



Development of Kenaf Biochar in Engineering and Agricultural Applications

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Abstract

The aim of this review is to investigate the recent development of kenaf derived biochar and its composites in various engineering and agricultural applications including nanostructure catalysts and polymer composites as kenaf biochar and activated carbon are mainly used as material adsorbents and soil amendments. A systematic review on the effect of process parameters of thermal decomposition, pyrolysis towards the production of desired biochar, therefore, is in crucial needs. Based on existing literature, the properties and production of kenaf biomass and resultant biochar are discussed in this paper. This analysis focuses on the unique characteristics of kenaf crops and the resulting biochar, which has a surprisingly large surface area and increased pore volume, to explain their prospective applications, whether in environmental utilization or engineering applications. Range of optimum surface areas for kenaf biochar are around 800–1000 m²/g where they show high adsorption properties. Whereas, the pore volume of activated carbon usually exceeds 1 cm³/g. Recent developments in engineered kenaf biochar technology and its future directions for research and development are also discussed.

Keywords Kenaf biochar · Agricultural waste · Pyrolysis · Composites · Kenaf crops

1 Introduction

Biomass supply systems inherit the expertise of established agriculture and forestry sectors, even though the widespread use of agricultural products and logging wastes for the generation of bioenergy is emerging. Biomass feedstocks are regarded as a clean energy sources due to their efficient and long-term use may significantly reduce the environmental effect of fossil fuels [1, 2]. Thus, biomass feedstocks or also called as renewable carbon source are mainly originated from plants and plant-based materials which were left behind, they are abundant, renewable and the best possible alternatives of sustainable supply for bio fuels, bio products and bio energy generation. According to Faaij [3], biomass

feedstocks that can be used for energy are diverse: (1) primary residue, produced during production of food crops and forest products which mainly referred to agricultural or forestry residues; (2) secondary residues, yielded during stage of processing biomass into products at processing facilities like saw-mill; and (3) tertiary residues which related to the biomass derived wastes, varying from the organic components of municipal solid wastes, sludge and waste wood.

Kenaf (*Hibiscus cannabinus* L.) is regarded as an industrial crop, and belongs to family Malvaceae and is grown commercially in various geographical regions including Central Africa, India, Bangladesh, Thailand and Malaysia [4, 5]. Kenaf is the most significant cultivated plant for fibre production throughout the globe, second to cotton, and was widely used as medicinal herbs in ancient Africa. It has already been grown in Africa for 4000 years, and its components have been utilized by indigenous tribes for animal feed, food, handcraft production, and fuel [6, 7]. The kenaf crop is gaining popularity as a high-yielding “non-food crop” for fibre production, notably in the newspaper, pulp, and other paper-based industries. Its quick growth and higher yielding rate are associated to the facile pulp processing as well as easy-to-grow, in terms of progressive maturity in dry, shallow and sandy soils, and low-water content

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environments. Figure 1 shows the scenery in a kenaf field cultivated in one of the Far East countries. Recently, about 79% of total kenaf production belongs to India, China, and Africa, contributing to 46% (100,000 tonnes), 26% and 7% to the world kenaf production, respectively [8].

Kenaf is agricultural biomass/feedstock, utilized with the thermal decomposition to yield biochar, from several researchers, prior to exposure with acid chemical activating agent to produce low-price activated carbon [10]. Pyrolysis is the most widely used and successful method for producing biochar, carbonization of biomass [10]. In addition, one of the most significant avenues to better biofuels is thermochemical conversion utilizing the pyrolysis process. In the absence of oxygen, the thermal breakdown converted the biomass solid matrix into gaseous, liquid, and solid components. The primary feedstock compositions and experimental pyrolysis settings impact the features and compositions of these different by-products; which mainly dominated by the production of solid biochar [11, 12]. Biochar, a porous carbon comparable to activated carbon, offers numerous agronomic and environmental beneficial effects, including soil improvement, surface pollution adsorption, and inorganic and organic pollutant remediation in grounds [13].

Biochar, charcoal, and activated carbons are three carbon compounds with a lot of similarities in structure and processing mechanics [14, 15]. In anaerobic environments, biochar propensity for lower temperatures, below 700 °C, is particularly advantageous with respect to minimal maintenance relative to activated carbon manufacturing. Furthermore, because of its large surface area, comparable porosity, and functional groups, biochar has the same great promise as activated carbon to be used as an adsorbent in water treatment. Evaluating a biomass source's biochar potential is an environmentally interesting method since the material is readily available in huge quantities which is also readily decomposed [16]. The biochar generated was not further burned to generate energy; instead, it was used as a soil amendment, where it has been found to enhance water and nutrient storage, reduce bulk density, and enhance pH values [17] to be utilized for several applications.

Fig. 1 Calm view of kenaf field in Far East countries [9]



