Review Article

WM&R

Waste Management & Research
2023, Vol. 41(1) 37–51

DOI: 10.1177/0734242X221127167
journals.sagepub.com/home/wmr


Coconut shell and husk biochar: A review of production and activation technology, economic, financial aspect and application

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Abstract

The coconut industry generates a relatively large amount of coconut shell and husk biomass, which can be utilized for industrial and environmental purposes. Immense potential for added value when coconut shell and husk biomass are turned into biochar and limited studies are available, making this review paper significant. This paper specifically presents the production and activation technology, economic and financial aspect and application of biochar from coconut shell and husk biomass. Pyrolysis, gasification and self-sustained carbonization are among the production technology discussed to convert this biomass into carbon-rich materials with distinctive characteristics. The surface characteristics of coconut-based biochar, that is, Brunauer-Emmett-Teller (BET) surface area (S_{BET}), pore volume (V_p), pore diameter (d_p) and surface functional group can be enhanced by physical and chemical activation and metal impregnation. Due to their favourable characteristics, coconut shell and husk-activated biochar exhibit their potential as valuable adsorption materials for industrial and environmental application including biodiesel production, capacitive deionization, soil amendment, water treatment and carbon sequestration. With the knowledge of the potential, the coconut industry can contribute to both the local and global biocircular economy by producing coconut shell and husk biochar for economic development and environmental remediation. The capital and operating cost for production and activation processes must be taken into account to ensure bioeconomy sustainability, hence coconut shell and husk biomass have a great potential for income generation.

Keywords

Coconut shell, coconut husk, biochar, production, activation, application

Received 15th January 2022, accepted 10th May 2022 by Associate Editor Sigrid Kusch-Brandt.

Introduction

Coconut shell and coconut husk biomass are generated by the coconut industry in some countries in Asia, Oceania, Caribbeans, Central and South America and West and East Africa (Perera, 2012). In 2019, Food and Agriculture Organization (FAO) reported that Indonesia (17.1 million tons), Philippines (14.8 million tons), India (14.7 million tons), Sri Lanka (2.5 million tons), Brazil (2.33 million tons), Vietnam (1.68 million tons), Mexico (1.29 million tons), Papua New Guinea (1.19 million tons), Thailand (0.80 million tons) and Malaysia (0.54 million tons) are the world's top 10 coconut producers (FAO, 2019), which contributes to 659.12 million USD import value and 540.50 million USD export value, with 0.8902 USD/EUR exchange rate (as of 31 December 2019) (European Central Bank, 2019). Coconut waste biomass is commonly mismanaged by direct disposal and open burning, hence causing significant green energy waste (Goh, 2018), detrimental human health, environmental pollution, greenhouse effects, global warming and climate change issues (Ferronato and Torretta, 2019; Jain et al., 2014). Therefore, an alternative method of coconut waste management is highly desired.

A new practice of coconut waste biomass involved transforming coconut biomass into biochar, which is a black, carbon-rich and highly porous material with a high degree of aromatization and strong anti-decomposition properties (Lehmann and Joseph, 2009; Spokas, 2013). Pyrolysis, gasification and self-sustained carbonization are adopted to produce coconut shell and coconut

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husk biochar. Pyrolysis thermally degrades biomass at elevated temperature in an oxygen-free condition to produce biochar, bio-oil and synthetic gas (Lee et al., 2019; Narzari et al., 2015), whereas gasification directly converts biomass into synthetic gas and yields a small amount of biochar (Sikarwar and Zhao, 2017). Self-sustained carbonization involves the combustion of biomass while the carbonization temperature is sustained on its own during the biomass transformation into biochar (Samsudin et al., 2019). Among these thermochemical processes, pyrolysis is reportedly having a lower biochar production cost (272 USD ton^{-1}) in comparison to gasification (380 USD ton^{-1}) (Brown et al., 2011; Meyer et al., 2011). However, there is no record of biochar production cost for self-sustained carbonization. While mitigation of air pollutant emissions caused by biochar production technology is required to be carried out (Sekar et al., 2021), previous studies indicated that converting coconut biomass into biochar is an effective method for coconut biomass management. Coconut shell and coconut husk biochar have different proximate (i.e. moisture (MC), ash, volatile matter (VM), fixed carbon (FC)), ultimate (i.e. carbon (C), hydrogen (H), oxygen (O), nitrogen (N)) and surface characteristics (i.e. BET surface area (S_{BET}), pore volume (V_p), pore diameter (d_p), surface functional group) depending on the selection of biochar production technology. Physical activation, chemical activation and metal impregnation can enhance the surface characteristics of coconut shell biochar in terms of BET surface characteristics and surface functional groups. The characteristics of coconut shell biochar, coconut husk biochar and coconut-shell-activated biochar make these carbon-rich materials to be potentially useful for industrial and environmental purposes. The knowledge of the usefulness of biochar and activated biochar from coconut waste biomass from different production technology and activation process enables the global coconut industry to use coconut shell and coconut husk biomass as potential assets for their specific industrial development and environmental remediation. However, the cost of different biochar production technology and activation process must be considered by the coconut industry in managing coconut shell and coconut husk biomass.

Characteristics of coconut shell and coconut husk biomass

Coconut shell and coconut husk biomass are mainly composed of lignin, cellulose and hemicelluloses (Borel et al., 2021). Increasing the rate of cellulose breakdown improves the porous structure of biochar (Li et al., 2020), whereas increasing the rate of lignin breakdown contributes to the formation of biochar with a high specific area, high FC content and fine aromatic structure (Jiang et al., 2020). The composition of lignin, cellulose and hemicellulose in a coconut shell and coconut husk biomass influences the characteristics of coconut shell and coconut husk biochar.

Previous studies indicated that the proximate characteristics of coconut shell and coconut husk biomass are different (Table 1). Coconut shell biomass contains 6–10 wt% MC, 0–2 wt% ash, 72–77 wt% VM and 15–23 wt% FC, whereas

Table 1. Characteristics of coconut shell and coconut husk biomass before biochar production.

Biomass feedstock	Proximate analysis (wt%)				Ultimate analysis (wt%)				Reference
	Moisture	Ash	Volatile matter	Fixed carbon	C	H	O	N	
Coconut shell	5.70	0.60	77.20	22.80	52.60	6.20	53.10	2.00	Windeatt et al. (2014)
	10.1	3.20	75.50	11.10	64.23	6.89	27.73	0.77	Khuenkaeo and Tippayawong (2020)
	–	–	–	–	46.80	5.80	47.10	0.30	Millán et al. (2021)
	7.85–7.93	1.34–1.53	71.50–75.93	14.61–19.31	45.20–50.50	–	46.61–52.71	1.04–1.14	Samsudin et al. (2019)
	9.99	0.38	–	–	–	–	–	–	Nuryana et al. (2020)
Coconut husk	–	0.92	82.94	16.14	47.00	6.07	46.60	0.21	Suman and Gautam (2017)
	7.50	5.30	85.30	14.70	44.70	7.50	61.80	0.80	Windeatt et al. (2014)

coconut husk biomass contains 0–8 wt% MC, 1–5 wt% ash, 83–85 wt% VM and 15–16 wt% FC. As coconut-based biomass has high VM and low ash and FC, there are higher possibilities for coconut shell and coconut husk biomass to be transformed into biochar (Shukla et al., 2019). Furthermore, both coconut shell and husk biomass have different compositions of C, H, O and N (Table 1). Under the biomass conversion process, coconut-based biomass with high carbon content (45–51 wt%) will have a higher biochar yield. Also, coconut-based biomass with lower nitrogen content (1–2 wt%) can reduce the possibility of toxic greenhouse gas (e.g., nitrogen oxides (NO_x)) emissions during the biomass carbonization process (Tripathi et al., 2016).

