Nabila et al. (2023); Zakaria et al. (2023).

in a fixed bed reactor (FBR) at 300°C–700°C for 0.3–0.5 hr produced a 25%–28% biochar with HHV range between 23–26 MJ/kg (Sukiran et al., 2011). The table also outlines the conditions for biochar production from OPF and OPT. This compilation facilitates a comparative analysis of biochar production methods from various oil palm biomass sources, aiding in understanding the influence of process parameters on biochar characteristics.

Kiln (insulated heating chamber), traditional drum and furnace are conventional heating technologies used in the carbonisation process to produce biochar. These traditional heating technologies typically use firewood to generate heat or electricity for furnaces. The heat produced on the contact surface is transferred to biomass via heat conduction, convection and radiation to reach steady-state conditions through thermal gradient, which often leads to inconsistent biochar quality (Liew et al., 2018). This is because the thermal gradient hinders efficient removal of volatile products such as carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) from the biomass to the surroundings, consequently reducing the quality of biochar produced. Therefore, a longer heating process is required to achieve the desired temperature, which requires more energy to produce high-quality biochar (Yek et al., 2019).

One of the significant obstacles in conventional heating technology, particularly in the indirect heating method, is that the system struggles to supply a constant temperature during the carbonisation process, regardless of the sizes, forms and shapes of the materials used as a heat source, since the surface heating is the hearth wall (Yang et al., 2010). Prolonged carbonisation's duration will concentrate the ash content, thus yielding a low biochar (Idris et al., 2015b; Sahu et al., 2010). Moreover, the characteristics and textural properties of biochar produced using conventional heating technology are inconsistent. This indirect conventional heating technology often produces biochar of variable quality under less controlled conditions. Additionally, this process leads to environmental pollution issues such as particulate matter emissions (Sparrevik et al., 2013).

According to Idris et al. (2015a), conventional heating technology without an internal heating element could produce high biochar yield with high HHV, within 5–8 hr of retention time. This study showed that a modified pilot-scale brick carbonisation reactor produced uniform hot air circulation in the reactor from top to bottom. A blower removed the air from the reactor and improved hot air distribution. This process developed a self-sustained carbonisation cycle, producing high-quality biochar with low ash content. Another example is bamboo, carbonised in a modified conventional metal furnace at 600°C using 280 kg of firewood as a heat source. This conventional heating system has a reactor with a size of 1.5 m height × 2.0 m diameter, which was covered with fibreglass and galvanised steel as an insulator to ensure that the heat can transfer to the biomass (Idris et al., 2015a). Six exhaust chimneys were connected to a condenser unit to collect wood vinegar. The moisture content of the raw bamboo was 30%, and it took about 42 hr of carbonisation to complete the process of producing biochar. These two studies showed that conventional heating technology with a properly controlled system using heat transfer is capable of reducing ash formation by 1% (Sangsuk et al., 2018); thus, a high biochar yield was obtained.

Therefore, the conventional heating system does not need an electric supply for heating, which could reduce energy consumption (Idris et al., 2015b, 2016). Handling conventional heating systems at an industrial scale is simple and requires minimal maintenance (Salakjani et al., 2019). This conventional heating system is recommended when all of the carbonisation parameters can be effectively controlled, including the system's physical operation, process variables and material characteristics. However, the biochar produced is still influenced by the process control methods, often empirical and based on the kiln operator's experience. To reduce fluctuation due to human operation, conventional heating systems must have a monitoring system to appropriately handle the carbonisation process.

TABLE 2. BIOCHAR PRODUCTION FROM VARIOUS TYPES OF OIL PALM BIOMASS (OPB) USING CONVENTIONAL HEATING TECHNOLOGY

Type of OPB	Reactor type	Carbonisation condition	Biochar yield (%)	HHV (MJ/kg)	Reference
OPEFB	Brick system	600°C, 1.0 hr	10.00–11.00	23.00–25.00	Idris et al. (2015b)
OPEFB	Fix bed reactor	300°C–700°C, 0.3–0.5 hr	25.00–28.00	23.00–26.00	Sukiran et al. (2011)
OPEFB	Muffle furnace	200°C–400°C, 0.5 hr	45.00	29.89	Sugumaran and Seshadri (2009)
OPF	Cylindrical reactor	500°C, 1.0 hr	29.29	-	Lawal et al. (2021)
OPT	Pyrolyser	400°C–550°C, 1.0–3.0 hr	37.00–42.00	17.99	Lim and Lim (1992)
OPT	Cylindrical reactor	550°C	27.80	19.60	Nudri et al. (2020)

Note: OPEFB - oil palm empty fruit bunch; OPF - oil palm frond; OPT - oil palm trunk; HHV - higher heating value.

Microwave Heating Technology

Microwave heating technology has recently gained attention in various industries, especially in AC production. *Table 3* summarises the findings in AC production using microwave heating technology. During carbonisation, microwaves, ionic conduction and dipole rotation convert electromagnetic energy into heat within the material's interior. When a high-frequency electromagnetic wave is applied to the material, heat is generated via orientation fluctuations in the opposite direction (Zhang et al., 2022). The high temperature increases in carbon particles resulted in a faster and more efficient microwave reaction; hence, it has higher potential to improve sustainability. For example, microwave biochar derived from wheat straw using various power levels and an AC catalyst as microwave absorber was investigated for its adsorption properties towards three heavy metals (Pb^{2+} , Cd^{2+} and Cu^{2+}) (Qi et al., 2023, 2024). The study revealed that microwaved biochar had the highest specific surface area ($156.09 \text{ m}^2/\text{g}$) and total pore volume ($0.0790 \text{ cm}^3/\text{g}$) when produced at 600 and 500 W power levels, respectively. This underscored the promising potential of microwaved biochar, produced with an AC catalyst, for efficient heavy metal removal from wastewater.