2 Agriculture Waste of Kenaf Fibre as Biomass for Biochar

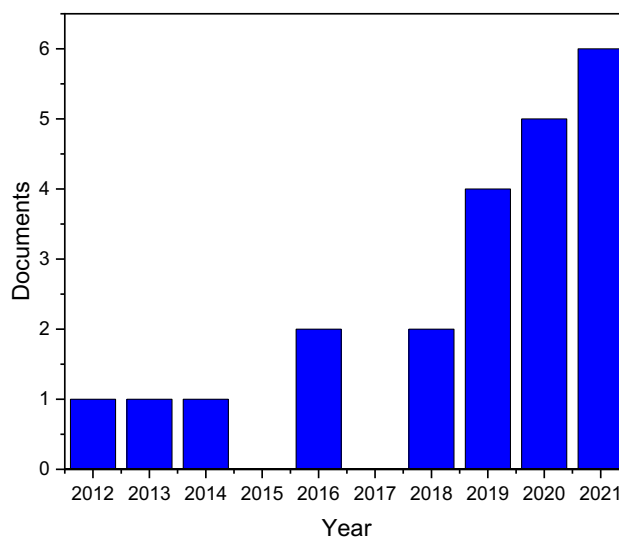


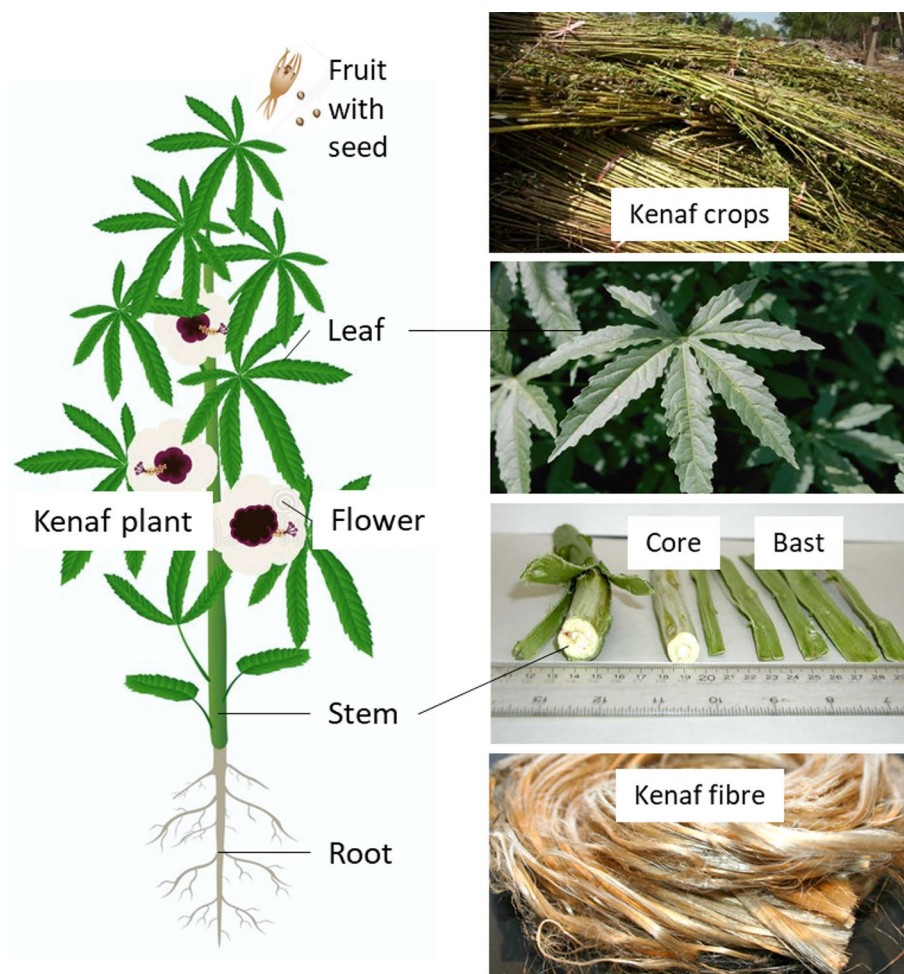
Fig. 2 Number of publications with topic of “kenaf biochar” from the year 2012 to 2021 (Source: Scopus, 9 October 2021). Many studies have examined the production of biochars from a wide variety of feedstocks into numerous applications including agricultural [18, 19], engineering [20, 21], wastewater treatments [22], electrochemical uses and renewable energy generation [23], with both positive and negative results. However, from this Fig. 2, there are only 22 publications related to the keyword “kenaf biochar” were discovered in Scopus (9th October 2021) from the year 2012 to 2021. In addition, there are only 57 scholarly works related to “kenaf biochar” were recorded from Lens.org (data extracted from <https://www.lens.org> on 9th October 2021). According to Web of Science, there are at least only 18 papers found related to the keyword where none of them is review work. Thus, these findings indicate the novelty of this work regarding providing literature review towards research on kenaf biochar throughout the globe. As for the novelties of this work, this paper elaborates on the fundamentals of biochar and its pyrolysis design, chemical and physical characteristics of kenaf biochar, as well as the developments and applications of biochar, especially kenaf derived biochar, in various sectors; agriculture, renewable energy, water purifications and composites engineering

Kenaf (*Hibiscus Cannabinus* L.) has been grown for its stem-derived fibres, which are often used for rope, during the last decade, as shown in Fig. 3. After fibre extraction, the rest of the plant is either left in nature or burned for heating or cooking, which plainly pollutes the environment. Furthermore, kenaf is regarded to be one of the most promising plants, leads to improved agricultural practices, enhanced processing processes, and research on future development [24]. Kenaf is a tropical annual herbaceous plant that is used in agriculture. This fibrous, herbaceous plant ranks third in biomass output and exhibits rapid growth rate, which takes less than 6 months to reach a size to be considered as matured suitable for practical uses [25]. The use of kenaf fibre cellulose has both environmental and economic benefits; for instance, it can grow up to 3 m tall with a 3–5 cm base diameter in 3 months under such a broad range of climatic circumstances, making it ideal for natural fibre surfaces and composites [26, 27]. When compared to other plants as potential sources of biochar materials, the crop provides a low-cost and ecologically safe choice in terms of its high fibre and cellulose component. Furthermore, kenaf is readily generated and widely available, particularly in

tropical areas; these important features make kenaf an excellent biochar material [16]. Long fibres make for roughly 30% of the overall plant volume, whereas short fibres account for the remaining 70% of the plant volume [10].

Kenaf is a multipurpose plant which could provide a variety of lucrative by-products for consumers and businesses. As a result, kenaf is widely utilized in pulp, paper, and cardboard manufacturing, as well as fibre reinforced composites, natural fuels, cellulose products, absorbent agents, and animal feed [30]. Kenaf has a low density, is very absorbent, is non-abrasive during processing, has excellent specific mechanical characteristics, and is biodegradable. Turning char by-product into carbon particles is one of the value-added benefits [2]. The carbon compounds might be employed in water and beverage purification systems, as well as in electrode manufacturing technologies as supercapacitor electrodes. The size distribution, surface area, pore diameters, and flexibility of biochar determine its quality. The mass ratio, milling hours, and sample post-treatment all play a role in producing high-quality biochars. These can be obtained by fine-tuning the process parameters throughout the manufacturing

Fig. 3 Kenaf plants as biomass feedstocks [28, 29]



process [31]. Consequently, biochar generated from kenaf fibres, which originate from its stems and leaves, has been utilized in a wide range of applications, including wastewater treatment [32], biofuels generation including biogas, bioethanol, biodiesel, and biohydrogen [9], polymer composites [33, 34], and horticultural substrate synthesis [35].

2.1 Proximate and Ultimate Analysis of Kenaf Fibre

The dried kenaf stems are shown in Fig. 4. The ultimate and proximate analyses, as well as the inorganic concentration in the kenaf samples, are shown in Table 1. The results are within the range of typical agricultural and food processing residue compositions described in the literature [24, 36]. The carbon content of raw kenaf is estimated to be around 47.32 wt%, according to the elemental composition of ultimate analysis. In addition, the production of biochar due to slow pyrolysis suggesting a fixed carbon content of 15.80 wt%. From the study, the heating value (HHV) and low heating value (LHV) of the kenaf fibre is 18.54 MJ/kg and 17.38 MJ/kg, respectively, which is comparable to the HHV of other biomasses [23, 37].

The elemental composition study in Table 2 reveals that the major minerals found in the kenaf stems are K (20.59 g/kg), Ca (8.16 g/kg), P (3.29 g/kg), and Mg (1.75 g/kg). These components, in its char yielded via slow pyrolysis, are extremely beneficial to plant growth and development.



Fig. 4 Dried kenaf stems

Table 1 Proximate analysis (wt%) of kenaf fibre

Moisture content	4.4
Volatile matter	83.05
Fixed carbon	15.80
Ash	1.15
LHV (MJ/kg)	17.38
HHV (MJ/kg)	18.54

2.2 Chemical Characteristics of Kenaf Fibre from Different Parts

Chemical composition variations occur along the stalks/branches of kenaf plant. From the bottom part of the stalks or branches to the top, the concentration of α -cellulose, lignin, and ash declines. This was hypothesized as mature tissues acquire more metabolic products than younger tissues located at the top part [38]. Several studies [39–41], however, have shown that the bast and core differ significantly in morphologic structure as well as in chemical composition.