Coconut-based biochar production technology

Pyrolysis is widely used to produce coconut shell biochar (Adorna et al., 2020; Baharum et al., 2020; Behera et al., 2020; Khuenkaeo and Tippayawong, 2020; Nuryana et al., 2020; Pituya et al., 2016; Sari et al., 2020; Windeatt et al., 2014), whereas gasification is an alternative technology used (Atienza et al., 2020; Millán et al., 2021). Self-sustained carbonization is the most current method to produce coconut shell biochar (Samsudin et al., 2019). As for coconut husk, by far, pyrolysis is the only technology selected for coconut husk biochar production (Isidoria et al., 2018; Suman and Gautam, 2017; Windeatt et al., 2014). While these production technologies can produce coconut shell and coconut husk biochar with relatively desirable characteristics for various biochar applications, pyrolysis, gasification and self-sustained carbonization have yet used heat waste to transform coconut shell and coconut husk biomass into coconut shell and coconut husk biochar (Marous, 2014).

Pyrolysis

Pyrolysis is a thermochemical process that thermally degrades biomass at elevated temperatures into biochar, bio-oil and syngas (Lee et al., 2019). This process can operate in various reactor types including a tube furnace (Adorna et al., 2020), muffle furnace (Baharum et al., 2020; Behera et al., 2020; Pituya et al., 2016; Suman and Gautam, 2017), fixed-bed reactor (Windeatt et al., 2014), microwave (Nuryana et al., 2020) or an ablative system (Khuenkaeo and Tippayawong, 2020) under different temperatures, heating rate, retention time and an inert gas flow rate. Pyrolysis is a two-stage process. In the first stage, the complex molecular bonds of lignin, cellulose and hemicellulose in the biomass undergo cleavage to form carboxyl, carbonyl and hydroxyl groups on the biochar surface (Patwardhan et al., 2011), which subsequently undergo decarboxylation, dehydration and dehydrogenation processes to form larger molecules or heavy compounds of biomass (Lee et al., 2019). In the second stage, by continuously applying thermal energy, the larger molecules or heavy compounds of biomass undergo several chemical reactions to produce biochar, bio-oil and syngas (Lee et al., 2019) such as methane (CH_4), hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2) (Dhyani and Bhaskar, 2019; Lee et al., 2019; Narzari et al., 2015).

Slow pyrolysis. In slow pyrolysis, biomass is thermally degraded at 300–800°C with a 5–10°C minute^{-1} heating rate (Liu et al., 2015). This process takes hours or days to be thermally degraded to yield 30–40 wt% biochar, 25–30 wt% bio-oil and 25–35 wt% synthesis gas (Dhyani and Bhaskar, 2019). Slow pyrolysis is the most preferred method to produce biochar as this process exhibits the highest biochar yield in comparison to bio-oil and biogas yield (Daful and Chandraratne, 2020; Mohan et al., 2006; Tripathi et al., 2016), but this process is more costly when it requires a longer retention time and higher energy to have a higher biochar yield (Zaman et al., 2017).

Microwave-assisted pyrolysis. In a conventional heating process, heat transfer between the solid biomass feedstock and its surroundings occurs through conduction, convection and radiation, which limits the flexibility of the heating process to control the operating temperature, whereas microwave-assisted pyrolysis applies microwave radiation which involves selective and volumetric heating for the thermal degradation of biomass (Huang et al., 2016; Lo et al., 2017; Motasemi and Afzal, 2013; Shukla et al., 2019). In microwave-assisted pyrolysis, an electromagnetic field first enters to penetrate the biomass material. This causes the generation of thermal energy throughout the penetration depth by dielectric heating. The dielectric heating takes place due to the interaction with dipoles present in the biomass material, which results in volumetric heating from inside the biomass material. Microwave heating usually requires a material with high dielectric constant and microwave absorbers are applied along with the biomass to facilitate dielectric heating during the process. Microwave-assisted pyrolysis is usually conducted under an operating temperature of 400–800°C, and it is considered an innovative approach to the conventional pyrolysis process (Sahoo and Remya, 2020; Shukla et al., 2019; Vijayaraghavan, 2019).

Ablative pyrolysis. In ablative pyrolysis, the biomass is degraded by thermal energy as the biomass particles are in intimate contact with a hot solid or surface (Peacocke and Bridgwater, 1994). Ablative pyrolysis is firstly used to process wood waste by using an electrically heated wire, which forms a thin vaporizing liquid layer (Diebold, 1980). The application of ablative pyrolysis proceeds with studying the ablative heat transfer during wood pyrolysis (Lede et al., 1985; Lédé et al., 1987; Martin et al., 1986). Then, the ablative pyrolysis was applied by using multiple blades inside the reactor, which yields 67% of bio-oil (Peacocke and Bridgwater, 1994). Currently, ablative pyrolysis is used to determine biochar and bio-oil yield by using a rotating blade ablative reactor (Khuenkaeo and Tippayawong, 2020). In ablative pyrolysis, applying inert gas may not be necessary, but a costly reactor, moderate temperature and low reaction rate during the pyrolysis process are required, thus making ablative pyrolysis one of the rarest pyrolysis types applied for biochar production (Zaman et al., 2017).

Gasification

Gasification is a partial combustion process in which biomass is partially combusted at higher temperatures (600–1200°C) under 10–20 seconds retention time (Brewer et al., 2009; McKendry, 2002). As dried biomass is subjected to the gasification process by using air, CO_2 or steam (H_2O) as a gasifying agent, the biomass undergoes four stages of gasification: (1) drying, (2) devolatilization, (3) partial oxidation and (4) reduction (Gómez-Barea and Leckner, 2010; Richardson et al., 2015). In the first stage, the biomass is dried to reduce its MC content. In the second stage, the dried biomass undergoes devolatilization to produce tar, water, synthesis gas and biochar (Cha et al., 2016; Huang et al., 2021). At the next stage, synthesis gases, such as CO, CO_2, H_2 and CH_4, as well as solid biochar undergo partial oxidization. Finally, biochar undergoes reduction or gasification that produces ash and more synthesis gases such as CO, CO_2, CH_4, N_2, H_2, H_2O and various VM ($C_xH_yO_z$). As gasification primarily aims to change biomass into gaseous products (e.g. CO, CO_2, CH_4. H_2 and H_2S), the gasification process should not be used to produce biochar (Bridgwater, 1995; Kirubakaran et al., 2009; Puig-Arnavat et al., 2010; Sikarwar and Zhao, 2017). Despite its low biochar yields (<10%), gasification generates biochar with a highly desirable surface area and hence nominates itself as one of the biochar production technologies (Brewer et al., 2009; Millán et al., 2021).