In conjunction with that, conventional approaches with or without an external electrical supply were pursued, predominantly causing

the carbonisation process to occur more slowly. This situation was due to isothermal holds in preventing thermal gradients at high temperature. This process eventually resulted in a longer time needed and greater energy consumption to produce good quality biochar (Mutsengerere et al., 2019). Despite the need for an external electrical supply, microwave heating offers immediate start-up and shutdown during the process, fewer steps, and lower activation temperature with faster reaction; hence, it has higher potential to reduce energy consumption than conventional heating (Foong et al., 2020). Microwave heating technology could lead to high biochar yield and quality (Yu et al., 2021). This is due to the interaction of electromagnetic waves with molecular material, forming a temperature gradient from the centre of the substance toward its surface. This leads to lower carbonisation duration and less ash than conventional heating technology (Liu et al., 2010a). Jamaluddin et al. (2013) reported that product yield and calorific value can be increased by increasing the microwave power for infiltration towards the biomass material. Besides, volatile matter can be released from the surface more rapidly and forms porous structures at a lower irradiation time in microwave heating technology. In contrast to the microwave technique, a longer processing time (>2 hr) was encountered in conventional heating technology, resulting in the pore structures being damaged (Hesas et al., 2013a). The advantages and disadvantages of microwave and

TABLE 3. BIOCHAR PRODUCTION FROM OIL PALM BIOMASS (OPB) USING MICROWAVE HEATING TECHNOLOGY

Type of biomass	Reactors type	Microwave power (kW)	Retention time (min)	Yield (%)	Biochar characteristics	Reference
OPKS	Microwave reactor	0.3	32.0	60.00	HHV Fixed carbon Volatile matter	29.9 MJ/kg 59.80% 36.40% Jamaluddin et al. (2013)
OPF	Microwave muffle reactor	n/a	0.2-1.4	31.00	Surface area Total pore volume *Avg pore diameter	158-166 m^2/g 0.13-0.14 cm^3/g 110.24-119.47 Å Hossain et al. (2017)
OPKS	Microwave reactor	0.7	25.0	38.00	HHV Moisture content Ash content Surface area	23-26 MJ/kg <3 wt.% 3 wt.% 210 m^2/g Liew et al. (2018)
OPKS OPEFB OPMF	Microwave reactor	0.3	16.7-32.0	34.75 25.80 32.25	HHV HHV HHV	28.75 MJ/kg 27.11 MJ/kg 22.27 MJ/kg Liew et al. (2018)
OPMF	Microwave oven	1.0	n/a	n/a	Surface area Total pore volume	281 m^2/g 0.02 cm^3/g Liew et al. (2018)
OPF	Microwave muffle reactor	0.4-0.9	n/a	28.04	Surface area	260 m^2/g Kundu et al. (2015)

Note: OPKS - oil palm kernel shell; OPF - oil palm frond; OPEFB - oil palm empty fruit bunch; OPMF - oil palm mesocarp fibre; HHV - higher heating value; n/a - not applicable.

conventional heating technology depended mainly on the type of reactors used, biomass characteristics and the overall operational cost, as summarised in Figure 3.

The operational and capital expenditure for setting up a microwave heating technology facility is more expensive than conventional heating technology (Figure 3). The commercial 2.450 GHz microwave uses 30 kW magnetrons and 0.915 GHz generators that provide up to 100 kW from a single magnetron. The frequencies for industrial microwaves for biochar production are 0.915, 2.450, 5.800 and 24.124 GHz, whereby 2.450 GHz is commonly used in the industry (Ao et al., 2018). A single small microwave power magnetron is typically inexpensive. However, the cost rises as the magnetron's capacity increases. Therefore, multiple magnetrons in microwave heating systems are commonly used by industries (Ao et al., 2018). Despite the high capital investment, industries are choosing microwave systems over conventional heating systems due to the lower operating conditions, which result in lower operational costs (Mutsengerere et al., 2019).

Higher yield could be obtained using materials such as OPKS than OPEFB and OPF. Material that could generate higher product yield and quality is preferable for microwave heating technology. Reactors built using high-quality stainless steel are needed for a microwave system to adapt to high power radiation and pressure to avoid explosions during the operating process (Zaini & Kamaruddin, 2013). High frequency is

required during penetration of microwave radiation depending on the density and moisture content of the raw materials (Ao et al., 2018). According to Mutyalu et al. (2010), microwave frequencies of 0.915 and 2.450 GHz as preferred in laboratory scale due to their excellent availability and good penetration depth under laboratory conditions. Microwave heating is a mature technology for the preparation of biochar. However, more research is required for biochar production, especially on a large or commercial scale. Several factors, such as chemical and reagents, physical agents, raw materials and magnetron sensitivity dielectric properties, must be optimised before reactor design and process scale-up (Su et al., 2022).

Hydrothermal Heating Technology

Hydrothermal carbonisation is a thermochemical conversion technique that requires carbonisation decomposition temperature between 150°C-350°C (Falco et al., 2012; Liu et al., 2010b; Sevilla et al., 2011; Titirici et al., 2012). This process needs subcritical water at 2-10 MPa saturated pressure and takes a few hours to convert biomass to biochar (Shen, 2020). Hydrothermal carbonisation could produce hydrochar with great oxygenated functional group (OFG), which is suitable for chemical activation to produce AC (Sevilla et al., 2011). OPB with high moisture content is also suitable for carbonisation using hydrothermal heating technology as it can be operated in wet conditions