Chemically, the chemical components of kenaf bast and core were significantly distinct. Table 3 shows the chemical analytical results for the entire kenaf (including its core and bast), kenaf core and bast [24, 36]. Excluding the ash, the percentages of all the chemical components of kenaf (non-wood) are more or less identical to those of wood products, according to the findings of this study. When compared to wood products, kenaf had a higher ash content. This demonstrated that the non-wood fibres had a significant silica content, which was known to be a disadvantage in mechanical strength qualities for the end products [40, 42]. The ash content of whole kenaf, its core, and its bast fibers was 4%, 1.9%, and 5.4%, respectively. Extractive was often wasted and was not utilized in manufacturing and production.

Table 2 Elemental and mineral composition of kenaf fibre

Elemental composition (wt%)	
C	47.32 (± 0.8)
H	5.20 (± 0.3)
N	0.38 (± 0.03)
S	<0.02
O	47.1
Mineral composition (g/kg)	
Al	0.30
Ca	8.16
Fe	0.38
K	20.59
Mg	1.75
Zn	0.12
Cl	0.23
P	3.29
Si	1.50

Table 3 Chemical composition of different fractions of kenaf fibre [43]

	Wood				
	Kenaf bast	Kenaf core	Kenaf whole (core and bast)	Softwood	Hardwood
Holocellulose (%)	86.8	87.8	87.7	60–80	71–90
α -Cellulose (%)	55.0	49.0	53.8	30–60	31–64
Lignin (%)	14.7	19.2	21.2	21–37	14–34
Extractive (%)	5.5	4.7	6.4	0.2–8.5	0.1–7.7
Ash (%)	5.4	1.9	4.0	<1	<1

According to Table 3, the percentage of chemical composition in kenaf fibres showed that kenaf core fibres were higher in holocellulose and lignin, whereas kenaf bast fibres were higher in α -cellulose and ash content when compared to others [44]. The high α -cellulose content of bast fibre is assumed to provide high strength in paper formation and other fibre end products. It was mentioned that the cellulose (bast fibre 52–59%, core 44–46%) and lignin (bast fibre 9.3–13.2%, core 18.3–23.2%) contents of the kenaf plant increased significantly during maturation [45]. Figure 5 shows the SEM images of kenaf core fibres and bast fibres.

Kenaf lignin was comprised of three major lignin units in varying ratios: *p*-hydroxyphenyl, guaiacyl, and syringyl. The total lignin content of the kenaf stalk (core and

bast) was approximately 21.2%, which was higher than the results acquired by Kuroda et al. [39]. Due to their reduced lignin composition, the core and bast samples comprised 19.2% and 14.7% lignin, respectively, which was slightly lower than that of softwood (21–37%) and is favourable for pulping compared to wood. The analysis of plant material samples at different heights/lengths revealed that lignin and cellulose concentration vary with tissue maturity however do not vary considerably within each species. Paper strength is also affected by the lignin and cellulose content of raw plant materials; pulp mechanical strength, particularly tensile strength, is directly proportional to cellulose content, whereas lignin is an undesirable polymer that

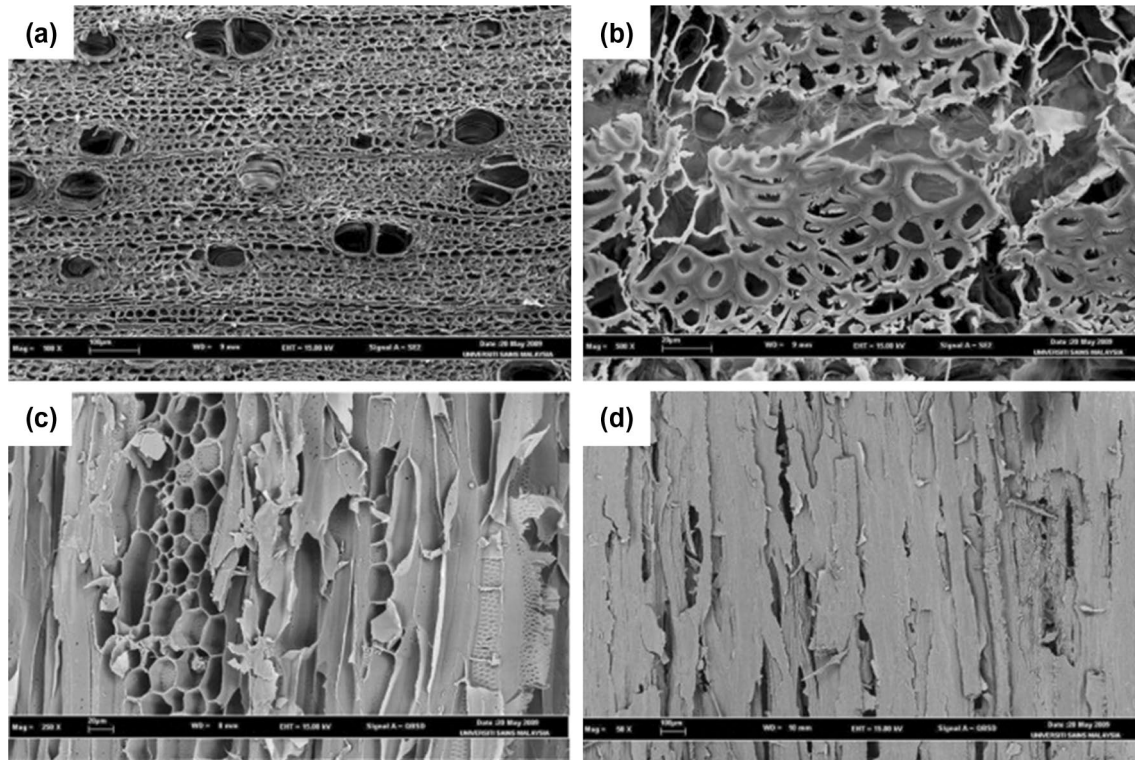


Fig. 5 Scanning electron micrograph of kenaf fibre at different parts: transverse section of **a** core fibres, and **b** bast fibres; longitudinal section of **c** core fibres, and **d** bast fibres

requires a lot of energy and chemicals to remove during the pulping process [40].

3 Manufacture of Kenaf Biochar and Its Characteristics

3.1 Pyrolysis Design for Kenaf Fibre Biochar

Biochar is a solid residue generated through the thermal decomposition of biomass into fuel by-products [46], and it has traditionally been considered as a lower-value by-product compared to syngas and bio-oil, which are even more desirable. Kenaf biochar is produced by carbonizing kenaf stems at 1000 °C in an inert environment [47, 48]. From another work, according to Yusof et al. [31], biochar is made from biomass compounds that are pyrolysed/gasified under controlled conditions in the absence of oxygen at temperatures ranging from 300 to 1000 °C. Incomplete gasification produced charcoal, also known as bio-char or agri-char, which is a by-product of pyrolysis technology used in bio-fuel and ammonia manufacturing. These processes created a large amount of biochar, necessitating a greater use of it. It is also possible to assist agricultural operations become more sustainable, dependable, and tangibly create a healthier green environment, despite the fact that it may be turned from waste to wealth [31].