Self-sustained carbonization

In self-sustained carbonization, the carbonization temperature is maintained by itself while the combusting biomass is changed into biochar inside the reactor (Idris et al., 2015a, 2015b; Samsudin et al., 2019). Dried biomass is fed into a self-sustained carbonization reactor, which is primarily made of high-temperature resistance bricks. Inside the reactor, the biomass undergoes the combustion process, and the brick reactor is closed to produce an oxygen-free environment in the reactor. The burning biomass used the generated heat energy to break down cellulose, hemicellulose and lignin in biomass to form a complex biochar network (Lee et al., 2019). Firstly, self-sustained carbonization was used for the production of palm kernel shell biochar (Idris et al., 2015a, 2015b). Self-sustained carbonization was then used to change coconut shell biomass into coconut shell biochar. The coconut shell biochar produced by one-step self-sustained, low-temperature carbonization technology using a pilot-scale brick reactor can produce biochar with a high BET surface area, which is suitable to produce an adsorption material (Samsudin et al., 2019).

The financial aspect of biochar production technology

The cost of pyrolysis, gasification and self-sustained carbonization is different depending on the chemical used, energy requirements and operating parameters involved in the biochar production. In pyrolysis, higher heat energy or longer retention time may be required to have a higher biochar yield with more enhanced surface characteristics, hence increasing the operational cost of the process (Dhyani and Bhaskar, 2019; Lee et al., 2017). Additionally, the involvement of nitrogen (N_2) gas may add to the capital cost of a pyrolysis reactor (Narzari et al., 2015). Though an ablative reactor is costly, the operating cost of ablative pyrolysis is low due to its absence of inert gas, moderate temperature requirement and low retention time (Zaman et al., 2017). For the gasification process, steam is an economic gasifying agent for biochar production (Chan et al., 2019), but the involvement of steam and the generation of toxic gases, such as nitrogen oxides (NO_x) and sulphur oxides (SO_x), may increase the capital cost and operational cost of the gasification process (Elkhalifa et al., 2019). A novel self-sustained carbonization process involves natural gas for biomass combustion, which lowers the energy requirement for biochar production and subsequently its lower operating cost (Idris et al., 2015a, 2015b; Samsudin et al., 2019). In addition, the absence of N_2 gas causes self-sustained carbonization to have low capital costs. Thus, self-sustained carbonization has lower capital and operating cost in comparison to the pyrolysis and gasification process.

Characteristics of coconut shell and coconut husk biochar

The properties of coconut shell biochar and coconut husk biochar produced by different biochar production technologies are summarized in Table 2. The highest yield can be observed when microwave-assisted pyrolysis was applied to produce coconut shell biochar (84–91 wt%) (Nuryana et al., 2020). In contrast, gasification which occurs in fluidized bed gasifiers has the lowest coconut shell biochar yield (13 wt%) as the main purpose of gasification is to change biomass into gaseous products (Millán et al., 2021). As for coconut husk biochar, pyrolysis which occurs in a top-lit updraft unit gives the highest biochar yield (45 wt%) (Isidoria et al., 2018), while the same process which occurs in a fixed bed reactor gives the lowest biochar yield (31 wt%) (Windeatt et al., 2014). Self-sustained carbonization also gives a relatively high coconut shell biochar yield (30–32 wt%) which exhibits its ability to produce a relatively large amount of coconut shell biochar.

Proximate and ultimate analysis shows that coconut shell and husk biochar are relatively dry, carbon-rich material with a considerable amount of hydrogen, oxygen, nitrogen and any inorganic material that exists on their biochar surface. The increment of FC and elemental carbon occurs when coconut shell biomass undergoes pyrolysis or gasification to be transformed into coconut shell biochar (Millán et al., 2021; Pituya et al., 2016). A similar trend can be seen for FC and elemental carbon when coconut husk biomass was thermally decomposed into coconut husk biochar (Suman and Gautam, 2018). Furthermore, carbon, hydrogen and oxygen explain the existence of different surface functional groups on the surface coconut shell biochar and coconut husk

Table 2. Proximate, ultimate and BET surface characteristics of coconut shell and coconut husk biochar produced by different biochar production technology.

Biomass	Technology (process variant)	Reactor	Operating conditions				Yield (wt%)	Proximate analysis (wt%)				Ultimate analysis (wt%)				BET surface characteristics			Reference
			Temp. (°C)	Heating rate (°C minute^{-1})	Retention time (hour)	Particle size (mm)		Moisture	Ash	Volatile matter	Fixed carbon	C	H	O	N	S_{BET} (m^2 g^{-1})	V_p (cm^3 g^{-1})	d_p (nm)	
Coconut shell	Pyrolysis (slow pyrolysis)	Tube furnace	550	5.0	2.0	0.074	–	–	–	–	–	–	–	–	–	97.40	0.115	–	Adorna et al. (2020)
		Muffle furnace	700	7.0	2.0	<1.00	–	–	–	–	–	–	–	–	–	434.83	0.174	2.23–2.44 mm	Baharum et al. (2020)
			300	10.0	1.0	<1.00	56.35	3.80	2.69	60.46	33.05	–	–	–	–	–	–	–	Behera et al. (2020)
			400	10.0	1.0	<1.00	44.87	4.40	4.30	52.45	38.83	–	–	–	–	–	–	–	
			600	10.0	30 minutes	<1.00	25.80	2.60	5.63	35.76	56.01	–	–	–	–	–	–	–	
		Ablative system	500		7.0 minutes	8.00–10.00	–	6.86	1.66	27.19	69.47	77.19	3.40	18.06	0.10	55.69	0.25	9.13	Khuenkaeo and Tippayawong (2020)
		Fixed bed reactor	600	5.0	1.0	3.35–10.0	28.20	7.10	4.10	8.10	91.90	93.90	3.00	2.60	0.40	222.50	0.150	–	Windeatt et al. (2014)
		Muffle furnace	300	10.0	1.0	–	–	–	–	–	–	53.47	3.70	42.57	0.10	1.03	–	60.60	Pituya et al. (2016)
					2.0	–	–	–	–	–	–	48.32	3.93	47.56	0.01	1.03	–	95.26	
					3.0	–	–	–	–	–	–	43.46	3.62	52.76	0.01	0.95	–	80.07	
			400	10.0	1.0	–	–	–	–	–	–	31.84	3.08	64.87	0.02	4.01	–	48.21	
					2.0	–	–	–	–	–	–	43.08	3.17	53.62	0.01	8.76	–	40.57	
					3.0	–	–	–	–	–	–	54.28	3.16	42.54	0.01	11.32	–	40.30	
			500	10.0	1.0	–	–	–	–	–	–	65.48	3.15	31.35	0.01	199.38	–	27.07	
					2.0	–	–	–	–	–	–	64.77	2.93	32.29	0.01	347.96	–	22.06	
					3.0	–	–	–	–	–	–	64.06	2.70	33.20	0.01	351.95	–	22.20	
	Pyrolysis (microwave-assisted)	Microwave reactor	126–205.40	–	15 minutes	1.18–2.00	91.31	–	–	–	–	–	–	–	–	0.199	0.0018	36.30	Nuryana et al. (2020)
					20 minutes	1.18–2.00	83.88	–	–	–	–	–	–	–	–	0.456	0.0014	12.39	
	Pyrolysis (unknown)	Pyrolysis reactor with tar scrubber	–	–	–	–	28.00	0.26	1.36	–	–	–	–	–	–	–	–	–	Sari et al. (2020)
	Gasification	Top lit updraft gasifier	–	–	–	–	–	10.05	3.21	9.41	77.33	–	–	–	–	–	–	–	Atienza et al. (2020)
		Fluidized bed gasifier	850	20.0	1.0	1.00–3.00	13.00	–	8.20	16.20	–	79.20	1.30	11.30	0.10	1041.8	>0.34	–	Millán et al. (2021)
	Self-sustained carbonization	Pilot-scale brick reactor	300–500	–	–	130.0–150.0	30.00–32.00	–	–	–	–	–	–	–	–	308.00	0.150	2.00	Samsudin et al. (2019)
Coconut husk	Pyrolysis (slow pyrolysis)	Top-lit updraft retort unit	500	–	1.0	–	45.00	16.50	10.10	15.00	75.00	79.80	2.21	7.42	0.42	77.20	–	3.91	Isidoria et al. (2018)
		Muffle furnace	400	5.0–15.0	2.0	<212 µm	43.33	0.00	26.27	30.56	43.17	47.92	3.50	47.06	1.34	39.57	–	–	Suman and Gautam (2017)
			600				36.00	0.00	21.99	20.82	57.19	58.43	3.01	37.38	1.02	120.73	–	–	
			800				34.00	0.00	17.32	5.33	77.35	67.31	2.67	28.98	0.87	256.60	–	–	
			1000				31.00	0.00	12.03	4.72	83.25	74.08	2.50	22.74	0.50	590.41	–	–	
		Fixed bed reactor	600	5.0	1.0	3.35–10.0	30.80	10.40	13.50	25.10	74.90	82.60	2.70	12.80	2.40	23.20	0.04	–	Windeatt et al. (2014)

