Jurnal Teknologi

Full Paper

EFFECTS OF METHANOL MODIFICATION ON THE PHYSICOCHEMICAL PROPERTIES OF COCONUT SHELL BIOCHAR

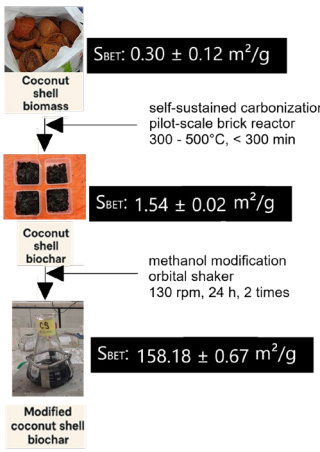
Azrine Ajien[a,b], Nurzawani Md Sofwan[c], Hazman Seli[a,b], Mohibah Musa[d], Rafidah Husen[e], Mohd Sani Sarjadi[f], Juferi Idris[a,b *]

[a]Faculty of Chemical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM) Sarawak Branch, Samarahan Campus, 94300 Kota Samarahan, Sarawak, Malaysia
[b]Faculty of Chemical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM) Selangor Branch, 40450 Shah Alam, Selangor, Malaysia
[c]Faculty of Health Sciences, Universiti Teknologi MARA (UiTM) Sarawak Branch, Samarahan Campus, 94300 Kota Samarahan, Sarawak, Malaysia
[d]Centre for Functional Materials and Nanotechnology, Institute of Science, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Malaysia
[e]Faculty of Applied Sciences, Universiti Teknologi MARA (UiTM) Sarawak Branch, Samarahan 2 Campus, 94300 Kota Samarahan, Sarawak, Malaysia
[f]Faculty of Science & Natural Resources, Universiti Malaysia Sabah, 88400, Kota Kinabalu, Sabah

Article history
Received
23rd July 2024
Received in revised form
27th July 2025
Accepted
27th February 2026
Published
1st November 2026

*Corresponding author
juferi@uitm.edu.my

Graphical Abstract



Abstract

Production of biochar for nano-adsorbents requires advanced technology and substantial energy input for large-scale production. This study evaluated the impact of surface modification using methanol on the properties of coconut shell biochar after low energy self-sustained carbonization. Methanol serves as a mild modifier that may alter surface polarity, improve pore accessibility, and enhance the availability of active sites for adsorption without complex processing. Self-sustained carbonization was carried at 300–500 °C for less than 300 minutes at low retention times. Subsequently, the produced biochar was modified by mixing it with methanol at 130 rpm for 24 hours. The modified biochar showed significant improvements, where BET surface area increased from 1.54 ± 0.02 to 158.18 ± 0.67 m²/g and total pore volume from 0.0005 ± 0.004 to 0.09 ± 0.06 cm³/g. This was supported by SEM images which indicate pore network development with increased porosity and surface roughness, suggesting the modified biochar's potential as an adsorbent. These results underscore the feasibility of developing effective adsorbents through appropriate technology for the coconut industry and environmental protection.

Keywords: coconut shell biomass, biochar, self-sustained carbonization, methanol modification, BET surface area

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

Abstrak

Penghasilan biochar untuk nano-adsorben memerlukan teknologi canggih dan penggunaan tenaga yang tinggi bagi pengeluaran berskala besar. Kajian ini menilai kesan pengubahsuaian permukaan menggunakan metanol terhadap sifat biochar tempurung kelapa selepas pengkarbonan kendiri yang menggunakan tenaga rendah. Metanol berfungsi sebagai pengubah suai ringan yang boleh mengubah keterpolaran permukaan, meningkatkan kebolehcapaian liang, dan menambah ketersediaan tapak aktif untuk penjerapan tanpa pemprosesan yang kompleks. Pengkarbonan kendiri dijalankan pada masa penahanan yang rendah dan dikarbonkan pada suhu 300–500 °C selama kurang daripada 300 min. Seterusnya, biochar yang dihasilkan diubah suai dengan mencampurkan biochar tersebut dengan metanol pada 130 rpm selama 24 jam. Biochar yang diubah suai menunjukkan peningkatan yang ketara, di mana keluasan permukaan BET meningkat daripada 1.54 ± 0.02 kepada 158.18 ± 0.67 m^2/g dan jumlah isipadu liang daripada 0.0005 ± 0.004 kepada 0.09 ± 0.06 cm^3/g. Hal ini disokong oleh imej SEM yang menunjukkan perkembangan rangkaian liang dengan peningkatan keliangan dan kekasaran permukaan, menunjukkan potensinya sebagai bahan penjerap. Keputusan ini menegaskan kebolehlaksanaan membangunkan bahan penjerap yang berkesan melalui teknologi yang sesuai untuk industri kelapa dan perlindungan alam sekitar.

Kata kunci: sisa kelapa, pengkarbonan mampan sendiri, pengubahsuaian permukaan, pengeluaran penjerap kos rendah, pemulihan alam sekitar

© 2026 Penerbit UTM Press. All rights reserved

1.0 INTRODUCTION

The coconut industry generates shell, husk, coir, frond, and leaves biomass, with coconut shell and husk being the primary coconut waste [1], [2]. In Malaysia, the coconut industry generates approximately 730 million kg of coconut shell biomass in 2022 [3]. A significant portion of the amount of coconut shell biomass is frequently mishandled either by open burning or direct disposal, thereby posing detrimental effects on the environment and the economy [4]. Open burning of coconut shell contributes to air pollution, which causes human respiratory health problems [5], whereas direct dumping of coconut shell waste in landfills results in inefficient land use and potential soil and water contamination due to leachate. In terms of economy, mismanagement of coconut shell biomass has resulted in missed opportunities to produce value-added products that could have boosted the local economy and generated employment. Concisely, direct disposal and open burning of coconut shell biomass can cause environmental hazards and economic losses due to the failure to capitalize on its potential. Hence, a sustainable waste management through the transformation of waste into value-added products is required.

One of the sustainable waste management methods is to have biomass undergo thermal decomposition to produce biochar. Biochar, a carbon-rich adsorption material with strong decomposition resistance and high-aromatization degree, is widely applied in a variety of environmental purposes, such as soil amendment, wastewater treatment, and carbon capture [6]. Despite its ability to yield a large amount of biochar with desirable surface characteristics, i.e, a relatively large surface area, pyrolysis is a high-cost biochar production technology due to its higher energy requirement [7]. Therefore, a low-cost biochar production technology is desired. Self-sustained carbonization, a low-cost biochar production method [8], has been proven to convert various biomass wastes – including coconut shell – into biochar [9]. Self-sustained carbonization, characterized by its simple usage, ease of operation, and low energy requirements [9]–[12], employs a self-sustaining carbonization temperature to produce biochar with desirable surface characteristics. However, due to the absence of temperature-control process system [11], biochar generated under short retention times may have undesirable surface characteristics, which includes relatively small surface area, hence necessitating surface treatment to improve its properties.