Based on previous works, Saeed et al. [50] proposed the value range of the pyrolysis temperature for kenaf from 300 to 600 °C. The range was chosen based on prior research's recommendations [31, 32, 51] which stated that the kenaf mass loss was attributed to three main stages: (1) drying and evaporation of light particles, happened at temperatures below 150 °C, (2) volatilization of hemicellulose and cellulose, started degassing from 150 to 375 °C, and (3)

decomposition of lignin, at temperatures above 400 °C. As a result, the suggested pyrolysis temperature range was 300–600 °C, which helped convert lignin into biochar while also keeping biochar stable. The pyrolysis temperature generally dominates the impact of residence time. As a result, determining the effect of residence time in biochar stability might be difficult at times [52]. The heating rate was set at 10 °C/min, which was deemed low though ideal for generating biochar from agricultural biomass [53] (Fig. 6). Moreover, a lower heating rate facilitated the development of aromatic structures in biochar and the preservation of structural complexity, whereas a high heating rate promoted the loss of structural complexity owing to local melting of cell structures, phase transitions, and swelling [54] (Table 4).

3.2 Kenaf Biochar Characteristics

When activated, microporous carbon with a large surface area generated in this way might be employed in pollution removal [58]. In anaerobic circumstances, biochars propensity for lower temperatures (below 700 °C) is particularly advantageous in perspective of minimal maintenance contrasted to activated char manufacturing. On the other hand, the heating value of kenaf residues in the fluidized bed gasification method is thought to be inefficient for generating electricity [59], even if the generated gas could fulfil the demand for energy generation by gas engines.

Furthermore, several pyrolysis products produced from the entire kenaf were discovered [10, 16, 24, 31], mainly bio-oil and biochar, with the possible to be transformed into more valuable chemicals, and their distribution was found to be comparable to that of hardwood, which the primary products are syringol and guaiacol compounds. The phenol concentration of the kenaf core pyrolysate was greater than that of the kenaf cuticle, indicating that the kenaf core had

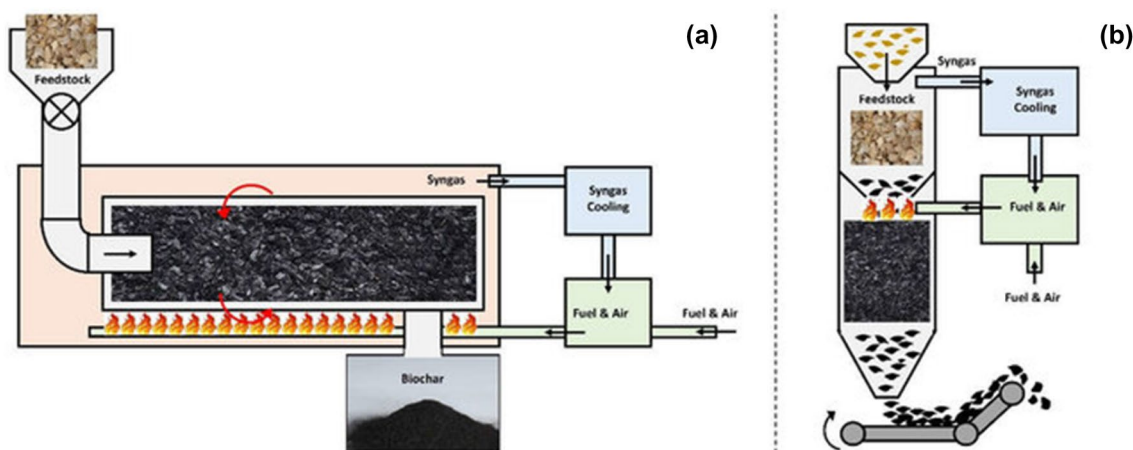


Fig. 6 Schematic illustrations of **a** horizontal pyrolysis reactor (such as rotary kiln reactor) and **b** vertical pyrolysis reactor (such as free-fall reactor) used to pyrolysed biomass feedstocks [23, 49]

Table 4 Literature work on pyrolysis of kenaf to yield biochar with different pyrolysis parameters

Biomass waste	Temperature range (°C)	Residence time (h)	Heating rate (°C/min)	Flowrate of inert gases (L/min)	Biochar yields (wt%)	Application	References
Kenaf	300–750	1	20	0.5	24.6	Triclosan adsorption of 77.4 mg/g	[55]
Kenaf fibre	550	3	10	100	28.6	Cd ²⁺ biochar adsorbent 23.48 mg/g	[50]
Kenaf fibre	1000	3	5	–	–	Oxidative degradation of bisphenol A in water	[56]
Kenaf core	400	1	7	–	35.44	Highly efficient removal of selected endocrine-disrupting compounds	[16]
Kenaf fibre waste	500	1	–	100	20	Adsorbents	[10]
Kenaf stem	400–600	1	20	10	31	Pollutants removal or gas storage and soil amendments	[24]
Kenaf stem	500	1	5	10	30	Soil amendments	[57]

more lignin. Kenaf has a low overall bio-oil production when equalled to wood, yet a high yield when compared to other agricultural crops [60].

3.2.1 Kenaf Biochar Chemical Characterization

Biochar is one of the most important kenaf stems pyrolysis by-products. Biochar will be produced during the final pyrolysis of kenaf feedstocks as shown in Fig. 7. Several main pyrolytic parameters, including such process temperature, heating rate, feed rate, catalysts, and pressure, will influence the formation of biochar [2, 63]. According to previous studies, the biochar yields are decreases with increasing of the used pyrolysis temperature [64]. The char obtained by pyrolysis will be characterized via several analyses.

3.2.1.1 Ultimate and Proximate Analysis Table 5 lists the chemical properties of kenaf biochars as determined. The carbon, hydrogen, nitrogen, oxygen, sulphur and ash content of kenaf biochar were approximately between 40.0–90.0, 1.0–3.0, 0.01–1.20, 10.0–50.0, 0.0–0.5, and 10.0–40.0%, respectively. Proximate analyses of the different biochars are summarized in Table 6. Comparison between the different pyrolysis temperatures shows higher amounts of

volatiles matter at 400 °C which decrease with increasing of temperature from 34.5 to 19.9 wt% at 600 °C. On the contrary, the weight loss associated with the fixed carbon increases with the increase of pyrolysis temperature from 60.2 to 73.2 wt%. Similar trend is recorded for ashes. Such result can be attributed to the low inorganic contents which is vital due to their abilities to produce low ash and high fixed carbon contents [36].

3.2.1.2 Mineral and Elemental Compositions Table 7 reveals that Mg and K are the most abundant mineral elements in the charcoal. Kenaf biochar contains non-negligible amounts of Ca, P, Zn, and Na. As a result of the decomposition/devolatilization of a portion of the kenaf, the biochars are rich in carbon and minerals. As a result, the use of kenaf char as an agricultural additive might be suggested.