biochar produced by pyrolysis and self-sustained carbonization such as carboxyl acid (–COOH), esters (–C=OOR'), aromatic, ketone (C=OR'), iso-cyanide (–C–CH_3–NC), hydroxyl (–OH), aryl ethers, quinone, organosilicon compounds (Si–O), alkyl (–CH_3), amide (–C=O–N) and alkyl ether (–O–CH_3) group (Nuryana et al., 2020; Samsudin et al., 2019; Sari et al., 2020; Suman and Gautam, 2017). Moreover, a considerable amount of ash found in both coconut shell and husk biochar produced by pyrolysis (Behera et al., 2020; Suman and Gautam, 2017) and gasification (Atienza et al., 2020; Millán et al., 2021) indicates the presence of minerals such as carbonates, oxides or phosphates of alkali or alkaline earth metals. As coconut biomass is changed into coconut biochar, alkali-earth elements, such as potassium (K) and sodium (Na), possibly nucleate, condense and coagulate together to form a certain amount of ash on the biochar surface (Jia and Lighty, 2012). Surface functional groups and minerals are important features of biochar that act as adsorption material (Gwenzi et al., 2021).

Another important feature of coconut shell and coconut husk biochar is the BET surface characteristics. BET surface area, pore volume and pore diameter of biochar are important to identify the adsorption capacity of biochar (Narzari et al., 2015). Commonly, the BET surface characteristics of coconut shell and husk biochar are greatly depending on the operating parameters of the pyrolysis process. As pyrolytic temperature increases, the BET surface area of coconut shell biochar and coconut husk biochar increases which in turn increases their porosity (Pituya et al., 2016; Suman and Gautam, 2017). Furthermore, at a certain temperature, the BET surface area of coconut shell biochar increases as the retention time for the pyrolysis process increases (Pituya et al., 2016). Moreover, the BET surface characteristics of biochar are also affected by selected biochar production technologies. A gasification system that uses steam as the gasifying agent causes coconut shell biochar to have the highest BET surface area and pore diameter (Millán et al., 2021). Coconut shell biochar which is produced by self-sustained carbonization also exhibits its potential as an adsorption material (Samsudin et al., 2019).

Activation of coconut-based biochar

Biochar activation involves the application of physical and chemical agents to improve the properties of characteristics of biochar in terms of BET surface characteristics and surface functional group (Sajjadi et al., 2018, 2019). The chemical reactions that occur during biochar activation also can be used for nutrient recovery (Marou and Gavurov, 2022; Stavkova and Maroušek, 2021). Coconut shell and coconut husk biochar activation are carried out to improve their porous structures by ash and uncarbonized biomass removal (Bushra and Remya, 2020). Therefore, the improvement of coconut-based biochar is carried out by employing several activation methods (Sajjadi et al., 2018, 2019) including physical activation (Guo et al., 2009; Koltowski et al., 2016), chemical activation (Adorna et al., 2020; Baharum et al., 2020; Prauchner and Rodríguez-Reinoso, 2012) and metal impregnation (Prauchner and Rodríguez-Reinoso, 2012).

Physical activation

Physical activation involves applying air, steam (H_2O) and CO_2 as activation agents (Guo et al., 2009; Koltowski et al., 2016; Sudaryanto et al., 2006). Physical activation is a favourable activation method as it is less costly and more environmentally friendly as compared to chemical activation (Bushra and Remya, 2020). Moreover, steam uses less energy than CO_2 for biochar activation, hence making the gasification rate in steam activation higher than in CO_2 activation (Fan et al., 2013; Hernández-Montoya et al., 2012; Nabais et al., 2008).

Steam activation. Steam activation applies to steam or water vapour as an activation agent (Koltowski et al., 2016; Sudaryanto et al., 2006). This process revolves around a series of partial gasification of carbon-rich material (Sajjadi et al., 2019). During partial gasification, some carbon atoms (C_f) on the biochar surface are exposed to steam (H_2O) molecules, which eliminates the VM and forms surface oxides (C(O)) on the biochar surface. Meanwhile, some C_f exposed to steam is changed into CO_2 and H_2 gas. From these gasification steps, some CO_2 and H_2 gas partially devolatilize other C_f on the surface of biochar to produce CO and CH_4.

In this series of steam activation reactions, the number of new pores and the size of existing pores increase due to the removal of uncarbonized biomass and trapped products which exist during biochar production (Dalai and Azargohar, 2007; Santos et al., 2015). Furthermore, the number of aromatic compounds will be greater and a few oxygenated functional groups are also developed on the biochar surface (Sizmur et al., 2017).

CO_2 activation. Biochar is subjected to partial gasification by CO_2 gas (Sudaryanto et al., 2006) which reacts with the biochar available amorphous carbon in a limited oxygen atmosphere to produce C(O) and CO gas (Bushra and Remya, 2020; Sajjadi et al., 2019). In turn, C(O) is desorbed from the biochar porous surface, which causes further development of the existing porous structure (Sajjadi et al., 2019; Sizmur et al., 2017). During further development, CO gas is absorbed by the carbon active site on the biochar surface, which retards the partial gasification by CO_2 gas (Sajjadi et al., 2019).

Chemical activation

Chemical activation involves the application of acid or alkali reagents to improve the properties of biochar. Both acid and alkali activation can improve or develop the porosity, pore volume, surface area and FC by eliminating any impurities found on the biochar surface, such as mineral ash, metals, organic matter and volatile carbon (Bushra and Remya, 2020; Gao et al., 2020; Sajjadi et al., 2018; Wang and Wang, 2019). In addition, acid and alkali activation can improve biochar surface properties by the

addition of surface functional groups. In acid activation, acid reagents introduce acidic surface functional groups, including the carboxyl group (–COOH), which improve the hydrophilicity of biochar (Liu et al., 2012; Yang et al., 2019; Zhao et al., 2017). Furthermore, acid activation removes oxygen, sulphur and hydrogen from biochar, thus increasing aromaticity and loss of aliphatic character which is promoted at lower activation temperatures (Wang and Wang, 2019). Alkali activation adds hydroxyl functional group (–OH) to the biochar surface (Sizmur et al., 2017; Vijayaraghavan, 2019), which improves biochar capacity as an adsorption material (Yang et al., 2019).