Surface modification can increase adsorption capacity and surface area of biochar [13], [14]. Methanol, a simple alcohol, can interact with oxygen-containing surface groups on biochar, such as carboxyl, hydroxyl, or carbonyl groups, through reactions such as esterification, hydrogen bonding, or mild oxidation, which may alter surface polarity, improve pore accessibility, and enhance the availability of active sites for adsorption [15], [16]. However, effective standardized procedures or extensive evaluations of surface modifications to improve biochar physicochemical characteristics are underdeveloped and require further exploration. Moreover, studies which includes methanol modification of biochar produced through self-

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

sustained carbonization remains limited, as are studies on its adsorption application.

In this study, coconut shell biochar was produced through self-sustained carbonization at low retention time and subsequently underwent surface modification using a novel method. The low-cost biochar production method and novel modification method can result in value-added products which indicate a feasible and sustainable waste management strategy for the coconut industry, while contributing to the bio-circular economy.

2.0 METHODOLOGY

2.1 Sample Preparation

The coconut shell was obtained from Sungei Marong Agri-Farm Company, Asajaya, Sarawak, Malaysia. The samples with a diameter range of 130 – 150 mm were sun-dried under a transparent roof to achieve a moisture content of less than 5 wt.% [9].

2.2 Pilot-scale brick reactor and carbonization process

The biochar was produced using self-sustained carbonization in a pilot-scale brick reactor, as depicted in Figure 1. A similar process was employed by Idris et al. [8].

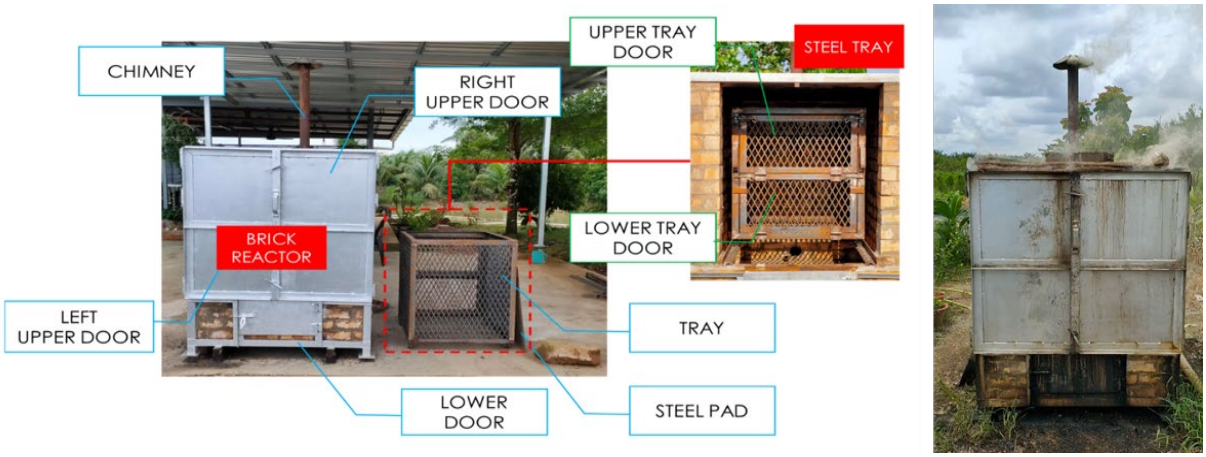


Figure 1 Pilot-scale brick reactor for coconut shell biochar production

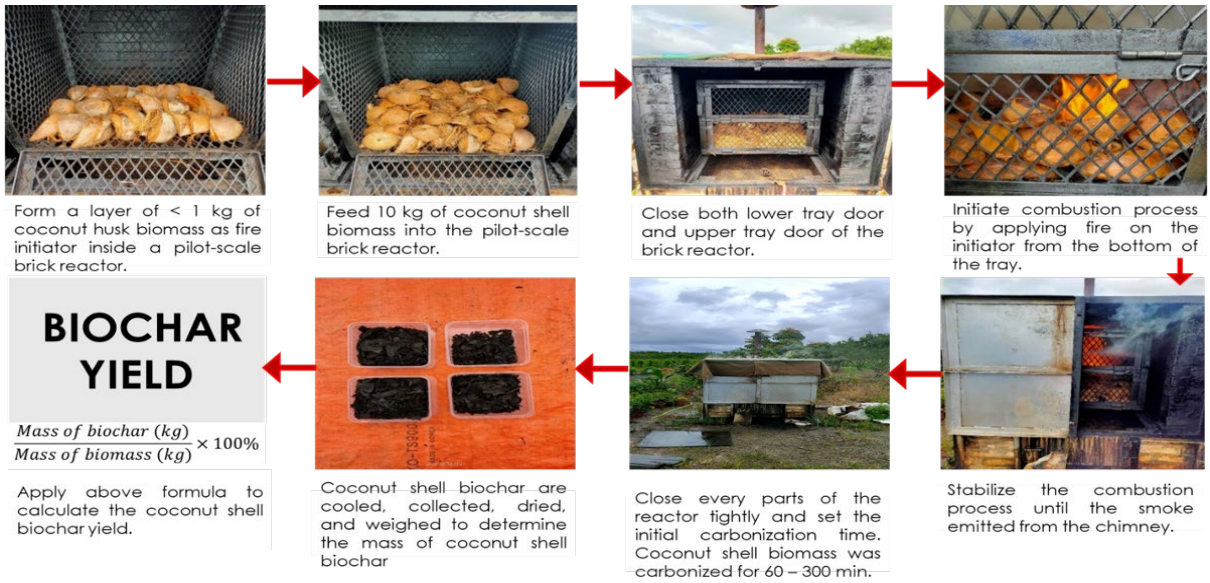


Figure 2 Self-sustained carbonization process for coconut shell biochar production

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

The self-sustained carbonization as shown in Figure 2 [9] was conducted at temperatures ranging from 300 to 500°C. The reactor was built with double-clay brick walls (1200 mm length × 1200 mm breadth × 1500 mm height external dimensions), functioned as a natural heat insulator [9], [10], [12]. The biochar yield was calculated as the proportion of the mass of biochar ($m_{biochar}$) to the mass of biomass ($m_{biomass}$) as Eq. 1 [11]:

$$Biochar\ yield\ (\%) = \frac{m_{biochar}}{m_{biomass}} \times 100\% \quad (1)$$

2.3 Biochar samples modification

The coconut shell biochar was modified using methanol (99.99% purity, HmbG Chemicals, Malaysia). Methanol was selected as the modifying agent due to its ability to interact with oxygen-containing surface functional groups such as carboxyl, hydroxyl, carbonyl through esterification, hydrogen bonding, or mild oxidation, which can improve surface polarity, enhance pore accessibility, and increase available adsorption sites [16]. Methanol is used for biochar modification due to its small size, high polarity, ability to alter surface chemistry, and ease of removal by washing and drying [17]. Approximately 20 g of powdered biochar was mixed with 100 mL of methanol in a conical flask. The mixture underwent agitation using an orbital shaker at 130 rpm for 24 h to enhance cleaning [13], [14]. After agitation, the mixture was allowed to settle for 12 h to ensure the biochar settled at the conical flask bottom. The solid biochar was then filtered using a vacuum filtration system and dried in an oven (Memmert UNE 600, Schwabach, Germany) at 110°C for over 3 h before transferring to a beaker. Subsequently, the solid residue was washed with hot distilled water, filtered, and dried. This process was repeated twice to ensure thorough removal of foreign debris prior to analysis.