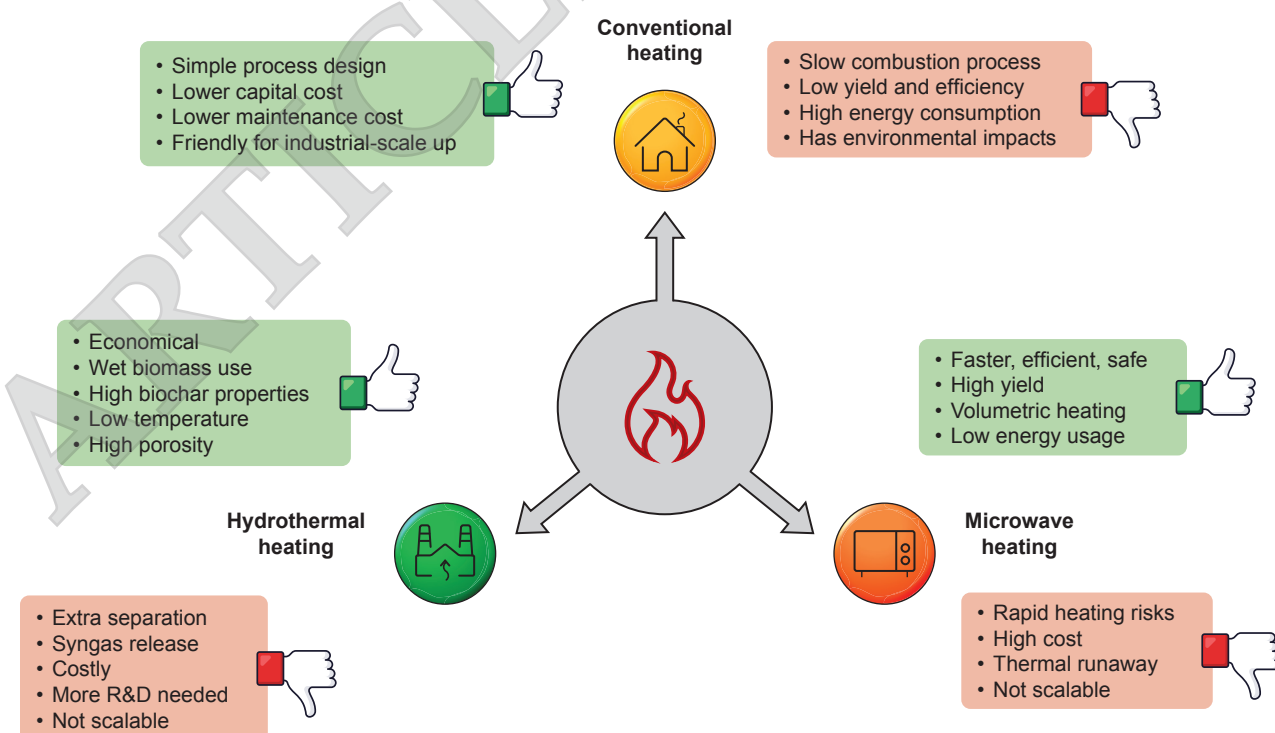


Figure 3. Benefits and drawbacks of biochar production between conventional, microwave and hydrothermal heating technology.

(Zhang et al., 2010). Water used in the treatment serves as a reaction medium and reactant for biomass, mainly hemicellulose decomposition while retaining cellulose and lignin composition in biochar production. Other biomass materials such as corn (Mbarki et al., 2019), wood (Sun et al., 2018), wheat straw (Xing et al., 2019), hazelnut shell, garlic peel and pineapple waste (Zhu et al., 2019) have been used for biochar production using hydrothermal heating technology. Hydrothermal carbonisation does not produce smoke, thus hindering the emission of hazardous syngas compared to conventional and microwave heating technology (Zhang et al., 2014).

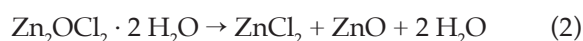
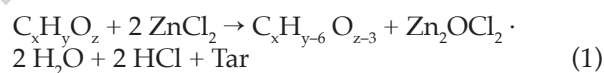
Hydrothermal carbonisation breaks down the lignin, hemicellulose and cellulose in biomass into smaller and simpler molecules by thermal degradation (Yuliansyah et al., 2019). Some degraded particles are dissolved into the liquid medium while the rest form gas. Calorific value is important for fuel consumption in high-quality hydrochar. A fundamental step in characterising hydrochar is by performing elemental analysis to determine the carbon (C), hydrogen (H) and oxygen (O) content. This allows for the calculation of O/C and H/C molar ratios used in the Van Krevelen diagram. The HTC process facilitates dehydration and decarboxylation reactions, reducing H/C and O/C ratios and making the hydrochar properties more similar to coal (Fang et al., 2018; Soh et al., 2022). According to Yuliansyah et al. (2019), OPB containing high lignin content will get higher C and lower O content. Therefore, the hydrochar produced will possess a higher calorific value. In this case, OPKS and OPMF had the highest lignin content compared to other OPBs, making them suitable for producing high-quality hydrochar. The increase in the C content of OPKS is due to decarboxylation and dehydration reactions during the hydrothermal process (Nizamuddin et al., 2015). These observations have also been documented in other studies for hydrochar produced from OPEFB by hydrothermal (Jamari & Howse, 2012; Parshetti et al., 2013).

OPEFB carbonised using hydrothermal technology at 180°C, 200°C and 220°C for 30 min holding time had improved calorific value. However, this material should be washed to remove potassium (K) before carbonisation to improve the quality, performance and utility of the resulting hydrochar (Ruksathamcharoen et al., 2018). Findings showed that the calorific value of OPEFB hydrochar improved from 16.69 MJ/kg (without washing) to 18.49 MJ/kg (with washing) (Nurdiawati et al., 2015). Although hydrothermal heating technology looked promising in converting OPB into biochar, this technology has not yet been applied in the industry, largely due to insufficient technical validation and limited scale-up studies (Figure 3).

ACTIVATION TECHNOLOGIES

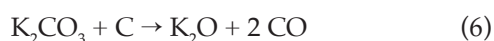
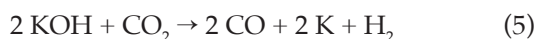
Chemical Activation

Chemical activation requires impregnating a chemical reagent in the substance before or after the carbonisation process. A chemical reagent is applied to dehydrate and remove dirt and tars in the biomass material. Both alkaline and acidic groups of chemical reagents such as phosphoric acid (H_3PO_4), potassium carbonate (K_2CO_3), potassium hydroxide (KOH) and sulphuric acid (H_2SO_4) are usually used for the chemical activation process (Tetteh et al., 2024). Different chemical reagents will react differently with the biomass material, affecting AC's yield, surface area and pore development. In a study by Hesas et al. (2013b), OPKS-AC with high pore volume and surface area was produced when using zinc chloride ($ZnCl_2$) as a dehydrating agent with 560 W microwave power and a radiation time of 9 min. $ZnCl_2$ is an effective dehydrating agent that can inhibit the production of tar and other undesirable liquid byproducts that obstruct the pores formed. $ZnCl_2$ may also accelerate the evaporation of volatile substances from the carbon matrix, increase porosity, hence improve adsorptive properties. The mechanism of $ZnCl_2$ is as Equation (1) and (2) (El-Nemr et al., 2022; Ma, 2017):



The main drawback of applying $ZnCl_2$ as an activating agent is corrosion, and unsuitability for use in the medical and nutritional industry due to health and pollution issues (Naji & Tye, 2022). Meanwhile, KOH activation is extensively studied for its ability to generate high microporous structures and functional groups on carbon surfaces. Introduction of potassium a strong base, facilitates dehydrogenation and carbon oxidation at elevated temperatures, leading to carbon decomposition, tar suppression and increased pore formation (Naji & Tye, 2022). The impregnation of KOH yielded AC with surface areas ranging from 1,272–1,597 m^2/g (Oginni et al., 2019). Nevertheless, the AC's porous structure remained unchanged due to the decomposition of lignin during biochar production and the difficulty for KOH to penetrate the fibrous structure. The morphology of the biomass could be maintained by lignin in biochar, but it was obliterated by KOH during the impregnation stage (Oh et al., 2003). Although highly microporous AC can be produced using KOH, the KOH itself can

be harmful causing severe gastrointestinal issues, up to fatality (Hui & Zaini, 2015). The mechanisms of chemical activation using KOH, include the following Equation (3) to (7) (Bergna et al., 2018; El-Nemr et al., 2022; Fuertes et al., 2018):