Acid activation

H_3PO_4 activation. There are six aspects of phosphorus acid (H_3PO_4) activation on biochar namely dehydration and elimination, swelling role, acceleration carbonization, framework role, oxidation and aromatic condensation (Danish and Ahmad, 2018; Gao et al., 2020; Olivares-Marín et al., 2006; Puziy et al., 2020; Shi et al., 2019; Z. Zhang et al., 2020). During the H_3PO_4 activation, the H_3PO_4 changes into the P_2O_5 compound. Subsequently, P_2O_5 reacts with carbon on the biochar surface to change the biochar pore structure and generate P_4 and CO_2 gas.

Alkali activation

KOH activation. In potassium hydroxide (KOH) activation, carbon (C_f) on the biochar surface reacts with KOH to produce metallic potassium (K), potassium carbonate (K_2CO_3) and H_2 gas (Sajjadi et al., 2018). Meanwhile, potassium-containing constituents (K_2O) react with the C_f to produce K, K_2CO_3 and H_2 (Gao et al., 2020). Then, the K_2CO_3 reacts with carbon on the biochar surface to produce another metallic K, CO and CO_2, hence changing the BET surface area, pore volume and pore diameter of biochar (El-Hendawy, 2009; Foo and Hameed, 2012; Lillo-Rodenas et al., 2003; Lozano-Castelló et al., 2007; Otowa et al., 1997).

NaOH activation. In sodium hydroxide (NaOH) activation, C_f reacts with NaOH to produce metallic sodium (Na), sodium carbonate (Na_2CO_3) and H_2) gas (Sajjadi et al., 2018). The generated Na_2CO_3 reacts with C_f to produce more metallic sodium (Na), sodium oxide (Na_2O) and CO_2. Meanwhile, Na reacts with CO_2 to produce more Na_2O and CO during the NaOH activation. These reactions create new pores, open previously inaccessible pores, widen the existing pores and merge existing pores due to pore wall breakage (Foo and Hameed, 2012; Yang et al., 2010).

Metal impregnation

In metal impregnation, metal ions from metal salts or metal oxides, such as magnesium (Mg), improve the biochar properties (Wang and Wang, 2019). Biochar activated by metal impregnation has nano-crystals of metal oxides and biochar matrix that enhance the adsorption capacity, magnetism and catalytic performance of biochar (Wang and Wang, 2019; Zhang et al., 2012).

$MgCl_2$ activation. During magnesium chloride ($MgCl_2$) activation, biomass is firstly loaded with $MgCl_2$ solution, which then is carbonized to produce activated biochar (Liu et al., 2013). In activating biochar, $MgCl_2 \cdot 6H_2O$ undergo dehydration and decomposition to form magnesium oxides (MgO) on the surface of biochar.

Effect of activation method on coconut-based biochar properties

Physical or chemical activation can influence the surface characteristics of coconut-based biochar (Table 3). During H_3PO_4 (acid) activation, the BET surface area (434.83–508.07 $m^2\ g^{-1}$) and pore volume (0.174–0.203 $cm^3\ g^{-1}$) in coconut shell biochar increases (Baharum et al., 2020). The effect of activation temperature on mesopore and micropore volume of coconut shell biochar during H_3PO_4 activation is also reported (Prauchner and Rodríguez-Reinoso, 2012). Under impregnation ratio of H_3PO_4: biochar of 0.30 and 2 hours activation time, the mesopore (0–0.37 $cm^3\ g^{-1}$) and micropore (0–0.74 $cm^3\ g^{-1}$ of coconut shell biochar change as activation temperature increases from approximately 150–600°C. As the impregnated ratio increases from 0 to 0.92, the maximum mesopore and micropore volume is 1.04 and 0.69 $cm^3\ g^{-1}$, respectively (Prauchner and Rodríguez-Reinoso, 2012). In KOH (alkali) activation, the porous structure in coconut shell biochar improves as BET surface area increases from 97.40 to 486.00 $m^2\ g^{-1}$ and pore volume increases from 0.115 to 0.236 $cm^3\ g^{-1}$ (Adorna et al., 2020). Some studies, however, found that chemical activation does not necessarily enhance the porous structure. During NaOH activation, BET surface area and pore volume decrease from 434.83 to 405.98 $m^2\ g^{-1}$ and 0.174 to 0.162 $cm^3\ g^{-1}$, respectively (Baharum et al., 2020).

The effect of metal impregnation for coconut shell biochar activation is also reported (Prauchner and Rodríguez-Reinoso, 2012). Under impregnation ratio, $ZnCl_2$: biochar of 0.40 and 2 hours activation time, as the activation temperature increases from 267.04 to 652.07°C, the mesopore volume range of the coconut-shell-activated biochar is 0.06–0.13 $cm^3\ g^{-1}$, whereas the micropore volume range of the coconut-shell-activated biochar is 0.31–0.66 $cm^3\ g^{-1}$ when temperature increases from 269.11 to 654.14°C. Under activation temperature of 500°C and 2 hours of activation time, the range of mesopore volume and micropore volumes are 0–0.79 and 0.12–0.70 $cm^3\ g^{-1}$, respectively, as the impregnation ratio increases from 0 to 1.20.

The effect of CO_2 temperature, CO_2 flow rate and activation time on the characteristics of coconut shell biochar produced by pyrolysis is also reported (Guo et al., 2009). Before activation, the coconut shell biochar has a 186 $m^2\ g^{-1}$ BET surface area and 0.268 $cm^3\ g^{-1}$ pore volume. After activation, the pore characteristics change significantly where the BET surface area and pore volume increase to 613.00 $m^2\ g^{-1}$ and 0.437 $cm^3\ g^{-1}$, respectively, after CO_2 activation at the temperature of 750°C and 4 hours activation period. Furthermore, the BET surface area and pore volume increase as activating parameters increase.

Table 3. BET surface characteristics of coconut shell biochar before and after physical activation, chemical activation and metal impregnation.