2.4 Analytical methods

The moisture, ash, volatile matter, and fixed carbon contents of the coconut shell biomass and biochar were analysed using the ASTM-D5142 standard [18]. Elemental analysis for carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulphur (S) was performed using a CHNS-O Analyzer (FlashSmart, Thermofisher Scientific, Italy) [11]. The Brunauer–Emmett–Teller (BET) surface area analysis was conducted using a surface area analyser (3flex, Micromeritics, USA) and calculated using the BET isotherms equation [19]. Surface functional groups of coconut shell biomass and biochar were determined using Attenuated Total Reflectance-Fourier-Transform Infrared (ATR-FTIR) spectroscopy (Spectrum One, Perkin-Elmer, USA) [20], [21]. The surface morphology of coconut shell biomass and biochar samples was observed using a scanning electron microscope (SEM) (HITACHI SU3500, Tokyo, Japan) at 1000× and 2500× magnification. Samples were sputtered on a magnet and coated with platinum prior to imaging [9].

3.0 RESULTS AND DISCUSSION

3.1 Self-sustained carbonization biochar yield

Table 1 shows that the self-sustained carbonization of coconut shell biomass in this study yielded 20.00 – 26.00% of coconut shell biochar, which is comparable to that obtained from oil palm empty fruit bunch biochar [10], [12]. However, compared to a study conducted by Samsudin et al. [9], this study reported a lower biochar yield, possibly due to differences in retention time and reactor design [22]. Lower retention times (60 – 300 min) can result in incomplete carbonization which reduces biochar output [23]. Nevertheless, lower retention time in self-sustained carbonization also enabled more cost-effective biochar production compared to previous studies.

3.2 Characterization

3.2.1 Proximate and ultimate analysis

Based on Table 2, the proximate analysis of coconut shell biomass revealed that it contained 8.58 ± 0.83 wt.% moisture, 1.79 ± 0.97 wt.% ash, 76.83 ± 0.39 wt.% volatile matter, and 12.79 ± 1.41 wt.% fixed carbon, while ultimate analysis showed 49.91 ± 0.61 wt.% carbon, 5.52 ± 0.01 wt.% hydrogen, 44.26 ± 0.63 wt.% oxygen, and 0.31 ± 0.01 wt.% nitrogen. Moisture can use up a certain amount of heat energy to evaporate, hence affecting the biomass thermochemical conversion process and the resulting biochar properties [24]. Low ash content helps prevent complications in the reactor [25] and reduces particulate matter emission during biochar production [12]. Low fixed carbon may indicate low energy storage, but combined with high volatile matter can indicate a significantly higher energy store, indicating advantages for biomass devolatilization during biochar production [26]. A considerably substantial amount of carbon, hydrogen, and oxygen possibly indicates a large amount of cellulose, hemicellulose, and lignin content in a biomass feedstock, which also exhibits biomass ability to undergo aromatization, polymerization, and intramolecular condensation reactions to form a biochar matrix [27]. Low nitrogen and the absence of sulphur in biomass indicate low

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

nitrogen oxides (NO_x) and sulphur oxides (SO_x) emission during biochar production [28].

Table 3 shows the proximate and ultimate analysis for coconut shell biochar produced by self-sustained carbonization at low retention time and methanol modification, which were comparable with previous studies. The lower moisture content in the coconut shell biochar and modified biochar was due to moisture loss during the self-sustained carbonization [29] and oven-drying during methanol modification [13]. Coconut shell biomass, as a feedstock containing high cellulose content, tends to produce biochar with higher ash content [30], but methanol modification lowered ash content in the coconut shell biochar due to pore swelling and surface wetting mechanisms [31]. Self-sustained carbonization promotes intense biomass devolatilization which lowers volatile matter [32], while methanol modification further lowered volatile matter content, possibly due to volatile matter dissolution on the biochar surface [33]. During self-sustained carbonization, hydrogen and oxygen decreased due to devolatilization [34], while carbon content increased as carbonization due to aromatization, polymerization, and condensation reactions to form a denser carbon structure [27], [35]. Methanol modification might further lower hydrogen and oxygen levels by dissolving a portion of these elements [36], [37], while increasing carbon levels by promoting additional carbon atoms in the biochar matrix. Meanwhile, biomass combustion decreases nitrogen levels via ammonia gases escape [38], while methanol modification promotes nitrogen dissolution in coconut shell biochar [39]. While comparable, the proximate properties and elemental compositions of the coconut shell biochar could be influenced by reactor type, modification process, carbonization temperatures, heating rate, retention time, and particle size [40]. However, the proximate and ultimate analysis results for coconut shell biochar showed self-sustained carbonization could become another effective biochar production method alongside pyrolysis and gasification process.

Table 1 Yield comparison of biochar from various biomass feedstock produced by self-sustained carbonization

Biomass type	Reactor	Particle size (mm)	Temperature (°C)	Retention time (min)	Yield (%)	Reference
Coconut shell	Modified pilot-scale brick reactor	130 – 150	300 – 500	60 – 300	20.00 – 26.00	Present study
	Pilot-scale brick reactor	130 – 150	300 – 500	1440	30.00 – 32.00	[9]
Oil palm empty fruit bunch	Pilot-scale brick reactor	100 – 150	300 – 500	310 – 462	26.00	[10]
		< 150	300 – 500	900 – 1800	10.00 – 16.30	[12]