Chemical activation generally produces AC with high yield and porosity at relatively low temperatures. Essential criteria that must be considered when using this activating agent include environmental issues, especially water pollution and how the generated AC will be used. Recycling the chemicals could reduce operational costs, minimise consumption and reduce the environmental impact. AC produced from OPB using a chemical activation agent has been widely reported (Table 4). A study on the effectiveness of two chemical activating agents (H_3PO_4 and ZnCl_2) in producing OPKS-AC has been conducted by Arami-Niya et al. (2011). Combining a physical agent with H_3PO_4 activating agent led to a better activation rate of 8.86% burn-off hr^{-1} than ZnCl_2 at 2.2% burn-off hr^{-1} . This study also showed that H_3PO_4 could lead to OPKS-AC with a higher micropore volume and surface area than ZnCl_2 .

TABLE 4. APPLICATIONS, CHARACTERISTICS AND CONDITIONS OF OIL PALM BIOMASS-ACTIVATED CARBON (OPB-AC) PRODUCED FROM VARIOUS CHEMICAL ACTIVATION AGENTS

OPB	Chemical reagent	Carbonisation condition	Activation condition	Surface area	Pollutant removal	Reference
OPKS	KOH	400°C	Thermally at 600°C	n/a	Removal of polycyclic aromatic hydrocarbon	Kumar et al. (2019)
OPEFB	KOH	700°C, 2 hr	900°C, 2–6 hr	707.79	n/a	Wei et al. (2016)
OPEFB	KOH	700°C	Microwave (350 W), 15 min	807.54	Methylene blue	Foo and Hameed (2011)
OPKS	KOH	600°C–700°C, 1 hr	850°C, 1 hr	1,890.00	CO ₂ capture	Ello et al. (2013)
OPEFB	KOH	-	800°C, 2 hr	663.00	n/a	Khalil et al. (2013)
OPKS	KOH	-	Microwave (0–1,400 W)	1,196.00–1,630.00	CO ₂ capture	Hesas et al. (2015)
OPKS	KOH/ H_3PO_4	-	800°C	490.00–810.00	Carboxylic acid	Ruiz et al. (2015)
OPKS	H_3PO_4	-	Microwave (350 W)	630.00	n/a	Yacob et al. (2013)
OPKS	ZnCl_2	-	Microwave (1,050 W)	1,672.00–1,195.00	n/a	Hesas et al. (2013a)
OPKS	ZnCl_2	-	500°C, 1 hr	1,253.50	Bisphenol A	Wirasnita et al. (2014)
OPF	KOH	700°C, 2 hr	750°C, 2 hr	1237.13	Pesticides: Bentazon, carbofuran and 2,4-D	Salman (2014)
OPF	KOH	700°C, 2 hr	850°C, 2 hr	n/a	Removal of 2,4 D	Salman et al. (2011)
OPF	Na_2CO_3 and NaCl	-	400°C–600°C, 1 hr	Iodine number = 888.51 mg/g	n/a	Maulina et al. (2020)
OPT	H_3PO_4	-	450°C, 6 min	1,657.00	Removal of tannin	Lim et al. (2020)
OPT	H_2SO_4	250°C, 1 hr	900°C, 1.5 hr	1,800.00	Removal of Cr (VI)	Lin et al. (2020)
OPT	H_3PO_4	200°C, 1 hr	-	Iodine number = 761.02 mg/g	n/a	Jaya and Khair (2020)

Note: OPB - oil palm biomass; OPKS - oil palm kernel shell; OPF - oil palm frond; OPEFB - oil palm empty fruit bunch; OPT - oil palm trunk; KOH - potassium hydroxide; H_3PO_4 - phosphoric acid; ZnCl_2 - zinc chloride; NaCl - sodium chloride; H_2SO_4 - sulphuric acid; n/a - not available.

Physical Activation

Physical activation is another typical process to activate the resulting biochar into high-quality AC (Rugayah et al., 2014). The physical activation stage eliminates the tars to increase the size of existing pores for better adsorption efficiency. This process must be conducted at high temperature between 700°C–1,000°C in the presence of gaseous substances (viz. steam, nitrogen [N₂], carbon dioxide [CO₂] or argon [Ar]). This process will eliminate volatile matter and create a reaction mechanism between carbonaceous and gaseous substances, forming AC pores (Kaithwas et al., 2012). Chemical activation can produce AC with a higher surface area (Table 4) than physical activation (Table 5). Surface area of AC (~1,000 m²/g) produced through physical activation is still acceptable for industrial application (Hidayu & Muda, 2016). Besides, physical activation is more environmentally friendly and requires less chemical usage during the process, thus preventing machinery from corrosion caused by chemical activating agents. The AC produced is also free from chemical activating agent; thus, no post-treatment is required. A comparison between chemical and physical activation is shown in Figure 4.

Technically, the high quality and yield of AC depended on the efficiency of the activation process. The most important parameter for physical activation is temperature (Fu et al., 2011). High temperature and low reaction time are needed to promote the pore structure evolution in the treated AC (Oluoti et al., 2016). This is because biomass contains 75%-85% volatile matter; thus, a higher heating rate may aid in the faster release of volatiles (Wu et al., 2019). Another crucial factor in promoting the activation process is the application of an activating agent. Steam and CO₂ are widely used due to their excellent diffusion properties (Diedhiou et al., 2019). Since oxygen (O₂) reacts faster with C than vapour and CO₂, adding O₂ as an activation agent is more effective in reducing activation time (Zhang et al., 2016). However, using O₂ alone could pose a high risk of surface burn-off. Therefore, a mixture of O₂ and steam can increase the reactivity and enhance the diffusion capacity of O₂ and vapour, respectively.