Activation type	Activation agent	Technology	Reactor	Carbonization condition				Activation Condition					Yield (%)	Before activation			After activation			Reference
				Temp. (°C)	Heating rate (°C minute^{-1})	Retention time (h)	Particle size (mm)	Temp. (°C)	Heating rate (°C minute^{-1})	Activ. time (hours)	Flow rate (mL minute^{-1})	Impreg. Ratio (chem.: biochar)		S_{BET} (m^2 g^{-1})	V_P (cm^3 g^{-1})	d_p (nm)	S_{BET} (m^2 g^{-1})	V_P (cm^3 g^{-1})	d_p (nm)	
Physical	Carbon dioxide (CO_2)	Pyrolysis	Tubular reactor	600	10.0	2.0	<2.00	750	–	4.0	600	–	72.00	186.00	0.268	–	613.00	0.437	–	Guo et al. (2009)
								800					64.67				860.00	0.590	–	
								850					50.00				1305.00	0.689	–	
								900					29.33				1391.00	0.838	–	
								950					11.33				1323.00	0.878	–	
								900		2.0			58.67				724.00	0.506	–	
										3.0			45.33				1075.00	0.744	–	
										5.0			24.00				1653.00	1.089	–	
										6.0			17.33				1331.00	0.819	–	
										4.0	200		38.67				1013.00	0.671	–	
											400		34.00				1192.00	0.768	–	
											800		23.33				1700.00	1.135	–	
											1000		10.67				1360.00	0.928	–	
	Steam (H_2O)		Fluidized bed reactor (activation reactor)	650	–	–	–	800	10.0	78 minutes	0.60	–	–	3.10	0.0009	1.20	626.8	0.3361	1.70	Koltowski et al. (2016)
Chemical	Phosphoric acid (H_3PO_4)		Tubular furnace	850	2.0	2.0	2.00–2.83	150.65–573.86	1.0	2.0	–	0.30	–	–	–	–	–	V_{meso-}, 0.00–0.37	–	Prauchner and Rodríguez-Reinoso (2012)
								150.65–575.49	1.0	2.0	–	0.30	–	–	–	–	–	V_{mic-}, 0.00–0.74	–	
								500	1.0	2.0	–	0.01–0.91	–	–	–	–	–	V_{meso-}, 0.00–1.04	–	
								500	1.0	2.0	-	0 – 0.92	–	–	–	–	–	V_{mic-}, 0.00–0.69	–	
			Muffle furnace	700	7.0	2.0	<1.00	80	–	1.0	–	–	–	434.83	0.174	–	508.07	0.203	–	Baharum et al. (2020)
	Zinc chloride ($ZnCl_2$)		Tubular furnace	850	2.0	2.0	2.00–2.83	267.04–652.07	1.0	2.0	–	0.40	–	–	–	–	–	V_{meso-}, 0.06–0.13	–	Prauchner and Rodríguez-Reinoso (2012)
								269.11–654.14	1.0	2.0	–	0.40	–	–	–	–	–	V_{mic-}, 0.31–0.66	–	
								500	1.0	2.0	–	0–1.20	–	–	–	–	–	V_{meso-}, 0.00–0.79	–	
								500	1.0	2.0	–	0–1.20	–	–	–	–	–	V_{mic-}, 0.12–0.70)	–	
	Potassium hydroxide (KOH)		Tube furnace	550	5.0	2.0	0.15	675	5.0	4.0	–	2:1	–	97.40	0.115	–	486.00	0.236	–	Adorna et al. (2020)
	Sodium hydroxide (NaOH)		Muffle furnace	700	7.0	2.0	<1.00	80	–	1.0	–	–	–	434.83	0.174	–	405.98	0.162	–	Baharum et al. (2020)

For example, the BET surface area increases from 1013 to 1360 m^2 g^{-1} when the CO_2 flow rate increases from 200 to 1000 cm^3 $minute^{-1}$. Applying CO_2 for biochar activation is proven to be effective as CO_2 activation can bring significant changes in coconut-based biochar pore characteristics. Steam activation can improve the pore characteristics of biochar from coconut biomass feedstock. A significant increase in BET surface area (3.10–626.80 m^2 g^{-1}), pore volume (0.0009–0.3351 cm^3 g^{-1}) and pore diameter (1.20–1.70 nm) is reported after employing steam activation on coconut shell biochar produced by pyrolysis process (Koltowski et al., 2016).

Cost estimation for physical and chemical activation process on coconut-based biochar

In estimating the cost of the physical and chemical activation process, capital cost, fixed capital investment, operating cost and net present value must be taken into consideration (Lai and Ngu, 2020). For physical activation, CO_2 and steam activation have similar annual capital costs (1.63 USD million), fixed capital investment (2.12 USD million), operating cost (1.22 USD million) and net present value (1.54 and 1.53 USD million). As for chemical activation, the different chemical has different cost estimation. All chemical activation has an identical capital cost (4.88 USD million) and fixed capital investment (6.32 USD million). Furthermore, the operating cost of KOH (2.82 USD million) and NaOH (2.92 USD million) is lower than the operating cost of H_3PO_4 (3.09 USD million). However, the net present value of H_3PO_4 activation (2.93 USD million) is higher than the net present value of KOH (2.09 USD million) and NaOH (2.39 USD million). As for metal impregnation, the cost estimation for $MgCl_2$ may be evaluated based on the cost estimation of $ZnCl_2$ impregnation, in which the capital cost, fixed capital investment, operating cost and net present value are 4.88, 6.32, 3.11 and 2.97 USD million, respectively. By comparison, the capital cost (1.63 USD million) and fixed capital investment (2.12 USD million) of physical activation are lower than the capital cost (4.88 USD million) and fixed capital investment (6.32 USD million) of chemical activation. Furthermore, the net present value of chemical activation is higher (2.10–2.97 USD million) than the net present value of physical activation (1.53–1.54 USD million). The lower net present value, capital cost and fixed capital investment cause physical activation to be more desirable in activating coconut shell biochar for surface enhancement.

Application of coconut-based biochar

Biochar from various types of biomass feedstocks can be used for 55 useful applications in both the industrial and environmental sectors (Schmidt, 2012). In industrial applications, biochar can be used in the building industry as a low-cost cement substitute (Maroušek et al., 2020) and energy source (Mardoyan & Braun, 2016). In environmental applications, biochar can be used as a soil conditioner, fertilizer and water treatment material (Braghiroli et al., 2018). The usefulness of biochar for industrial and environmental applications is due to the biochar surface characteristics (Bushra and Remya, 2020). The surface characteristics of coconut shell and coconut husk biochar exhibit their potential as adsorption material for industrial application and environmental remediation. The industrial applications of coconut shell biochar include biodiesel production (Behera et al., 2020) and capacitive deionization (Adorna et al., 2020), whereas environmental application of coconut shell and coconut husk biochar involves soil amendment (Millán et al., 2021; Pituya et al., 2016; Suman and Gautam, 2017; Windeatt et al., 2014), water treatment (Nuryana et al., 2020) and carbon sequestration (Windeatt et al., 2014). However, any literature regarding wider applications of coconut-based biochar and activated biochar, such as gas emission treatment, heavy metal contaminants and building materials, is still scarce, and thus the potential of coconut shell biochar, coconut husk biochar and coconut-shell-activated biochar for the various applications is required to be widely explored.

Industrial application

Biodiesel production. Coconut shell biochar, activated by sulphuric acid (H_2SO_4) produced via pyrolysis, was subjected to sulfonation to evaluate its suitability as a catalyst for transesterification (Behera et al., 2020). The maximum sulfonic density achieved (0.35 mmol g^{-1}) as coconut shell biochar was pyrolysed at 300°C, and the sulfonic density declined (0.12 mmol g^{-1}) as the carbonization temperature rises to 600°C. As carbonization temperature increases, the number of acidic functional groups and the number of acidic sites decreases, which resulted in the reduction of sulfonic density (Cheng and Li, 2018; Konwar et al., 2019). Nevertheless, this data shows that coconut shell biochar exhibited its potential as a catalyst for biodiesel production.

Capacitive deionization. Similarly, coconut shell biochar, activated by KOH produced via pyrolysis, was subjected to an indirect co-precipitation method with magnesium dioxide (MnO_2) to prepare coconut shell-derived activated biochar-MnO_2 nanocomposite (Adorna et al., 2020). During the preparation, the BET surface area of coconut-shell-activated biochar decreases from 486 to 304 m^2 g^{-1}. The activated biochar-MnO_2 nanocomposite derived from coconut shell, however, has a relatively high specific electrosorption capacity (33.90–68.40 mg g^{-1}) at 1.2 V, which is caused by its high mesopore volume ratio, high capacitance retention, good hydrophilicity and suitable pore texture which shorten the diffusion distance of ions (Adorna et al., 2020). This finding indicates the coconut shell activated biochar is suitable for electrochemical applications material such as water purification, desalination, and energy storage.