Table 2 Characteristics of coconut shell biomass

Analysis		Present study	References	
Proximate (wt.%) [a]	Moisture	8.58 (± 0.83)	5.70 – 10.10	[9], [41]–[44]
	Ash	1.79 (± 0.97)	0.38 – 3.20	[9], [41]–[44]
	VM[b]	76.83 (± 0.39)	71.50 – 77.20	[9], [41]–[44]
	FC[b,c]	12.79 (± 1.41)	11.10 – 22.80	[9], [41]–[44]
Ultimate (wt.%)	C[b]	49.91 (± 0.61)	45.20 – 64.23	[9], [41]–[44]
	H[b]	5.52 (± 0.01)	4.89 – 6.89	[9], [41]–[45]
	O[b,c]	44.26 (± 0.63)	27.73 – 53.10	[9], [41]–[44]
	N[b]	0.31 (± 0.01)	0.30 – 2.00	[9], [41]–[44]
	S[b]	0.00 (± 0.00)	0.00 – 0.10	[45]

[a] Wet basis; [b] VM: volatile matter; FC: fixed carbon; C: carbon; H: hydrogen, O: oxygen; N: nitrogen; S: sulphur
[c] Calculated by difference

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

Table 3 Comparison of the proximate and ultimate characteristics of porous coconut shell biochar at different carbonization methods

Technology	Reactor	Modification Process	Operating Conditions				Proximate Analysis (wt.%)[a]				Ultimate Analysis (wt.%)					References
			Temperature (°C)	Heating rate (°C min^{-1})	Retention time (min)	Particle size (mm)	Moisture	Ash	VM[b]	FC[b,c]	C[b]	H[b]	O[b,c]	N[b]	S[b]	
Self-sustained carbonization	Modified pilot-scale brick reactor	-	300 – 500	-	60 – 300	130 – 150	0.25 (± 0.02)	11.45 (± 5.87)	0.64 (± 0.08)	87.66 (± 6.77)	70.34 (± 7.45)	2.45 (± 0.10)	27.09 (± 7.19)	0.12 (± 0.17)	-	Present study
		Methanol	300 – 500	-	60 – 300	130 – 150	0 .18 (± 0.01)	1.50 (± 0.71)	0.50 (± 0.50)	97.82 (± 0.64)	75.76 (± 2.16)	1.96 (± 0.32)	22.17 (± 1.83)	0.11 (± 0.01)	-	Present study
Pyrolysis	Tube furnace	-	550	5.0	120	0.074	-	-	-	-	-	-	-	-	-	[46]
	Muffle furnace	-	700	7.0	120	< 1.00	-	-	-	-	-	-	-	-	-	[47]
		-	300 – 600	10.0	30 – 60	< 1.00	2.60 – 3.80	2.69 – 5.63	35.76 – 60.46	33.05 – 56.01	-	-	-	-	-	[48]
	Ablative system	-	500		7.0	8.00 - 10.00	6.86	1.66	27.19	69.47	77.19	3.40	18.06	0.10	-	[42]
	Fixed bed reactor	-	600	5.0	60	3.35 – 10.00	7.10	4.10	8.10	91.90	93.90	3.00	2.60	0.40	-	[41]
	Muffle furnace	-	300 – 500	10.0	60 – 180	-	-	-	-	-	31.84 – 65.48	2.70 – 3.93	31.35 – 64.87	0.01 – 0.10	-	[49]
	Pyrolysis reactor with tar scrubber	-	-	-	-	-	0.26	1.36	-	-	-	-	-	-	-	[50]
Gasification	Top-lit updraft gasifier	-	-	-	-	-	10.05	3.21	9.41	77.33	-	-	-	-	-	[51]
	Fluidized bed gasifier	-	850	20.0	60	1.00 - 3.00	-	8.20	16.20	-	79.20	1.30	11.30	0.10	-	[43]

[a] the biochar sample was pre-dried in a drying oven for more than 24h as the moisture content of carbonized biomass should be negligible, i.e. < 1.00% [24]
[b] Calculated by difference

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

Table 4 Surface area characteristics of coconut shell biomass, coconut shell biochar, and modified coconut shell biochar

Sample	Technology	Reactor	Temperature (°C)	Retention time (min)	Modifying Agent	S_{BET}[a] (m^2 g^{-1})	$V_{p,\ total}$[a] (cm^3 g^{-1})	$V_{p,\ meso}$[a] (cm^3 g^{-1})	$V_{p,\ micro}$[a] (cm^3 g^{-1})	d_p[a] (nm)	References
Coconut shell biomass	-	-	-	-	-	0.30 (± 0.12)	0.0021 (± 0.001)	0.00 (± 0.00)	0.0021 (± 0.001)	29.56 (± 3.70)	Present study
Coconut shell biochar	Self-sustained carbonization	Modified pilot-scale brick reactor	300 - 500	60 – 300	-	1.54 (± 0.02)	0.0005 (± 0.004)	0.0002 (± 0.003)	0.0003 (± 0.0004)	1.33 (± 0.02)	Present study
		Modified pilot-scale brick reactor	300 - 500	60 – 300	Methanol	158.18 (± 0.67)	0.09 (± 0.06)	0.06 (± 0.03)	0.03 (± 0.02)	2.28 (± 0.06)	Present study
		Pilot-scale brick reactor	300 - 500	1440	-	308.00	0.150	-	-	2.00	[9]
	Pyrolysis	Tube furnace	550	120	-	97.40	0.115	-	-	-	[46]
		Muffle furnace	700	120	-	434.83	0.174	-	-	2.23 – 2.44 mm	[47]
		Ablative system	500	7	-	55.69	0.25	-	-	9.13	[42]
		Fixed bed reactor	600	60	-	222.50	0.150	-	-	-	[41]
		Muffle furnace	300 – 500	60 – 180	-	1.03 – 351.95	-	-	-	22.06 – 95.26	[49]
		Microwave reactor	126 - 205.40	15	-	0.199	0.0018	-	-	36.30	[44]
				20	-	0.456	0.0014	-	-	12.39	[44]
	Gasification	Fluidized bed gasifier	850	60	-	1041.8	> 0.34	-	-	-	[43]

[a]S_{BET}: BET surface area, $V_{p,\ total}$: total pore volume; $V_{p,\ meso}$: mesopore volume; $V_{p,\ micro}$: micropore volume; d_p: average pore diameter