Mechanisms of physical activation using steam as Equation (8) to (10):



TABLE 5. CONDITION AND CHARACTERISTICS OF OIL PALM BIOMASS-ACTIVATED CARBON (OPB-AC) PRODUCED FROM VARIOUS PHYSICAL ACTIVATION AGENTS

OPB	Physical treatment	Carbonisation condition	Activation condition	Surface area (m ² /g)	Pore volume (cm ³ /g)	Pore diameter (nm)	Reference
OPKS	Steam	400°C, 3 hr	500°C–1,000°C, 4 hr	935.0	n/a	n/a	Nahrul Hayawin et al. (2018)
OPEFB	CO ₂	700°C, 2 hr	900°C, 30 min	937.0	0.28	2.00	Abd Wafti et al. (2017)
OPKS	CO ₂	479°C–555°C, 30–197 min	900°C, 3 hr	807.0	0.38	n/a	Choi et al. (2015)
OPKS	Steam	25°C–1,000°C, 8 days	900°C–1,000°C, 12 hr	607.0	0.25	n/a	Rugayah et al. (2014)
OPEFB	Ar	700°C, n/a	700°C, 1 hr	823.0	0.98	4.20	Tobi et al. (2019)
OPEFB	Steam	n/a	765°C, 77 min	720.0	0.34	1.89	Hidayu et al. (2013)
OPEFB	Steam	600°C–900°C, 30 min	900°C, 15 min	603.7	0.34	4.00	Alkhatib et al. (2011)
OPEFB	Steam and CO ₂	n/a	900°C, 15 min	635.1	n/a	n/a	Amosa et al. (2014)
OPEFB	CO ₂	250°C–400°C, 1–2 hr	900°C, 1 hr	632.0	0.26	n/a	Lee et al. (2014)
OPKS	CO ₂	500°C–700°C, 1 hr	700°C, 1 hr	905.0	0.66	n/a	Herawan et al. (2013)
OPKS	CO ₂	900°C, 1 hr	850°C, 1–7 hr	1,213.0	0.66	2.13	Arami-Niya et al. (2011)

Note: OPB - oil palm biomass; OPKS - oil palm kernel shell; OPEFB - oil palm empty fruit bunch; CO₂ - carbon dioxide; Ar - argon; n/a - not available.

	Physical	Chemical
Process	Two-step carbonisation and activation; one-step carbonisation-activation; activating agent steam, CO ₂ , N ₂ , Ar	Two-step carbonisation and activation; one-step carbonisation-activation; activating agent alkali/acidic group
Advantages	Low chemical use; not corrosive; inexpensive; no environmental impact	Low temperature; high yield; high quality AC; shorter time; low energy consumption
Disadvantages	High energy usage; time-consuming; high operational cost; low-quality AC	Corrosive; high environmental impact; expensive; high chemical consumption; pre-treatment needed
Solution	Combining a single-step process would require less the raw material, operating process and maintenance costs	Combining physical and chemical activation methods to reduce chemical consumption for better quality of AC at one-stage activation process
Reference	Álvarez et al. (2004); Nahrul Hayawin et al. (2018); Rugayah et al. (2014); Yun et al., (2000)	Azevedo et al. (2007); Lua and Yang (2005); Ozdemir et al. (2014)

Figure 4. Benefits and drawbacks of chemical and physical activation methods for activated carbon (AC) production.

The process commenced by generating C-H surface developments, which have higher stability than C-O, thereby significantly restraining the reaction. The diverse characteristics of activation resulted from the effective balancing of these surface developments (Bergna et al., 2019). The mechanism for physical activation with CO₂ is as Equation (11) to (13):



Results from the economic feasibility of OPB production from chemical and physical activation in a pilot scale evaluation showed that physical activation, particularly by steam, had the lowest production cost at USD2.72/kg AC, which was significantly lower than the coal or coconut shell-based ACs market price of USD3.30/kg (Lai & Ngu, 2020; Ng et al., 2003). Coal and coconut shell-derived AC are two major commercial AC products

in the market. Hence, these OPB-ACs have the potential to be commercialised and compete with existing coal- and coconut-shell-derived ACs in a tailor-made industrial application. Besides that, the undersupply of coconut shell raw material has caused a surge in coconut shell-derived AC market prices due to the increasing demand for AC worldwide. Thus, the OPB-AC could offer a highly efficient adsorbent alternative to cater to the growing AC demand. Production cost of AC through chemical activation varies depending on the cost of the chemical used during the activation process, which is still lower in comparison to coal and coconut-shell-derived AC selling prices (Table 6). It was estimated that OPB-AC production at physical and chemical activation technology requires a total fixed capital investment of USD2.12 million and USD6.32 million, respectively. The annual operating cost for physical activation is estimated to be lower than the chemical activation cost at USD1.53 and USD2.57, respectively. Hence, physical activation is more economical than chemical activation (Lai & Ngu, 2020). This pilot scale study showed that OPB-AC has a relatively lower price than the ceiling price of coal and coconut shell-based AC; hence, OPB-AC can be an alternative in the AC industry to cater to the ever-growing market demand for AC in the future.

TABLE 6. COST OF PRODUCT (USD/KG) OF OPB-AC PRODUCED THROUGH CHEMICAL AND PHYSICAL ACTIVATION TECHNOLOGY

Activation technology	Agent	Product cost (USD/KG)	Reference
Chemical	H ₃ PO ₄	3.22	Lai and Ngu (2020)
	H ₂ SO ₄	2.98	
	ZnCl ₂	3.24	
	KOH	2.93	
	K ₂ CO ₃	2.97	
	NaOH	3.04	
Physical	Steam	2.72	
	CO ₂	2.73	
Commercialised AC (Coal and coconut shell)	N/A	3.30	Ng et al. (2003)

Note: KOH - potassium hydroxide; H₃PO₄ - phosphoric acid; ZnCl₂ - zinc chloride; H₂SO₄ - sulphuric acid; NaOH - sodium hydroxide; K₂CO₃ - potassium carbonate; CO₂ - carbon dioxide; N/A - not applicable; OPB-AC - oil palm biomass-activated carbon.

Integrating Carbonisation-activation Technology

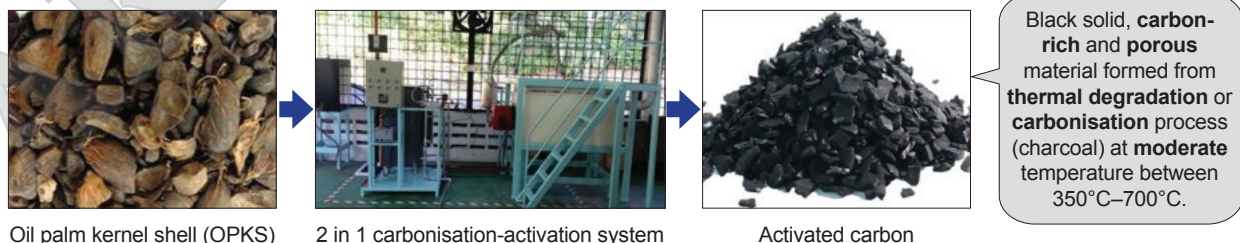
Integrated carbonisation-activation technology has been introduced to solve problems associated with carbonisation followed by activation technology, such as a longer processing time, many stages, additional workload to transfer the carbonised material into the activating