3.2.1.3 Specific Surface Area Charcoals are non-specific or at least poorly specific adsorbents, exhibiting numerous macro-and transition pores of various diameters, and as a consequence of the large surface areas. Range of optimum surface areas for kenaf biochar are around 800–1000 m²/g where they show high adsorption properties [68]. Table 5 shows the findings of the BET surface area study and the

Fig. 7 **a** FESEM images of kenaf biochar pyrolyzed at 450 °C and **b** image of kenaf biochar yielded via slow pyrolysis [55]

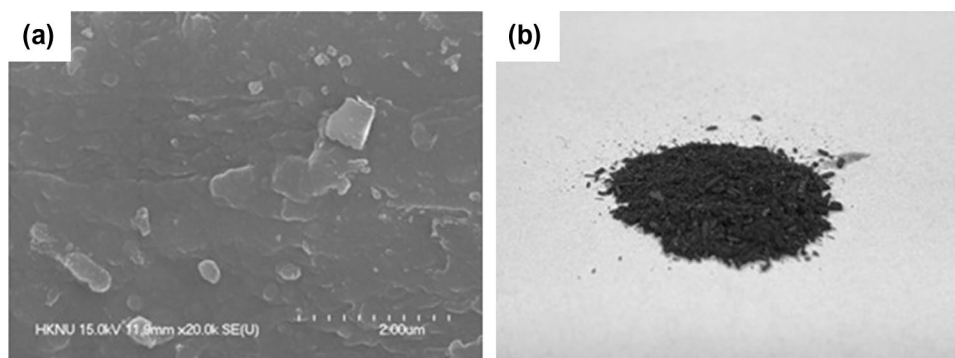


Table 5 Chemical characteristics of kenaf and its biochar

Biochar	Pyrolysis temperature (°C)	Specific surface area (m ² /g)	Pore volume (cm ³ /g)	Pore width (nm)	Elemental composition (wt%)						References
					C	H	N	O	S	Ash	
Raw kenaf core	400	1.1381	0.0212	464.54	46.210	2.850	0.510	–	0.510	–	[16]
Bleached kenaf core	400	4.8168	0.0001	38.79	49.650	2.110	0.013	–	0.480	–	[16]
Biochar	550	117.70	0.0639	2.17	67.52	1.270	1.23	19.18	–	10.80	[61]
Magnetic biochar	550	175.55	0.1024	2.33	58.32	1.120	1.06	25.75	–	13.75	[61]
Kenaf fibre biochar	1000	289.50	–	–	50.50	1.878	0.268	8.47	0.025	38.86	[62]
HCl treated KFC	1000	346.57	0.0040	~3.00	55.54	1.957	0.142	39.31	0	3.049	[62]
Kenaf	500	261.20	–	–	97.70	–	–	–	0.075	–	[57]
Kenaf biochar	500	261.20	0.088	1.36	67.50	–	–	–	1.5	6.6	[24]
Kenaf fibre biochar	500	11.4	0.017	5.92	46.70	2.31	1.2	56	0.113	22.7	[10]
Kenaf biochar	450	4.6	0.0224	19.26	54.10	2.2	0.7	12.1	0.6	–	[55]

Table 6 Proximate analyses of the produced biochars (%)

Biochar	Moisture content	Volatile matter	Fixed carbon	Ash content	References
KFB	3.4	17.5	56.4	22.7	[10]
KB	–	25.9	67.5	6.6	[24]

Table 7 Mineral composition of the biochars obtained at different temperatures (g/kg)

Element (wt%)	Kenaf biochars			Other biochars [65–67]
	[24]	[57]	[55]	
Na	2.4	0.1	–	1–5
Mg	10.3	0.6	0.4	0–2
Al	0.5	0.03	–	–
Si	0.8	0.1	–	–
P	1.3	0.16	–	0.1–2
S	1.5	0.08	0.6	–
Cl	0.2	–	0.4	–
K	7.3	0.64	4.2	2–10
Ca	6.8	0.53	0.7	5–20
Fe	0.3	–	–	–
Zn	2.3	–	–	–
Sr	0.1	–	–	–
N	–	–	–	0–1
O	–	–	14.0	–

textural characteristics of the kenaf biochars. The observed values are rather high, which is a significant benefit for using kenaf biochars to remove contaminants from effluents. The kenaf biochars' specific surface area was estimated using the BET technique and CO₂ adsorption isotherms. According to Khiari et al. [24], the surface area of the produced biochar

increased considerably from 162 to 261 m²/g as the pyrolysis temperature increased. This progression is explained by a change in the textural characteristics of the biochars, which can be related to the minor devolatilization observed between 400 and 500 °C, which creates more microporosity in the carbon matrix. In addition, greater temperatures appear to influence the porosity of the char [16].

The surface of the biochars grew rougher and more porous as the pyrolysis temperature high. The organic component of pyrolyzed kenaf at high temperatures vanished owing to devolatilization/decomposition, resulting in pyrolyzed kenaf with a rough surface [9]. Cho et al. [55] observed that when the pyrolysis temperature increased, the specific surface area of kenaf biochar grew dramatically from 5 to 270 m²/g, which is improved >65 times, and even the porosity of kenaf biochar enhanced. Previous studies [2, 69, 70] has also found that when the pyrolysis temperature rises, the specific surface area increases by more than ten-fold. The liberation of volatile organic chemicals and the oxidative breaking of cellulose, hemicellulose, and lignin are due to the rise in specific surface area caused by pyrolysis temperature increase [55]. Furthermore, inside the biochar that was pyrolyzed at high temperatures, a complex pore structure with a rough surface was discovered as a result of dissolving the unstable component and softening the stable structure in biomass, which resulted in shrinkage, collapse, and melting of the pore [71].

3.2.1.4 Raman Spectroscopy Raman spectroscopy is used to determine phase and polymorphisms, as well as pollution and impurities. Figure 8 depicts Raman spectrometry curves from this investigation by Khiari et al. [24]. The Raman spectra at 400 °C showed a signal with no discernible peaks, which was attributable to the high amount of amorphous carbon structures generated at low pyrolysis temperatures. The Raman spectra at 500 °C showed two relatively large

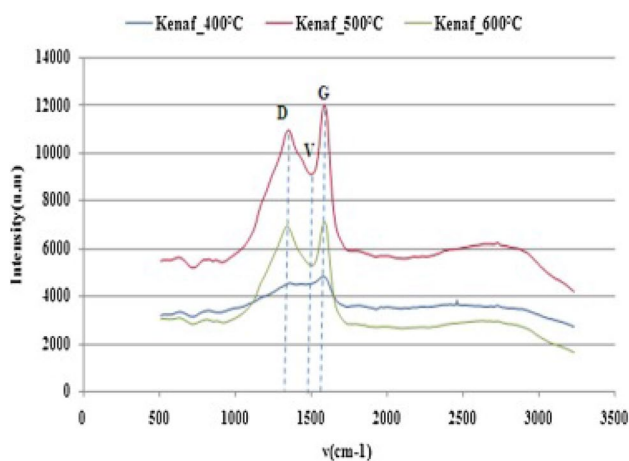


Fig. 8 Raman spectra of the kenaf biochar produced at 400, 500 and 600 °C [24]

Raman bands at 1300 and 1600 cm^{-1} . The D-band is associated with sp^2 bonded carbon with structural flaws, whereas the G-band is associated with the in-plane vibrations of sp^2 bonded graphitic carbon structures. The valley area “V” between the D-band and the G-band is connected to the amorphous carbon structure. Structure characteristics such as I_D (D band intensity height), I_G (G band intensity height), I_V (valley region intensity height) and the distinct ratios I_D/I_G , I_V/I_G , and I_V/I_D have been computed from these spectra in order to obtain detailed information on the structure of the individual chars [24].