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

3.2.2 Surface area analysis

Different production technologies and reactor types significantly influence the surface area characteristics of coconut shell biochar. This study provides an overview of various production methods and their effects on parameters such as BET surface area (S_{BET}), total pore volume ($V_{p,\ total}$), mesopore volume ($V_{p,\ meso}$), and micropore volume ($V_{p,\ micro}$). Table 4 provides a detailed comparison of the surface area characteristics of coconut shell biomass, coconut shell biochar, and modified coconut shell biochar. Coconut shell biomass exhibited an S_{BET} of 0.30 ± 0.12 $m^2\ g^{-1}$, with a total pore volume ($V_{p,\ total}$) and micro-pore volume ($V_{p,\ micro}$) both measured at 0.0021 ± 0.001 $cm^3\ g^{-1}$. At temperatures ranging from 300 to 500°C and durations from 60 to 300 minutes, self-sustained carbonization produced coconut shell biochar with an S_{BET} of 1.54 ± 0.02 m^2/g, $V_{p,\ total}$ of 0.0005 ± 0.004 cm^3/g, $V_{p,\ meso}$ of 0.0002 ± 0.003 cm^3/g, $V_{p,\ micro}$ of 0.0003 ± 0.0004 cm^3/g, and pore diameter of 1.33 ± 0.02 nm. Such undesirable biochar surface characteristics might be due to low retention time [9] or ash formation on the biochar surface due to lack of temperature-control features [11]. Coconut shell biochar with methanol modification achieved an S_{BET} of 158.18 ± 0.67 m^2/g, with Vp, total of 0.09 ± 0.06 cm^3/g, $V_{p,\ meso}$ of 0.06 ± 0.03 $cm^3\ g^{-1}$, and $V_{p,\ micro}$ of 0.03 ± 0.02 $cm^3\ g^{-1}$. The diverse production methods, including pilot-scale brick reactors, tube furnaces, muffle furnaces, ablative systems, fixed bed reactors, microwave reactors, and fluidized bed gasifiers, demonstrate considerable variability in surface area and pore volume characteristics of coconut shell biochar, reflecting the influence of temperature, duration, and reactor type on the final product properties. In biochar surface modification, methanol opens inaccessible pores, creates new pores, and widens existing pores, leading to higher surface area and pore volumes[52], [53].

Factors such as production technology (including ablative systems, fixed bed reactors, muffle furnaces, microwave reactors, and fluidized bed gasifiers) [41]–[44], [46], [47], [49], carbonization temperature (e.g., temperatures exceeding 700°C in muffle furnaces) [47], retention time (including longer durations observed in pilot-scale brick reactors up to 1440 minutes) [9], and the use of modifying agents such as methanol, significantly impact biochar surface area properties. These variables affect pore structure development with methanol-modified biochar showing notably higher S_{BET} values compared to unmodified biochar. Specific carbonization methods, such as self-sustained carbonization in modified pilot-scale brick reactors, as well as controlled pyrolysis and gasification processes, also yield biochars with enhanced surface areas and pore volumes, crucial for applications requiring superior adsorption and catalytic capabilities. However, this study did not address the optimization of the self-sustained carbonization conditions for biochar production, indicating a need for further research in this area. Understanding these relationships is vital for optimizing biochar production tailored to specific application.

3.2.3 Surface functional group

In Figure 3, the FTIR spectra of coconut shell biomass, biochar, and methanol-modified biochar showed progressive chemical transformations during self-sustained carbonization and subsequent modification. In the raw biomass, O–H stretching (~3400 cm^{-1}) indicates hydroxyl groups, C–H stretching (~2900 cm^{-1}) corresponds to aliphatic hydrocarbons, C=O stretching (~1700 cm^{-1}) reflects carbonyl groups, C=C stretching (~1600 cm^{-1}) suggests aromatic structures, and C–O stretching (1300–1000 cm^{-1}) relates to alcohols, ethers, carboxylic acids, and esters. After carbonization, diminished O–H, C–H, and C=O bands indicate dehydration and volatile loss, while more pronounced C=C signals confirm the formation of stable aromatic structures with partial retention of oxygenated groups. The methanol modification further reduced O–H and C–H intensities, altered C–O stretching, and preserved aromatic C=C structures, reflecting increased carbonization and surface functional rearrangement. These observations agree with previous reports, where Sari et al. (2020) detects hydroxyl and aromatic bonds in coconut shell biochar from pyrolysis [50], and Nuryana et al. (2020) shows that carbonization time introduces ketone, carboxylic acid, and ester groups [44]. Similarly, Samsudin et al. (2019) reports on the retention of –OH, aromatic, and C–H groups in biochar produced by self-sustained carbonization [9]. Collectively, the results demonstrate that carbonization stabilizes aromatic structures and further modification tailors the surface chemistry of biochar surface.

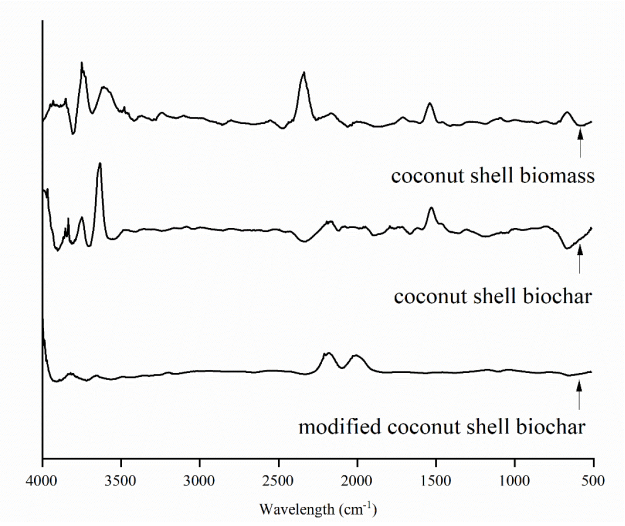
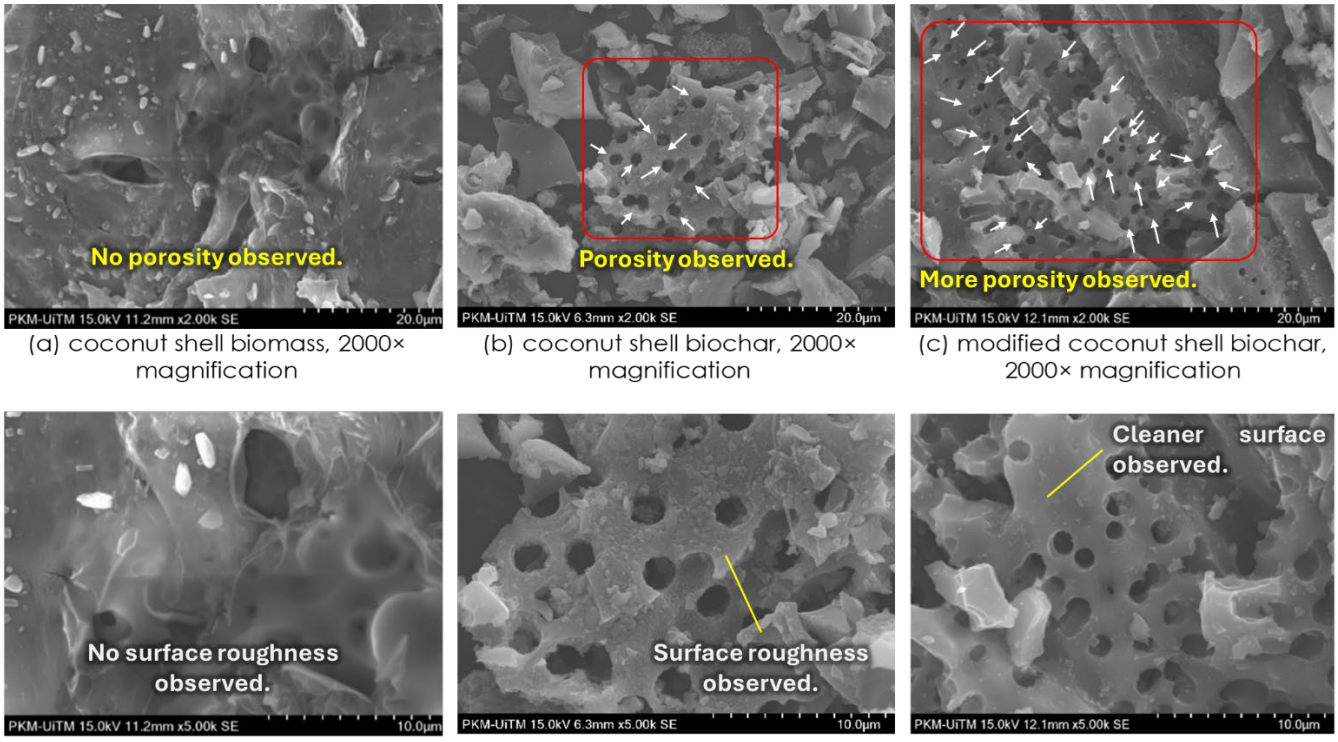