Environmental application

Soil amendment. Soil amendment is a common environmental application of coconut shell and coconut husk biochar. This is due to their favourable characteristics such as cation exchange

capacity (CEC), water-holding capacity (WHC), nutrients composition, mineral release rate and pH value. At certain pyrolytic parameters, coconut shell biochar has 61.23 cmol kg^{-1} maximum CEC and 75.30% maximum WHC (Pituya et al., 2016). Biochar with high CEC and WHC can maximize plant nutrient uptake, improve root development and enhance soil fertility which can maximize crop production (Hansen et al., 2016). In addition, coconut shell and coconut husk biochar contain a relatively high concentration of essential minerals including phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), molybdenum (Mo), zinc (Zn), manganese (Mn), copper (Cu), nickel (Ni), iron (Fe) and silicon (Si) (Millán et al., 2021; Windeatt et al., 2014). Coconut shell biochar produced by the steam-gasification process contains 20393.80 mg kg^{-1} of K, 4188.70 mg kg^{-1} of Na, 387.70 mg kg^{-1} of Ca, 274.00 mg kg^{-1} of P, 954.60 mg kg^{-1} of Si and 561.20 mg kg^{-1} of Cu (Millán et al., 2021). Additionally, the amount of P, K, Ca and Mg is higher in coconut husk biochar in comparison to coconut shell biochar produced by pyrolysis (Windeatt et al., 2014). Meanwhile, the coconut husk biochar produced by pyrolysis at 8000°C contains C, Na, Al, Si, Cl and K (Suman and Gautam, 2017). Moreover, coconut shell biochar has relatively high mineral release under neutral condition, in which coconut shell biochar from the gasification process release approximately 99% of K, 80% of P, 20% of Ca, 10% of Mg, 75% of Na and 35% of Si to the soil under pH 7 (Millán et al., 2021). Higher mineral concentration or mineral release rate indicates higher CEC of coconut shell and coconut husk biochar, which promote higher nutrient uptakes for plant growth. Coconut-based biochar is alkaline. The pH value of coconut shell and coconut husk biochar produced by pyrolysis is 8.50 and 9.60, respectively (Windeatt et al., 2014), whereas the pH value of coconut shell biochar produced by gasification is 10.20 (Millán et al., 2021). The higher pH value of coconut-based biochar promotes higher microbial activity, higher organic matter mineralization, higher plant nutrient availability and higher acid neutralization (Millán et al., 2021; Windeatt et al., 2014). Steam activation can improve the performance of coconut shell biochar in soil remediation. A significant increase in pore characteristics of coconut shell biochar by steam activation promotes the significant increment of the removal efficiency of freely dissolved C_{free} (10–84%) and bioaccessible fraction C_{bioacc} (50–99%) of polycyclic aromatic hydrocarbons (PAHs), hence effectively decrease the leachate toxicity in soil (Koltowski et al., 2016).

Water treatment. Water treatment is another environmental application for coconut-based biochar (Nuryana et al., 2020). Coconut shell biochar produced by microwave-assisted pyrolysis has different methylene blue removal efficiency and adsorption capacity at different pH, adsorbent dosage, retention time and chemical agent. Nuryana et al. (2020) evaluated the effect of retention time on the performance of the coconut shell biochar to remove methylene blue from water. At 550 W, the adsorption capacity of the coconut shell biochar decreases from 0.6875 (removal efficiency = 55.00%) to 0.5165 mg g^{-1} (removal efficiency = 41.32%) as the carbonization time increases from 15 to 20 minutes. Baharum et al. (2020) had evaluated the effectiveness of biochar and activated biochar from coconut shell in removing diazinon from water at different pH values. Under pH 3 and 2 hours contact time, 1.0 g L^{-1} of coconut shell biochar achieved the highest diazinon removal efficiency (92.16%) at pH 3, which was slightly higher than at pH 5. The diazinon removal efficiency increases at pH 7 but declines as the pH value of the treating water increases to 9. Meanwhile, coconut shell biochar activated by H_3PO_4 (84.55%) and NaOH (87.93%) achieved their maximum diazinon removal efficiency at pH 7. Baharum et al. (2020) also evaluated the effect of adsorbent dosage (1.0–10.0 g L^{-1}) on the diazinon removal efficiency by coconut shell biochar and H_3PO_4- and NaOH-activated biochar from coconut shell. At 2.0 g L^{-1} of adsorbent dosage, coconut shell biochar, coconut shell biochar activated by H_3PO_4 and coconut shell biochar activated by NaOH exhibited more than 80–90% of diazinon removal efficiency. While increasing adsorbent dosage does not always result in higher removal percentage of diazinon compound, the removal efficiency of diazinon by coconut shell biochar (98.28%) and coconut shell biochar activated by NaOH (97.95%) became higher at 10.0 g L^{-1}. Baharum et al. (2020) also evaluated the adsorption capacity of coconut shell biochar and the H_3PO_4- and $NaOH^-$-activated biochar from coconut shell. Under pH 7, coconut shell biochar (5.85 mg g^{-1}), $H_3PO_4^-$-activated biochar from coconut shell (5.47 mg g^{-1}) and $NaOH^-$-activated biochar from coconut shell (5.69 mg g^{-1}) achieved their highest adsorption capacity in removing diazinon during the water treatment process.

Carbon sequestration. Coconut shell and coconut husk biochar also show their ability for carbon sequestration, which is defined as a process of capturing, and storing CO_2, which causes global climate change and greenhouse effects, from the atmosphere (USGS, 2019). The theoretical potential of coconut shell and husk biochar for carbon sequestration was made to predict the amount of CO_2 that can be stored by coconut shell and coconut husk biochar (Windeatt et al., 2014). According to the prediction, 4.90 million tons of coconut shell biochar and 2.50 million tons of coconut husk biochar can store up to 9.90 million tons and 2.90 million tons of atmospheric CO_2, respectively.

Economic aspects of coconut-based biochar application

The information regarding the economic aspects and concerns of coconut-based biochar application is still limited. The biochar production mainly in rural areas can help develop the region while assisting small and medium-sized industries to produce sufficient energy, improve farmer income and give solutions for coconut waste management (Amalina et al., 2022). Besides, despite market price uncertainty, a review of biochar prices indicated that the biochar market is still beneficial for the economy (Campbell et al., 2018). In 2014, a survey conducted by International Biochar Initiative indicates that the cited price of wood biochar sold by U.S. biochar sellers and global biochar

Table 4. Application of coconut shell biochar, coconut husk biochar and coconut-shell-activated biochar for industrial and environmental purposes.