chamber and low yield due to weight loss during operation. In a one-step carbonisation-activation process, the feedstock will undergo pyrolysis and activation simultaneously in the furnace to produce AC directly without halting the process post-carbonisation to collect biochar before proceeding with activation (Demir & Doguscu, 2022). Meanwhile, the common carbonisation-activation involves carbonisation at the feedstock, whereby the biochar will then be collected and dried post-carbonisation before the activation process to produce AC (Kan et al., 2016). A study by Nahrul Hayawin et al. (2018) found that a one-step physical activation process produced 30% more yield than a two-step process with low gaseous emission, and increased biomass surface area from 305 to 935 m²/g within a seven-hour retention time (Figure 5). The carbonisation and activation processes of OPKS were carried out continuously without stopping the operation. The system was also enhanced by modifying the reactor to a double layer to enable efficient heat transfer into the bed and avoid heat loss during the process. A mixture of steam and O₂ as activation agents was applied to this system during the activation process. With a temperature range between 950°C-990°C, the one-step physical activation process was completed within a short treatment time. The integrated system could minimise the cost of production, energy, human effort and time, without compromising the quality and yield of AC produced as well as preventing the use of chemical activation agent. Using chemical activating agents in a one-step process at a lower temperature would benefit from lower energy consumption while producing AC with higher porosity, surface area and yield than physical activation. However, a few requirements must be addressed, as chemical activating agents may lead to environmental problems, particularly water contamination (Nahrul Hayawin et al., 2018). Table 7 lists the studies that have been conducted using either one or

two-step physical/chemical activation processes in conventional heating technology for the production of OPB-AC.

As one-step carbonisation-activation technology is still new; thus, there is very limited literature on the production of AC at a pilot scale. Li et al. (2009) produced AC coconut shell using a pilot-scale microwave tubular reactor. The AC was prepared using a water-cooled assembly of 60 magnetrons (2.45 GHz) with 1 kW power each and steam as the activating agent. The AC produced had a Brunauer-Emmett-Teller (BET) surface area of 891.0 m²/g, higher than the 671.0 m²/g of commercial coconut-based AC. Lin et al. (2012) conducted a similar pilot scale study to produce AC from sewage sludge in a microwave. Sewage sludge was dried in a stirred tank reactor using 12 magnetrons cooled water at 2.45 GHz and 0.8 kW. Chemical activating agents (KOH, ZnCl₂, H₃PO₄) were used as activating agents, and the BET surface area of the resulting AC was 130.7 m²/g (with KOH as activating agent). The temperature of the microwave reactor was maintained in both studies using closed-loop temperature control with microwave power as the manipulated variable.

Several author applied a one-step activation method to OPB with steam and CO₂, for AC preparations resulted in excellent AC properties (Alkhatib et al., 2011; Herawan et al., 2013; Lee et al., 2014). According to Şentorun-Shalaby et al. (2006), steam is the most common physical activating agent in a one-step process. The steam functions in widening microporosity to mesoporosity. Steam activation can lead to a higher surface area in a shorter time, depending on the types of reactors. The brick heating reactor usually takes longer treatment time than when a stainless-steel furnace is used. One-step physical activation could deliver lower impact than one-step chemical activation (Rashidi & Yusup, 2017). Moreover, the treatment time of the overall process using one-step physical activation is comparable to one-step chemical activation in



MPOB technology for the production of charcoal and activated carbon from oil palm biomass

*Carbonisation-activation system can be installed at the mill using excess energy and steam available to reduce effluent treatment cost

Source: Nahrul Hayawin et al. (2018)

Figure 5. Carbonisation-activation system for producing high-yield AC from OPKS.

TABLE 7. DIFFERENT PROCESS PARAMETERS OF CONVENTIONAL HEATING TECHNOLOGY FOR THE PRODUCTION OF OIL PALM BIOMASS-ACTIVATED CARBON (OPB-AC)

Process	Type of reactor	Carbonisation-activation temperature (°C)	Duration (hr)	Physical/chemical treatment	Surface area (m ² /g)	Reference
One-step chemical activation	Fluidisation chamber	600	n/a	KOH	430	Kumar et al. (2019)
	Furnace	n/a	2	KOH	1,028	Gopal (2015)
	Furnace	800	2	KOH	1,212	Khalil et al. (2013)
	Furnace	800	24	H ₃ PO ₄ /KOH	784	Ruiz et al. (2015)
	Furnace	500	2	ZnCl ₂	1,504	Hesas et al. (2013a)
	Furnace	500	1	ZnCl ₂	86.62	Wirasnita et al. (2014)
One-step physical activation	Heating reactor	400, 900	7	Steam	935	Nahrul Hayawin et al. (2018)
	Fixed bed reactor	500, 950	5	CO ₂	807	Choi et al. (2015)
	Furnace	700	1	Ar	592–823	Tobi et al. (2019)
	Furnace	900	1	Steam	635.16	Alkhatib et al. (2011)
	Furnace	900	1	CO ₂	928	Lee et al. (2014)
	Furnace	700	2	CO ₂	905	Herawan et al. (2013)
Two-step chemical activation	Furnace	700, 900	2	CO ₂	937	Abd Wafti et al. (2017)
	Vertical tubular reactor/ microwave oven	700	5 min	KOH	474	Nor Faizah et al. (2016)
	Furnace	600, 700, 850	2	KOH	1,890	Ello et al. (2013)
	Closed-system brick kiln/ rotary kiln	1,000	192 (8 days)	Steam	607.76	Rugayah et al. (2014)
	Stainless steel reactor	765	1.15	Steam	720	Hidayu et al. (2013)
	Furnace	900	n/a	CO ₂	635.16	Amosa et al. (2014)

Note: KOH - potassium hydroxide; H₃PO₄ - phosphoric acid; ZnCl₂ - zinc chloride; CO₂ - carbon dioxide; Ar - argon.

producing AC of similar quality. Unlike one-step chemical activation, a one-step physical activation process hinders liquid discharge that demands further effluent treatment. Therefore, this process is considered a green technique and can be developed on a larger scale (Xu et al., 2022).