Figure 3 FTIR spectra of coconut shell biomass, biochar, and modified biochar

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

3.2.4 Scanning electron microscopy (SEM)

As depicted in Figure 4, at magnifications of 2000× and 5000×, SEM images illustrate the morphological changes as coconut shell biomass underwent self-sustained carbonization to produce coconut shell biochar, which later underwent methanol surface modification to produce modified coconut shell biochar. The SEM images of raw coconut shell biomass (Figure 2a,d) appeared smooth and compact with visible fibrous structures, while the SEM images of coconut shell biochar (Figure 2b,e) showed a rougher texture and increased porosity due to the self-sustained carbonization process, which removed volatile components and enhanced the surface area [54]. The SEM images of modified coconut shell biochar (Figure 2c,f) displayed more changes in porosity and surface roughness, indicating developed pore network creation of more micro- and mesopores [55], hence making it suitable for applications requiring high adsorption capacity in environmental and industrial applications [56].



(a) coconut shell biomass, 2000× magnification

(b) coconut shell biochar, 2000× magnification

(c) modified coconut shell biochar, 2000× magnification

(d) coconut shell biomass, 5000× magnification

(e) coconut shell biochar, 5000× magnification

(f) modified coconut shell biochar, 5000× magnification

Figure 4 SEM images of coconut shell biomass, biochar, and modified biochar at 2000× and 5000× magnifications. Arrows indicates the morphological transformation from smooth surface (a, d), to initial pore development (b, e), and finally changes in porosity and roughness (c, f) after methanol modification. Scale bars represent 20 µm (top row) and 10 µm (bottom row).

DOI: https://doi.org/10.11113/jurnalteknologi.v89.23077

4.0 CONCLUSION

This study evaluated the properties of coconut shell biochar produced via low-cost self-sustained carbonization at low retention times and introduced a methanol modification method to enhance its surface characteristics. After methanol modification, the BET surface area of the biochar improved significantly from 1.54 ± 0.02 to 158.18 ± 0.67 m²/g, while the total pore volume increased from 0.0005 ± 0.004 to 0.09 ± 0.06 cm³/g, at carbonization temperatures of 300–500 °C and retention times of 60–300 min. This enhancement was supported by SEM images, showing the development of pore networks with increased surface roughness and porosity, indicating the potential of coconut shell biochar as an adsorption material. The utilization of coconut shell biomass for biochar production via self-sustained carbonization at low retention times, followed by a methanol surface modification, successfully yielded a promising adsorbent for cleaner production, offering a feasible and sustainable coconut waste management strategy contributing to the bio-circular economy. However, this study was limited to self-sustained carbonization followed by methanol modification method. Future work should assess large-scale production feasibility, explore alternative modifications strategies, evaluate adsorption performance in real applications, and conduct both economic and environmental impact assessments.

Acknowledgement

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; Faculty of Health Sciences, Universiti Teknologi MARA (UiTM) Sarawak Branch, Samarahan Campus; and Faculty of Science & Natural Resources, Universiti Malaysia Sabah, for the analytical laboratory facilities and excellent technical support towards this research.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics declaration

Formal ethical approval was not obtained for this study. However, the authors confirm that the research was conducted in accordance with established ethical principles and good research practices, with due consideration given to participant rights, informed consent, confidentiality, and responsible data handling.

References

[1] J. O. Ighalo *et al.*, "Biochar from coconut residues: An overview of production, properties, and applications," *Ind. Crop. Prod.*, vol. 204, no. PA, p. 117300, 2023, doi: 10.1016/j.indcrop.2023.117300.

[2] E. Taer, R. Taslim, A. W. Putri, A. Apriwandi, and A. Agustino, "Activated carbon electrode made from coconut husk waste for supercapacitor application," *Int. J. Electrochem. Sci.*, vol. 13, no. 12, pp. 12072–12084, 2018, doi: 10.20964/2018.12.19.

[3] MOPC, "National Biomass Action Plan 2023-2030." Ministry of Plantation and Commodities, Putrajaya, Malaysia, pp. 1–22, 2023.

[4] C. H. Goh, "Green energy source going to waste," *The Star*, Petaling Jaya, Sep. 24, 2018.

[5] N. Ferronato and V. Torretta, "Waste mismanagement in developing countries: a review of global issues," *Int. J. Environ. Res. Public Health*, vol. 16, no. 1060, pp. 1–28, 2019, doi: 10.3390/ijerph16061060.

[6] J. Lehmann, "Black carbon decomposition under varying water regimes," *Org. Geochemical*, vol. 40, p. 846, 2009.

[7] A. Ajien, J. Idris, N. Md Sofwan, R. Husen, and H. Seli, "Coconut shell and husk biochar: A review of production and activation technology, economic, financial aspect and application," *Waste Manag. Res. J. a Sustain. Circ. Econ.*, vol. 41, no. 1, pp. 37–51, Jan. 2023, doi: 10.1177/0734242X221127167.

[8] J. Idris *et al.*, "Improved yield and higher heating value of biochar from oil palm biomass at low retention time under self-sustained carbonization," *J. Clean. Prod.*, vol. 104, pp. 475–479, Oct. 2015. doi: 10.1016/j.jclepro.2015.05.023.