Application	Technology (process variance)	Operating temperature (time)	Activation temperature (time)	Findings	Reference
Biodiesel production (catalyst)	Pyrolysis (slow pyrolysis)	300–600°C (30 minutes to 1–hour)	–	• Coconut shell biochar achieved its maximum sulfonic density (0.45 mmol g^{-1}) at 300°C, and the sulfonic density decline (0.12 mmol g^{-1}) at 600°C, may indicate its potential as a catalyst for transesterification to produce biodiesel.	Behera et al. (2020)
Capacitive deionization	Pyrolysis (slow pyrolysis)	550°C (2 hours)	KOH activation 675°C (4 hours)	• As an electrode material, coconut shell-derived activated biochar-MnO_2 nanocomposite prepared by indirect co-precipitation has a relatively high specific electrosorption capacity (33.90–68.40 mg g^{-1}) at 1.2 V.	Adorna et al. (2020).
Soil amendment	Pyrolysis (slow pyrolysis)	300°C (3 hours)	–	• Coconut shell biochar has a 75.30% maximum water-holding capacity.	Pituya et al. (2016)
		500°C (3 hours)		• Coconut shell biochar has 61.23 cmol kg^{-1} of the maximum cation exchange capacity.	
		600°C (1 hour)	–	• Coconut shell biochar contains approximately 2000 mg kg^{-1} of K, 1000 mg kg^{-1} of Ca and 100 mg kg^{-1} of Mg. • Coconut husk biochar contains approximately 3000 mg kg^{-1} of P, 18,000 mg kg^{-1} of K, 8000 mg kg^{-1} of Ca and 4200 mg kg^{-1} of Mg. • Coconut shell has high surface areas and porosities which indicate good water retention properties and potential habitat for microbial communities. • Coconut-based biochar (i.e. shell and husk) is highly alkaline (pH = 8.5–9.6), which can increase microbial activity, organic matter mineralization, plant-nutrient bioavailability, acid neutralization in soil.	Windeatt et al. (2014)
	Gasification	850°C (1 hour)	–	• Coconut shell contains 20,393.80 mg kg^{-1} of K, 4188.70 mg kg^{-1} of Na, 387.70 mg kg^{-1} of Ca, 274.00 mg kg^{-1} of P, 954.60 mg kg^{-1} of Si and 561.20 mg kg^{-1} of Cu. • Coconut shell biochar releases approximately 99% of K, 80% of P, 20% of Ca, 10% of Mg, 75% of Na and 35% of Si to the soil at pH = 7.	Millán et al. (2021)
	Pyrolysis (slow pyrolysis)	650°C (–)	Steam activation 800°C (78 minutes)	• Steam activation causes the coconut-shell-activated biochar to remove more PAH contaminants in soil, whereby the removal efficiency increases from 10 to 84% for immobilization of freely dissolved (C_{free}) and from 50 to 99% for a bioaccessible fraction (C_{bioacc}) of polycyclic aromatic hydrocarbons in soil.	Koltowski et al. (2016)
Water treatment	Pyrolysis (microwave-assisted)	126–205.40°C (15–20 minutes)	–	• The methylene blue adsorption capacity of the coconut shell biochar decreases from 0.6875 (removal efficiency = 55.00%) to 0.5165 mg g^{-1} (removal efficiency = 41.32%) as the carbonization time increases from 15 to 20 minutes at 550 W.	Nuryana et al. (2020)
	Pyrolysis (slow pyrolysis)	700°C (2 hours)	H_3PO_4, NaOH activation 80°C (1 hour)	• At pH 3, coconut shell biochar has 92.16% removal efficiency after treating 1000 mg L^{-1} of diazinon in an aqueous solution for 2 hours. • At pH 7, the maximum diazinon removal efficiency for coconut shell biochar activated by H_3PO_4 and NaOH is 84.55% (adsorption capacity = 5.47 mg g^{-1}) and 87.93% (adsorption capacity = 5.69 mg g^{-1}) respectively. • At 2000 mg L^{-1} of adsorbent dosage, biochar and H_3PO_4- and NaOH-activated biochar from coconut shell exhibited more than 80–90% of diazinon removal efficiency. • At 10,000 mg L^{-1} of adsorbent dosage, coconut shell biochar removes 98.28% of diazinon from aqueous solution, whereas the diazinon removal efficiency for coconut-shell-activated by H_3PO_4 and NaOH are 97.95 and 98.2%, respectively.	Baharum et al. (2020)
Carbon sequestration	Pyrolysis (slow pyrolysis)	600°C (1 hour)	–	• 4.90 million tons of coconut shell biochar can theoretically capture or store 9.900 million tons of atmospheric CO_2. • 5.00 million tons of coconut husk biochar, can theoretically capture or store 2.90 million tons of atmospheric CO_2.	Windeatt et al. (2014)

sellers are 2.47 and 2.06 USD kg^{-1} (Tomlinson and Jirka, 2014). These data prove that biochar production, activation and application also can be financially beneficial for the coconut industry, which in turn can contribute to the growth of the global economy.

Safety concerns and negative impacts of coconut-based biochar application

In industrial and environmental applications, several negative impacts of coconut-based biochar application, though found to be scarce, must be addressed. Coconut shell biochar, coconut husk biochar and coconut-shell-activated biochar contain small particles, which if inhaled, irritate the eyes, skin and respiratory system (Ravi et al., 2016). While coconut-shell-activated biochar has higher PAH removal efficiency (Koltowski et al., 2016), the contaminant from biochar may cause a detrimental effect on human health (Zhang et al., 2019). Therefore, biochar must be pretreated for PAH removal. Besides, applying coconut shell and coconut husk biochar for soil amendment (Millán et al., 2021; Suman and Gautam, 2017; Windeatt et al., 2014) may cause negative alteration to soil properties and soil biota (Zhang et al., 2019). In terms of soil properties, coconut shell and coconut husk biochar may not necessarily improve soil porosity due to the stimulation of microbial activity which causes pore blockages (Mukherjee et al., 2014). As for soil biota, applying coconut-based biochar to soil may change the native soil biota, which causes negative responses of the earthworm and hence retarding the plant growth (Lehmann et al., 2011; Li et al., 2011; Tammeorg et al., 2014). While coconut shell and coconut husk biochar were predicted to store a relatively large amount of CO_2 gas (Windeatt et al., 2014), coconut-based biochar may also cause greater CO_2 emissions, which is caused by the abiotic release of inorganic carbon, the decomposition of labile components of biochar and the decomposition of organic matters by biochar (Mukherjee and Lal, 2014; Spokas and Reicosky, 2009). As for water treatment, applying coconut shell biochar for water treatment to remove specific contaminants causes biochar to have contaminants with high concentrations (Hossain et al., 2011; Nuryana et al., 2020). With these possible negative impacts, an elevated level of coconut-based biochar amendment must be taken into consideration and require further assessment (Table 4).

Conclusion

Coconut shell and husk biochar and coconut-shell-activated biochar were confirmed to have favourable characteristics, such as high alkalinity, porous structure, CEC, WHC and mineral composition, which causes the biochar and activated biochar to become potentially useful for various applications such as biodiesel production, capacitive deionization, soil conditioning, toxic remediation, water treatment and CO_2 storage. Such potential enables the coconut industry to manage coconut waste biomass and mitigate environmental issues effectively while providing income for biochar producers and sellers. The production and activation technology, economic and financial aspect, as well as potential application of coconut shell and coconut husk biochar is significantly directed towards value-added biomass for income generation particularly in the coconut industry.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors thank the Sarawak Research Development Council (SRDC), Ministry of Education, Innovation and Talent Development (Government of Sarawak, Malaysia) for funding the research study (grant no. RDCRG/CAT/2019/12; RMI File No: 100-TNCPI/PRI 16/6/2 (019/2020)), the School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM) Sarawak Branch, Samarahan Campus; School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM) Selangor Branch, Shah Alam; Faculty of Applied Sciences, Universiti Teknologi MARA (UiTM), Sarawak Branch, Samarahan 2 Campus; and Faculty of Health Sciences, Universiti Teknologi MARA (UiTM) Sarawak Branch, Samarahan Campus for the analytical laboratory facilities and excellent technical support towards this research.

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