The main benefits of microwave heating over conventional heating are lower regeneration costs for AC production, faster activation (e.g., 20 min) and lower pyrolysis time. Electricity consumption for one-step microwave activation can be predicted if the mass of the sample, radiation duration, and microwave power level are known. For instance, at a 1.5 g/g impregnation ratio, 3.0 g of dried siris seed pods were combined with 20 mL of K₂CO₃ solution. After drying, the sample was subjected to irradiation at 540 W microwave within a quartz reactor for 8 min. With 70% conversion efficiency from electricity to microwave energy, the electricity usage for each tonne of dried biomass was 34,000 kWh (Ahmed & Theydan, 2013). Study by Foo and Hameed (2012) showed that in a muffle furnace, 500 g dry raw materials were carbonised at 700°C with a 150 mL/min N₂ flow rate, yielding 43.17 wt.% char. 200 kWh of electricity were used

for each tonne of dried biomass (or 469 kWh for each tonne of char) in a glass reactor activated with 600 W microwave for 7-min. The two-step processes resulted in higher electricity consumption in simultaneous carbonisation and activation in a single reactor.

Simulation from laboratory scale showed that production of 1 kg AC using microwave heating costs about USD32.43 compared to USD70.67 with conventional heating (Puchana-Rosero et al., 2016). This showed that microwave heating offers good potential to minimise the total cost of OPKS-AC for future mass production. Total expenses must be lower than the market price of the products for profit. The electricity used could be reduced to minimise the cost of microwave heating production (Liew et al., 2018). This could be accomplished by installing a power generator capable of supplying sufficient electricity to partially or fully cater to the microwave pyrolysis operation. The electricity generator will utilise solid fuel (e.g., biochar). Certain amount of biochar produced from the carbonisation process may serve as feedstock for power generation, thereby substantially decreasing the use of total electricity.

Technical readiness level (TRL) is a point-based methodology for assessing the maturity of technology from concept to commercialisation. It is categorised into nine categories, ranging from generation to full industrialisation, using a point-based system from 1–9. TRL 4–5–6 (lab-pilot scale) and 7–8–9 (industrialisation/commercialisation) were separated into three stages (Yang et al., 2012b). Conventional heating technology is well-positioned and has reached a high technical maturity for biochar production at pilot and commercial scales. Thus, the TRL of conventional heating technology is now within 8–9. A new patent for AC manufacturing from nuts using microwave heating has a TRL of 5.

APPLICATIONS AND DEMANDS OF OIL PALM BIOMASS-ACTIVATED CARBON (OPB-AC)

AC is an excellent adsorbent material due to its high pore volume and surface area. Generally, AC is the most appropriate and effective solution for treating polluted water and wastewater. AC can adsorb unwanted components and toxic substances such as heavy metals and organic contaminants into water systems. AC is also widely used to remove inorganic and organic water-solubles from municipal and industrial wastewater, such as dyes, pharmaceuticals, cosmetics, palm oil mill industry and chemical manufacturing. Bhatnagar et al. (2013) reported that the extensive application of carbon adsorbents in environmental protection is attributable to their substantial surface area and pore structures, comprising macropores (>50 nm), mesopores (2–50 nm) and micropores (<2 nm). The molecular size of liquid pollutants is significantly larger than gaseous pollutants, making the microporous adsorbent suitable for gas-phase applications. In contrast, mesoporous carbon is used for liquid-phase adsorption. Mesoporous OPKS-AC activated via steam could sufficiently adsorb and reduce the concentration of total suspended solids (TSS), COD, BOD and colour up to 80%–98% in palm oil mill effluent (POME) final discharge (Nahrul Hayawin et al., 2018). Those characteristics have met the standard limit requirements imposed by the Malaysian Department of Environmental (DOE) and the Government of Indonesia Standard Limit, i.e., 40 g/L of bioadsorbent dosage when applying OPKS-AC. Compared to liquid-phase applications, AC in gas-phase applications must have higher density, larger particles, higher adsorptive capacity per unit volume and well-developed microporosity (Table 8). Other qualities required for gas adsorbing AC include the ability to adsorb gases in moist

media and a large surface area (1,000–2,000 m²/g) (Kayiwa et al., 2021). Microporous AC is suitable for gas-phase adsorption due to the small molecular size of these gas pollutants (0.4–0.9 nm).

AC produced from OPB has been utilised for hydrogen storage instead of being used to absorb gas and liquid pollutants due to its physicochemical properties such as excellent kinetics in discharging hydrogen, high surface area (1,500–3,800 m²/g), lightweight and good thermochemical stability. Microporous AC is suitable for hydrogen storage (Yang et al., 2012a). Studies have shown the application of AC in a supercapacitor system. AC is ideal as supercapacitor due to its capability in rapid energy charging and prolonged storage (Ajay & Dinesh, 2021; Yang et al., 2014).

OPKS-AC is extensively utilised in several environmental pollution management technologies due to its excellent adsorption efficacy and cost-effectiveness. However, limited studies have been conducted on the properties and applications of OPKS-AC in adsorption air-conditioning systems. Recent study highlighted the potential of advancements in adsorption technology for automobile air-conditioning. This technology could be viable with enhancements to overcome current restrictions. Utilisation of chemical-free refrigerants in adsorption air-conditioning systems diminished the generation of ozone-depleting compounds, making it an environmentally friendly option worth serious consideration for automobiles (Abdullaha et al., 2011).

With a size ranging from 4–9 Å, gas molecules are well-suited for microporous AC in gas-phase applications. AC with mesopores is necessary for effective use in liquid applications since liquid molecules are larger than gas molecules. Porous materials in environmental preservation are crucial for the collection of gaseous pollutants such as NO₂ and SO₂. OPF was used to absorb SO₂ gas (Iberahim et al., 2022). Preparation of OPF biochar and activated biochar was optimised, in which OPF-activated biochar was found to be a better adsorbent than OPF biochar. OPF-activated biochar produced at 753°C, 73 min activation time and 497 mL/min CO₂ had the highest SO₂ adsorption capacity (33.09 mg/g). OPF pyrolysed at 450°C, 12°C/min heating rate, and 98 min holding time had the adsorption capacity of 18.62 mg/g (Iberahim et al., 2022).

Cruz Jr. et al. (2024) produced AC from Amazonian biomass with microwave-assisted hydrothermal carbonisation and CO₂ activation. The specific surface areas and pore volumes of AC produced ranged from 0.35 to 0.50 cm³/g and 840 to 1,096 m²/g, respectively. Their high selectivity for CO₂/CH₄, combined with large surface areas and narrow micropores, allowed for effective methane adsorption. The study found that the AC has a

notable methane capture capacity of 150 V/V at 40 bar pressures and a CH_4/CO_2 selectivity of 0.49 up to 1 bar.

Functional groups, large surface area and high porosity in AC are all related to materials and activation methods. The chemical and physical properties of AC have a significant impact on their adsorptive abilities. *Table 8* summarises the applications of AC produced from various types of biomass.