[9] M. H. Samsudin *et al.*, "A one-step self-sustained low temperature carbonization of coconut shell biomass produced a high specific surface area biochar-derived nano-adsorbent," *Waste Manag. Res. J. a Sustain. Circ. Econ.*, vol. 37, no. 5, pp. 551–555, May 2019, doi: 10.1177/0734242X18823953.

[10] J. Idris *et al.*, "Improved yield and higher heating value of biochar from oil palm biomass at low retention time under self-sustained carbonization," *J. Clean. Prod.*, vol. 104, pp. 475–479, Oct. 2015, [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652615005697.

[11] M. H. Samsudin *et al.*, "Production of nanopore

structure bio-adsorbent from wood waste through a self-sustained carbonization process for landfill leachate treatment," *Biochem. Eng. J.*, vol. 189, no. September, p. 108740, 2022, doi: 10.1016/j.bej.2022.108740.
[12] J. Idris *et al.*, "Self-sustained carbonization of oil palm biomass produced an acceptable heating value charcoal with low gaseous emission," *J. Clean. Prod.*, vol. 89, pp. 257–261, Feb. 2015, doi: 10.1016/j.jclepro.2014.11.016.
[13] N. Hasana, R. Wahi, and Y. Yusof, "Ethanol, methanol, and magnesium-treated palm kernel shell biochar for methylene blue removal: adsorption isotherms," *Int. J. Curr. Res. Rev.*, vol. 13, no. 4, pp. 02–11, 2021, doi: 10.31782/IJCRR.2021.SP130.
[14] W. C. Oh, "Surface transition by solvent washing effects and biological properties of metal treated activated carbons," *Bull. Korean Chem. Soc.*, vol. 25, no. 5, pp. 639–646, 2004, doi: 10.5012/bkcs.2004.25.5.639.
[15] X. R. Jing, Y. Y. Wang, W. J. Liu, Y. K. Wang, and H. Jiang, "Enhanced adsorption performance of tetracycline in aqueous solutions by methanol-modified biochar," *Chem. Eng. J.*, vol. 248, pp. 168–174, 2014, doi: 10.1016/j.cej.2014.03.006.
[16] T. Ai, X. Jiang, Z. Zhong, D. Li, and S. Dai, "Methanol-modified ultra-fine magnetic orange peel powder biochar as an effective adsorbent for removal of ibuprofen and sulfamethoxazole from water," *Adsorpt. Sci. Technol.*, vol. 38, no. 7–8, pp. 304–321, 2020, doi: 10.1177/0263617420944659.
[17] G. Murtaza *et al.*, "Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants," *Sci. Rep.*, vol. 14, no. 1, p. 217, Jan. 2024, doi: 10.1038/s41598-023-50623-1.
[18] P. . Rangari and P. Chavan, "Preparation of activated carbon from coconut shell," *Int. J. Innov. Res. Sci. Eng. Technol.*, vol. 6, no. 7, pp. 220–225, 2017.
[19] S. J. Gregg and K. S. . Sing, *Adsorption, Surface Area, and Porosity*, 2nd Ed. New York, United States of America: Academic Press Incorporation, 1982.
[20] H. Kaur, B. Rana, D. Tomar, S. Kaur, and K. C. Jena, *Fundamentals of ATR-FTIR Spectroscopy and Its Role for Probing In-Situ Molecular-Level Interactions*, vol. 13, no. April. Springer Singapore, 2021.
[21] J. Coates, "Interpretation of Infrared Spectra, A Practical Approach," *Encycl. Anal. Chem.*, pp. 1–23, 2006, doi: 10.1002/9780470027318.a5606.
[22] K. Yadav and S. Jagadevan, "Influence of Process Parameters on Synthesis of Biochar by Pyrolysis of Biomass: An Alternative Source of Energy," in *Recent Advances in Pyrolysis*, IntechOpen, 2020, pp. 1–14.
[23] F. Amalina, A. S. A. Razak, S. Krishnan, A. W. Zularisam, and M. Nasrullah, "A comprehensive assessment of the method for producing biochar, its characterization, stability, and potential applications in regenerative economic sustainability – A review," *Clean. Mater.*, vol. 3, no. September 2021, p. 100045, 2022, doi: 10.1016/j.clema.2022.100045.
[24] M. Amer and A. Elwardany, *Biomass Carbonization*. 2020.
[25] R. K. Ahmad, S. A. Sulaiman, S. Yusup, S. S. Dol, M. Inayat, and H. A. Umar, "Exploring the potential of coconut shell biomass for charcoal production," *Ain Shams Eng. J.*, vol. 13, no. 1, p. 101499, Jan. 2022, doi: 10.1016/j.asej.2021.05.013.
[26] M. Inayat, S. A. Sulaiman, and M. Y. Naz, "Thermochemical characterization of oil palm fronds, coconut shells, and wood as a fuel for heat and power generation," *MATEC Web Conf.*, vol. 225, 2018, doi: 10.1051/matecconf/201822501008.
[27] V. Dhyani and T. Bhaskar, "Pyrolysis of Biomass," in *Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels*, 2nd ed., A. Pandey, C. Larroche, E. Gnansounou, S. K. Khanal, C.-G. Dussap, and S. Ricke, Eds. Amsterdam, Netherlands: Elsevier: Amsterdam, Netherlands, 2019, pp. 217–244.
[28] C. F. Núnez, J. Jochum, and F. Sierra Vargas, "Characterization and feasibility of biomass fuel pellets made of Colombian timber, coconut and oil palm residues regarding European standards," *Environ. Biotechnol.*, vol. 8, no. 2, pp. 67–76, 2012.
[29] A. Tomczyk, Z. Sokołowska, and P. Boguta, "Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects," *Rev. Environ. Sci. Biotechnol.*, vol. 19, no. 1, pp. 191–215, Mar. 2020, doi: 10.1007/s11157-020-09523-3.
[30] A. G. Adeniyi, K. O. Iwuozor, E. C. Emenike, O. J. Ajala, S. Ogunniyi, and K. B. Muritala, "Thermochemical co-conversion of biomass-plastic waste to biochar: a review," *Green Chem. Eng.*, vol. 5, no. 1, pp. 31–49, Mar. 2024, doi: 10.1016/j.gce.2023.03.002.
[31] N. Schapiro and E. J. Moreau, "Deashing Process of Coal," 19, 1986.
[32] Á. D. G. Llamas, N. Guo, T. Li, R. Gebart, and K. Umeki, "Rapid change of particle velocity due to volatile gas release during biomass devolatilization," *Combust. Flame*, vol. 238, p. 111898, Apr. 2022, doi: 10.1016/j.combustflame.2021.111898.
[33] J. G. O'Neill, "The Volatile Matter of Coal," *J. Am. Soc. Nav. Eng.*, vol. 28, no. 1, pp. 11–19, Feb. 1916, doi: 10.1111/j.1559-3584.1916.tb00597.x.
[34] Y. Y. Gan *et al.*, "Torrefaction of microalgal biochar as potential coal fuel and application as bio-adsorbent," *Energy Convers. Manag.*, vol. 165, no. March, pp. 152–162, 2018, doi: 10.1016/j.enconman.2018.03.046.
[35] J. Lehmann and S. Joseph, *Biochar for environmental management : science and technology*. Earthscan, 2009.
[36] Q. Liu, F. Takemura, and A. Yabe, "Solubility of hydrogen in liquid methanol and methyl formate at 20 °C to 140 °C," *J. Chem. Eng. Data*, vol. 41, no. 5, pp. 1141–1143, 1996, doi: 10.1021/je9601321.
[37] T. Sato, Y. Hamada, M. Sumikawa, S. Araki, and H. Yamamoto, "Solubility of oxygen in organic solvents and calculation of the Hansen solubility parameters of oxygen," *Ind. Eng. Chem. Res.*, vol. 53, no. 49, pp. 19331–19337, 2014, doi: 10.1021/ie502386t.
[38] S. Xu *et al.*, "Effect of biomass type and pyrolysis temperature on nitrogen in biochar, and the comparison with hydrochar," *Fuel*, vol. 291, no. October 2020, p. 120128, 2021, doi: 10.1016/j.fuel.2021.120128.
[39] T. Katayama and T. Nitta, "Solubilities of Hydrogen and Nitrogen in Alcohols and n-Hexane," *J. Chem. Eng. Data*, vol. 21, no. 2, pp. 194–196, 1976, doi: 10.1021/je60069a018.
[40] J. O. Ighalo *et al.*, "Biochar from coconut residues: An overview of production, properties, and applications," *Ind. Crops Prod.*, vol. 204, no. PA, p. 117300, 2023, doi: 10.1016/j.indcrop.2023.117300.
[41] J. H. Windeatt, A. B. Ross, P. T. Williams, P. M. Forster, M. A. Nahil, and S. Singh, "Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment," *J. Environ. Manage.*, vol. 146, pp.