The I_V/I_D and I_V/I_G ratio decreases due to the char evolution structure with pyrolysis severity from amorphous to more organized carbon (turbostratic char). As for I_D/I_G , this ratio decreases indicating an increase of the proportion of condensed aromatic ring structures having defects. Condensation of tiny aromatic amorphous carbon structures results in D structures. These findings are consistent with the results observed for exhausted grape marc char after various thermal treatments [72], see Fig. 9. This behavior can be due to the significant amount of amorphous carbon structures formed during low-temperature pyrolysis [57]. The Raman spectra above 500 °C showed two reasonably wide Raman bands. The other biochar has a similar tendency. This behaviour may be described by the char evolution structure with the severity of pyrolysis from amorphous carbon to structured carbon (turbostratic char).

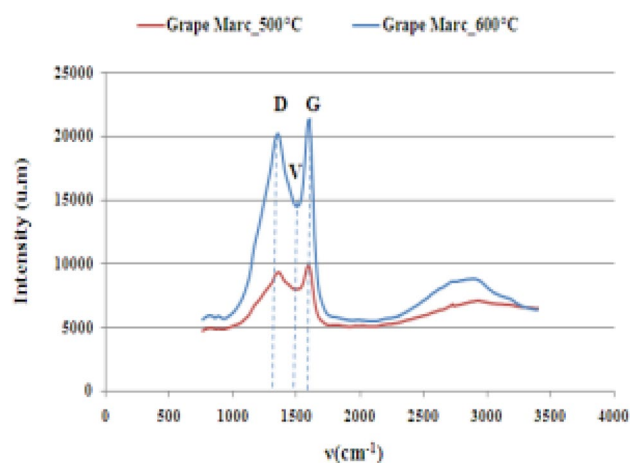


Fig. 9 Raman spectra of the grape marc biochars produced at different temperature [57]

4 Recent Applications of Kenaf Biochar and Its Composites

4.1 Materials Adsorbents for Wastewater Treatments

Lacks in wastewater treatment happened when there are no alternatives in purifying and treating the sludge prior to disposal. Sludge with a high concentration of heavy metals such as Fe, Ti, Mn, Zn, As, Cu, Ni, Zr, and Ga is often disposed of in landfills [11]. The recovery of valuable minerals like manganese from sludge is an alternative to zero disposal of solid wastes and a means to reduce pollution emission into the environment. It may be accomplished by adsorption, which is a low-cost, versatile, and simple-to-implement technique. Kenaf derived biochar which then chemically activated into activated carbon has been shown to be an excellent adsorbent material for heavy metals removal. The goal of this research is to use kenaf fibre as activated carbon in batch adsorption to recover heavy metals from wastewater sludge. The adsorption effectiveness of adsorbents was studied in relation to contact time, sludge pH, and temperature as well as its surface area and pore properties. The results indicated that the newly produced kenaf activated carbon and biochar are the most possible alternative adsorbents for heavy metals [50].

According to a batch adsorption research [13], kenaf fibre-derived activated carbon is capable of removing 30% of the heavy metal element from the sludge. It was also discovered that the optimum removal occurs in a neutral pH solution, that increasing contact duration increases equilibrium absorption, and that raising temperature increases the amount of heavy metal removal [13]. The development of heavy metal removal methods for aquatic environments is in great demand. Saeed et al. [10] had

investigated the pyrolysis of raw materials including rice husk and kenaf fibre as agricultural lignocellulosic wastes for the adsorption of Cu^{2+} . The surface area of biochar produced increases proportionately to the increasing quantity of kenaf fibre in the mixing ratio rice husk/kenaf fibre as biomass feedstocks, according to BET characterization findings. This morphology and surface area analysis revealed that pure biochars made from kenaf fibre had a lot of promise as adsorbents. However, blending both fibres does not provide the intended outcome for utilization as an adsorbent, which has a detrimental impact on biochar production since the oxygen-to-carbon and hydrogen-to-carbon ratios were outside the usual range, affecting biochar stability. As a result, it impacted copper ion adsorption from aqueous solutions [10].

In another work from Saeed et al. [61], the adsorption study on cadmium materials had resulted with optimum adsorption under pH 5–6. The textural characteristics of biochars, such as surface area and pore volume, were improved by increasing the amount of oxygen-containing groups and creating inner-sphere complexes with oxygen-containing groups. Increased adsorption capacity was achieved by increasing the initial ion concentration and solution temperature. The use of iron oxide on the surface of biochar to impart a magnetic characteristic allowed for simple separation and regeneration using an external magnet. In comparison to pure biochar, the magnetic biochar composite had a greater affinity for Cd^{2+} . By acid treating kenaf fibre biochar with HCl, an adsorbent was created. In batch system experiments, the treatment increased the BET surface area, which resulted in an increase in the adsorption of methylene blue dye (MB). Variations in the initial dye concentration, adsorbent dosage, pH, and temperature were used to examine the adsorption process. At a concentration of 50 mg/L, the greatest percentage removal of MB was determined to be 95 wt%. The dye sorption was optimal at a pH of 8.5 [32].

4.2 Soil Amendments in Agriculture

Ferjani et al. [57] studied three agricultural biomass including grape marc, kenaf stems, and flax shive, for biochar production. For a future possible application in agriculture, the pyrolysis operation was carried out at 400, 500, and 600 °C with a continuous heating gradient rate of 5 °C/min. The biochar yields declined as the applied pyrolysis temperature increased, but remained relatively stable at 500 °C for all feedstocks, according to the results. Grape marc and kenaf contain the largest quantity of theoretically accessible minerals, as well as an intriguing surface area and microporosity value, according to their physico-chemical characteristics [57]. These characteristics make biochars excellent for soil improvements and the adsorption of contaminants from environment.

Yao et al. [73] had successfully investigated the utilization of biochar derived from Mg-enriched tomato tissues in order to adsorb and recover phosphate from wastewater, which was then cycled back into grounds as an efficient slow-release phosphate fertilizer. According to Vithanage et al. [74], acid treatment enhanced the specific surface area of bur-cucumber derived biochar, exhibit better sulfamethazine adsorption ability and should be utilized as possible soil bioremediation suitable for sulfamethazine-polluted soils.