CONCLUSIONS AND FUTURE OUTLOOKS

As OPB is abundantly available throughout the year with consistent supply and cost-efficient transportation of raw materials, it is a promising candidate as a raw material to produce AC from renewable sources. Microwave heating has higher efficiency and uniform heating, resulting in superior char properties compared to traditional heating for carbonisation. Traditional heating methods, while widely used due to their simplicity and scalability, are often energy-intensive and less efficient. However, should microwave heating technology be upgraded to pilot or commercial scale, factors such as overall cost and some technical problems need to be addressed.

Hydrothermal heating offers a unique advantage by operating in a water-based medium, enabling the conversion of biomass into char at moderate temperatures. However, it requires

further optimisation for cost-effectiveness and scalability. To enhance the feasibility of microwave and hydrothermal technologies for large-scale AC production, future research should focus on optimising energy study, improving process design and conducting detailed cost-benefit analyses. The techniques and processes used for biomass carbonisation and activation must be well-designed to be economic and environmentally friendly.

The cost of materials and apparatus is high in the two-step process for carbonisation and activation. It is also time and energy-consuming with low AC yield. In contrast, one-step or integrated process is a more efficient and stimulating method for AC production due to low energy usage and processing cost with short retention time. However, the assessment of the AC produced via a one-step process at a commercial scale is limited. Therefore, further research should be conducted to prove the efficiency and practicality of the integrated technology for the production of AC.

There might be a shortage of AC supply, depending on its production and usage. AC will become saturated quickly when applied in wastewater treatment. Therefore, existing wastewater treatment in the mill could be combined into two integrated systems. The AC consumption, operation and maintenance costs could be reduced when using this integrated system.

TABLE 8. PROPERTIES OF VARIOUS TYPES OF BIOMASS ACTIVATED CARBON (AC) FOR VARIOUS APPLICATIONS

Biomass	Treatment	Sorption adsorbates and findings	Efficacy	Reference
Oil palm decanter cake	Carbonised at 700°C, activated using steam at 700°C	Copper (Cu (II)), lead (Pb (II)) and zinc (Zn (II)) Surface area: 153.52 m ² /g	45.01 mg/g Cu (II), 128.51 mg/g Pb (II) and 39.21 mg/g Zn (II) (maximum adsorption capacity)	Yusoff et al. (2019)
Coconut shell	Carbonised and activated with sulphuric acid (1:1) at 200°C for 24 hr.	Cadmium (Cd), chromium (Cr) and lead (Pb) removal Iodine number: 558 mg/g Bulk density: 0.53 g/mL	Reduce heavy metal accumulation on <i>Salvinia cucullate</i> 32% Cd, 21% Cr and 34% Pb removal efficiency	Irshad et al. (2024)
OPMF	Impregnated with ZnCl ₂	Removal of acetaminophen (ACE), cephalexin (CPX) and valsartan (VAL) Surface area: 76.05 m ² /g Carboxylic groups: 1.343 mmol/g	Maximum uptake: 7.30 mg/g ACE, 7.90 mg/g CPX and 23.85 mg/g VAL	Grisales-Cifuentes et al. (2021)

TABLE 8. PROPERTIES OF VARIOUS TYPES OF BIOMASS ACTIVATED CARBON (AC) FOR VARIOUS APPLICATIONS (continued)

Biomass	Treatment	Sorption adsorbates and findings	Efficacy	Reference
OPKS	Carbonised at 650°C with acid washing, K ₂ CO ₃	Phosphate (PO ₄ ³⁻) and ammonium (NH ₄ ⁺) adsorption Surface area: 253 m ² /g	1.49 mg/g NH ₄ ⁺ and 0.89 mg/g PO ₄ ³⁻	Munar-Florez et al. (2021)
OPKS	Microwave activation temperature at 550°C	Removal of methylene blue Surface area: 570.8 m ² /g Micropore: 763.1 m ² /g	Remove 38.5 mg of methylene blue	Yek et al. (2019)
OPF	Carbonised at 500°C	Adsorption of phenol and tannic acid Surface area: 422 m ² /g	62.89 mg/g phenol and 67.41 mg/g tannic acid	Lawal et al. (2021)
Bottom ash	Activated at 625°C, 30 min, 10°C-15°C/min ramp rates	CO ₂ uptake Surface area: 643.6 m ² /g	1.29 mmol/g at 50°C	Gorbounov et al. (2024)
OPKS	One-step activation at 850°C	CO ₂ uptake	CO ₂ adsorption capacity of 2.13 mmol/g and product yield of 25.15 wt.%	Rashidi and Yusup (2019)
Resin-based AC	Conducted in a continuous-flow fixed-bed.	Volatile organic compounds (VOCs), carbon disulfide (CS ₂) and odour Micropores <0.71 nm influenced CS ₂ adsorption Micropores <2.00 nm influenced toluene adsorption	CS ₂ adsorption 24.8 mg/g and toluene adsorption 521.0 mg/g	Guo et al. (2024)
Malt bagasse	Impregnation of KOH solution, followed by calcination (catalyst)	Heterogeneous catalysis for biodiesel production Surface area: 2.495 and 1.140 m ² /g	Biodiesel yield: 91.8 ± 1.0%, 1:12 oil/ethanol molar ratio and 2 hr reaction time.	Ali et al. (2024)
Avocado	<i>Persea americana</i> leaf-derived natural oxygen (O), magnesium (Mg) and calcium (Ca) self-doped activated carbon Carbonised and activated at 850°C.	High-performance symmetric supercapacitors Surface area: 875.77 m ² /g Rich natural O, Mg and Ca heteroatoms composition	Gravimetric capacitance of 209 F/g at 1 A/g. Energy density of 28.4 Wh/kg at power density 135.5 W/kg.	Armynah et al. (2024)
OPF	Carbonised at 700°C and activate at 700°C with nitrogen (N ₂) at 5 L/min flow rate	Supercapacitor	1.92 Wh/kg energy and 50.00 W/kg power density	Tobi et al. (2021)
OPKS	Carbonised at 500°C and activated using steam at 150 cm ³ /min at 900°C	28 wt.% into paraffin composite and added with 520 kg/m ³ cement and 852 kg/m ³ sand	Compressive strength up to 25 MPa	Chin et al. (2020)

Note: OPMF - oil palm mesocarp fibre; OPKS - oil palm kernel shell; OPF - oil palm frond; ZnCl₂ - zinc chloride; K₂CO₃ - potassium carbonate; KOH - potassium hydroxide; CO₂ - carbon dioxide.

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