189–197, Dec. 2014, doi: 10.1016/j.jenvman.2014.08.003.
[42] N. Khuenkaeo and N. Tippayawong, "Production and characterization of bio-oil and biochar from ablative pyrolysis of lignocellulosic biomass residues," *Chem. Eng. Commun.*, vol. 207, no. 2, pp. 153–160, Feb. 2020, doi: 10.1080/00986445.2019.1574769.
[43] L. M. R. Millán, F. E. S. Vargas, and A. Nzihou, "Characterization of Steam Gasification Biochars from Lignocellulosic Agrowaste Towards Soil Applications," *Waste and Biomass Valorization*, vol. 12, no. 7, pp. 4141–4155, Jul. 2021, doi: 10.1007/s12649-020-01241-9.
[44] D. Nuryana *et al.*, "Methylene blue removal using coconut shell biochar synthesized through microwave-assisted pyrolysis," *J. Teknol.*, vol. 82, no. 5, pp. 31–41, 2020.
[45] T. Rout, D. Pradhan, R. K. Singh, and N. Kumari, "Exhaustive study of products obtained from coconut shell pyrolysis," *J. Environ. Chem. Eng.*, vol. 4, no. 3, pp. 3696–3705, 2016, doi: 10.1016/j.jece.2016.02.024.
[46] J. Adorna, M. Borines, V. D. Dang, and R. Doong, "Coconut shell derived activated biochar – manganese dioxide nanocomposites for high performance capacitive deionization," *Desalination*, vol. 492, p. 114602, 2020, doi: 10.1016/j.desal.2020.114602.
[47] N. A. Baharum, H. M. Nasir, M. Y. Ishak, N. M. Isa, M. A. Hassan, and A. Z. Aris, "Highly efficient removal of diazinon pesticide from aqueous solutions by using coconut shell-modified biochar," *Arab. J. Chem.*, vol. 13, no. 7, pp. 6106–6121, 2020, doi: 10.1016/j.arabjc.2020.05.011.
[48] B. Behera, M. S. Selvam, B. Dey, and P. Balasubramanian, "Algal biodiesel production with engineered biochar as a heterogeneous solid acid catalyst," *Bioresour. Technol.*, vol. 310, p. 123392, 2020, doi: 10.1016/j.biortech.2020.123392.
[49] P. Pituya, T. Sriburi, and S. Wijitkosum, "Properties of biochar prepared from acacia wood and coconut shell for soil amendment," *Eng. J.*, vol. 21, no. 3, pp. 63–76, 2016, doi: 10.4186/ej.2017.21.3.63.
[50] R. M. Sari, S. Gea, B. Wirjosentono, S. Hendrana, and Y. A. Hutapea, "Improving quality and yield production of coconut shell charcoal through a modified pyrolysis reactor with tar scrubber to reduce smoke pollution," *J. Environ. Study*, vol. 29, no. 2, pp. 1815–1824, 2020, doi: 10.15244/pjoes/110582.
[51] A. H. Atienza, J. Orcullo, C. Salamat, and C. Wassmer, "Coconut shell feedstock based top lit updraft gasifier for biochar and heat cogeneration," *J. Phys. Conf. Ser.*, vol. 1519, p. 012014, 2020, doi: 10.1088/1742-6596/1519/1/012014.
[52] N. R. A. Manap, R. Shamsudin, M. N. Maghpor, M. A. Abdul Hamid, and A. Jalar, "Adsorption isotherm and kinetic study of gas-solid system of formaldehyde on oil palm mesocarp bio-char: pyrolysis effect," *J. Environ. Chem. Eng.*, vol. 6, no. 1, pp. 970–983, 2018, doi: 10.1016/j.jece.2017.12.067.
[53] B. Sajjadi, W. Chen, and N. O. Egiebor, "A comprehensive review on physical activation of biochar for energy and environmental applications," *Rev. Chem. Eng.*, vol. 35, no. 6, pp. 735–776, Jul. 2018, doi: 10.1515/revce-2017-0113.
[54] P. R. Yaashikaa, P. S. Kumar, S. Varjani, and A. Saravanan, "A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy," *Biotechnol. Reports*, vol. 28, p. e00570, 2020, doi: 10.1016/j.btre.2020.e00570.
[55] B. Sajjadi, T. Zubatiuk, D. Leszczynska, J. Leszczynski, and W. Y. Chen, "Chemical activation of biochar for energy and environmental applications: a comprehensive review," *Rev. Chem. Eng.*, vol. 35, no. 7, pp. 777–815, Oct. 2019, doi: 10.1515/revce-2018-0003.
[56] Y. Zhou *et al.*, "Production and beneficial impact of biochar for environmental application: A comprehensive review," *Bioresour. Technol.*, vol. 337, no. June, p. 125451, Oct. 2021, doi: 10.1016/j.biortech.2021.125451.