4.3 Electrochemical Applications of Kenaf Biochar

Biochar has been utilized as an electro catalyst and photo catalyst in the electrochemical water-splitting process to produce hydrogen and oxygen [75, 76]. The addition of a heteroatom produces active sites in biochar, allowing for a more efficient hydrogen evolution process (HER). S-doped and N-doped biochars produced from peanut root nodule (see Fig. 10), for example, have been shown to be effective HER electro catalysts. Because of its large electrochemical area of 27.4 mF/cm^2 , the doped biochar demonstrated an

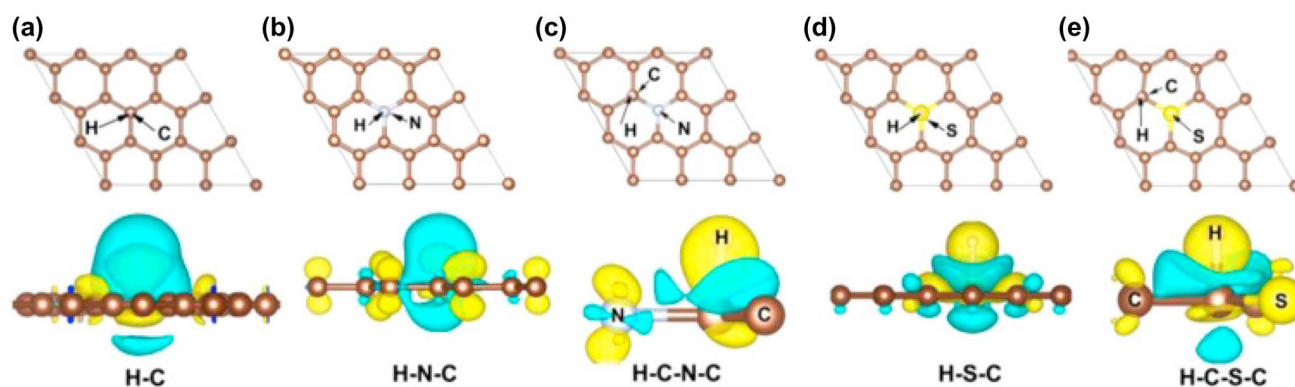


Fig. 10 Structural models and charge density of H adsorbed on the surface of graphene, N-doped graphene and S-doped graphene. The blue and yellow symbols represent a drop in charge density and a rise in charge density, respectively

outstanding onset potential of 27 mV compared to reversible hydrogen electrode (RHE) for HER, which is similar to a commercial Pt/C catalyst with a loading of 20 wt% [77]. Figure 10 shows the effect of S and N doping into carbon on HER. The flowing process was as follows: (a) H atom was combined on the C atom; H atom was combined on the N (b) or S (d) dopant atom; H atom was combined on the C atom around N (c) or S (e) dopant atom.

Nanostructure catalysts made from sunflower seed shell charcoal and molybdenum carbide (Mo_2C) nanoparticles are another example. At an over potential of only 60 mV, this integrated electro catalyst produced a current density of 10 mA cm^{-2} for HER. Most notably, this catalyst has a near-unity faradaic efficiency and is extremely durable [78]. Growth of molybdenum diselenide (MoSe_2) nanosheets on a carbon fibre aerogel is another example. Cotton wool biomass was used to make the carbon aerogel. At an onset potential of 104 mV, this MoSe_2 /carbon fibre electro catalyst demonstrated HER vs RHE [79]. Without a doubt, current biochar catalyst performance lags well below that of the most effective water-splitting catalysts, with over-potentials of 13 and 17 mV at a current density of 10 mA/cm^2 [80]. It does, however, have the potential to be employed as an abundant alternative catalyst material for the generation of hydrogen and oxygen.

The utilization of biomass waste materials to manufacture activated carbons has become a huge technology in carbon supercapacitor electrodes [81, 82]. Various kind of agricultural biomass including cotton stalks [83], discarded coffee beans [84], seaweed biopolymers [85], corn stalks [86], roselle [87, 88], and sugarcane bagasse [89] have all been reported as carbon electrodes in supercapacitors. The carbon precursor and modification circumstances utilised ascertain the electrochemical attributes of double-layer capacitance, including such high surface area, porosity distribution, conductivity, as well as the existence of electrochemically active surface functional groups, and hence impact the performance [82, 90]. Because of their enormous surface areas, relative inertness, and abundant possibilities for doping and structural tweaking, carbons generated from biomass play such an important role in electrochemistry [91].

4.4 Horticultural Applications

Biochars may be utilized in a variety of horticultural applications, such as replacing peat moss on soilless substrates for containerized greenhouse and nursery crops. Hardwood pellets and pelletized wheat straw were used to make biochar via pyrolysis as shown in Fig. 11. The potassium concentration and pH of straw biochar were greater than those of wood biochar [46]. In comparison to non-activated biochar, steam activation of biochar might hasten its beneficial effects on nutrient retention and uptake by plants. In all cases, steam

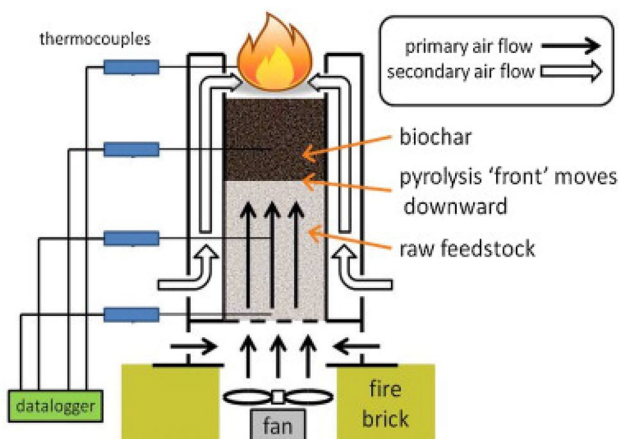


Fig. 11 Schematic illustrations of thermal decomposition of raw biomass [46]

activation almost doubled the beneficial benefits of biochars, making it a promising choice in order to use biochar in future [92]. After modification, biochars' adsorption ability of nitrate and phosphate improves, implying that activated biochars could also be used as adsorbent materials to reduce nutrient loss in grounds and for further horticultural purposes [93] (Table 8).

4.5 Future Directions of Kenaf Biochar in Composite Applications

There is difficult to find any published works on kenaf derived biochar uses in composite applications. However, it is remarkably found that the surface area (approximately $120\text{--}300 \text{ m}^2/\text{g}$) and micropore volumes (over $0.088 \text{ cm}^3/\text{g}$) of kenaf biochar is quite similar to the other commercialised biochars such as durian rind, sugarcane bagasse, rice straw and corn straw, as according to previous works [10, 24, 31]. Thus, numerous applications could be found in composite engineering with the contribution from distinct characteristics of kenaf biochar based composites including production of magnetic biochar for low-cost supercapacitor application [94], low-price novel engineered adsorbents [95], biochar composite-based catalysts [96], bacterial/biochar composites for bioremediation [97], and antibacterial composite for water treatment [98].

Despite the difficulties in finding research work on kenaf biochar uses in composites engineering, biochar derived from other biomass feedstocks had been widely commercialised as reported in literature. Matykiewicz [99] had fabricated carbon fibre reinforced biochar/epoxy composites for mechanical reinforcements. From the results, the mechanical and thermal properties of the biochar reinforced composites improved by almost 5% compared to the neat one. Das et al. [100] had utilized biochar originated from pine wood waste

Table 8 Current application of kenaf and other biomass derived biochar in various applications

Biochar	Applications	Uses	Key points	References
Kenaf biochar	Wastewater treatments	Cd ²⁺ adsorbents	Optimum adsorption achieved under pH 5–6 Surface modification of biochar using iron oxide for imposing magnetic property allowed for easy separation by external magnet and regeneration, with the maximum adsorption capacity of 47.90 mg/g	[61]
Kenaf fibre activated carbon (KFAC)	Sludge treatment	Heavy metals adsorbents	BET surface area—11.4 m ² /g; micropore volume—0.1072–0.2169 cm ³ /g; cumulative adsorption area—210–600 m ² /g	[13]
Kenaf biochar	Wastewater treatments	Cu ²⁺ adsorbents	BET surface area—400–500 m ² /g; pore volume—0.017 cm ³ /g; removal efficiency of Cu ²⁺ —12.30%	[10]
Rice husk biochar	Wastewater treatments	Cu ²⁺ adsorbents	The rice husk biochar showed good adsorption of copper ions from aqueous solutions. BET surface area—13.6 m ² /g; pore volume—0.0076 cm ³ /g; removal efficiency of Cu ²⁺ —65.80%	[10]
Kenaf fibre biochar	Agriculture	Soil amendments	KF has the most theoretically accessible minerals, as well as an attractive surface area (261.2 m ² /g) and microporosity value	[57]
P-laden biochar	Agriculture	Slow-release fertilizer	Maximum P sorption capacity of the biochar— > 100 mg/g	[73]
Burcucumber biochar	Agriculture	Soil amendments	Acid activation showed enhanced sorption of Sulfamethazine (SMZ) Activated biochar has BET surface area of 571 m ² /g The predicted maximum equilibrium concentration of biochar for loamy sand soils was 182 mg/kg	[74]
MoP/biomass carbon flake	Electrochemistry	Electrocatalysts	Highly active HER electrocatalyst with excellent durability in acidic electrolytes	[76]
Sugarcane bagasse biochar	Electrochemistry	Electrochemical capacitance	High specific capacitance of 280 Fg ⁻¹ at a current density of 1 A/g 72% retention at a very high current density of 20 A/g Good energy density of 5 Wh/kg at a power density of 3.5 kW/kg	[89]
Peanut root nodules derived carbon nanosheets	Electrochemistry	Non-metal catalysts	S and N-doped carbons exhibit a porous and multilayer structure with a specific surface area of 513.3 m ² /g and high electrochemical area of 27.4 mF/cm ²	[77]
Corn stover biochar	Super capacitor	Carbon electrode	High specific capacitance of 245.9 Fg ⁻¹ at a current density of 0.1 A/g	[86]
Cotton stalks derived activated carbon	Super capacitor	Electric double-layer capacitor	Activated carbon with a BET surface area of 1.481 cm ² /g and micropore volume of 0.0377 cm ³ /g The capacitance is 114 Fg ⁻¹	[83]

Table 8 (continued)

Biochar	Applications	Uses	Key points	References
Waste coffee beans derived carbon	Super capacitor	Nanoporous carbon electrode	The energy densities up to 20 Wh/kg in 1 M H ₂ SO ₄ , with excellent stability at high charge–discharge rates The two-electrode cell has capacitance of 368 Fg ⁻¹ Stable performance over 10,000 cycles at a cell potential of 1.2 V and current load of 5 A/g The distribution of micropores and mesopores 2–4 nm wide	[84]
Wheat straw biochar	Horticulture	Potting substrates	pH—5.8, container capacity—65.6%, total porosity—89.8% Greenhouse experiments using tomato and marigold plants grown in 3.0-L pots showed positive results	[46]
Beech wood biochar	Horticulture	Soil fertilizer	Biochar applications of 15 g/kg soil resulted in higher levels of accessible P and N in the surface soil	[92]

as reinforcement agents within polypropylene matrix, the biochar exhibits comparable carbon content of 82 wt% and specific surface area, 335 m²/g, as of kenaf biochar. Thus, large surface area of the engineered biochar allowed polypropylene to flow, resulting in mechanical interlocking and improved mechanical characteristics [11, 101].

Conclusively, biochar should be used in biocomposites to increase its usefulness and generate better composites while also managing waste in a sustainable manner [102]. However, no research including kenaf derived biochar in biocomposites have been done so far. As a result, this opinion may encourage researchers to investigate the use of the biochar in biocomposites.

5 Conclusion and Future Projects

In this paper, current developments of kenaf-derived biochar and its composites in engineering and agricultural applications, such as nanostructure catalysts and polymer composites, had been discussed. Kenaf biochar and activated carbon are mostly utilized as soil amendments and material adsorbents, and they are yet to be utilized in other engineering applications such as biocomposites, supercapacitors and optical applications. Thus, thorough literature review on the influence of process parameters of thermal decomposition, pyrolysis, and biochar formation on the manufacture of desired biochar is critical. This review had been focused on the unique characteristics of kenaf crops and the resulting biochar, which has a surprisingly large surface area and increased pore volume, in order to explain their prospective use, whether in environmental

or technical applications. Recent advances in engineered kenaf biochar technology, as well as future research and development directions, were briefly highlighted. As a result of the preceding debate, it is obvious that low-cost, environmentally friendly, green, and facile processing products must be taken into account for solving current environmental issues toward sustainable environment in the future. Thus, it is paramount to create approaches and products that (1) reduce the usage of fossil fuels, (2) recycling trash, and (3) are biodegradable plus environmentally friendly.

Kenaf biochar promises to be a novel potentially cost-effective and ecologically friendly carbon material with a wide range of applications. Despite the fact that current research on the manufacture and application of activated biochar in a variety of fields is expanding [103], a number of research gaps still exist. The following ideas are suggested to alleviate these gaps in knowledge:

- (i) The characteristics of activated biochar may be considerably affected by feedstock with varied compositions, manufacturing circumstances, and activation parameters of biochar. Future research will be required to select feedstock with acceptable compositions, as well as optimize production circumstances and activation parameters, in order to create biochar with appropriate and intended characteristics for specific uses.
- (ii) More relevant and innovative treatments for activation, as well as improvements to existing techniques, are required. Furthermore, using multiple main activation methods for biochar activation may give a

good opportunity to improve activation efficiency by integrating the benefits of diverse approaches.

- (iii) The majority of biochar applications are focused on water pollution remediation, whereas applications for CO₂ capture and energy storage are comparatively underutilized and should be broadened. Furthermore, there are several possible applications for activated biochar that should be studied in the future. It might be utilized as a novel possible in-situ amendment for polluted soil and sediment management, for example.
- (iv) For future practical engineering applications of biochar, more research are required to gain insight into the issues surrounding its large-scale manufacturing, scaled-up application, stability, reuses, and wasted biochar management.

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