

A Review of Biochar Applications in the Non-Agro Sector

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ABSTRACT

Biochar is the solid residue that is recovered after the thermal cracking of biomasses in an atmosphere of limited oxygen or oxygen-free atmosphere. Biochar has been used for many years as a soil amendment and in general, for soil applications. Nonetheless, biochar is far more than a mere soil amendment material. In this review, we delved into the burgeoning field of non-agro biochar utilization, encompassing catalyst production, energy storage, composite materials, and environmental remediation. We present a comprehensive overview of recent advancements in biochar-based material science, highlighting its transformation from a waste-derived product into a high-value carbon source with diverse and promising applications.

1. Introduction

Carbonaceous materials have been prevalently deployed in the field of material science over the centuries [1]. In recent decades, carbon fibres have become a valuable asset globally due to their common usage in a variety of commodities [2]. In addition to carbon fibres, carbon black dominates the carbon market income because of its versatile usage in tyre production [3]. Other carbon materials like carbon nanotubes and graphene have been satisfying the aspirations of scientists and developers with remarkable conductive, optical, and mechanical properties [4,5]. Despite the anticipated revolution, commercialization of these carbon materials has been difficult due to their high cost of production. In 2009, Segal *et al.* [6] asserted that the world was prepared for massive production of graphene, but, in 2020, single-layer graphene was sold at \$230/cm² and graphene oxide went for

\$140,000/kg [7], but carbon black was sold for between \$1.5 - 0.95/kg [8]. These high-tech carbon materials (carbon nanotubes, graphene, and graphene oxide) are yet to fulfil the aspirations of the new carbon era. While the world awaits the production of inexpensive carbon allotropes on a large scale, new methods are being explored to produce engineered carbon cheaply. In recent years, integrating carbon production with waste management has been considered the most promising approach [9-11]. Biomass waste stream is readily generated globally in varying amounts from country to country. Biomass management remains a major challenge, especially in developing countries where it is generally disposed of through open-air burning. This poses a threat to humans, the environment and economic dues to the disposal of valuable feedstock such as heat and ashes.

A more beneficial method is to process the biomass for the production of biofuels [12,13], chemicals [14], and materials [15]. Converting biomass into liquid biofuels requires several complex processes occasioned by the high oxygen levels in biomass. Nevertheless, converting biomass into solid carbonaceous materials is quite promising, and these materials are commonly known as biochar [16]. Due to their properties, biochar can be used for many applications. Currently, biochar is mainly applied for soil health enhancement [17 -19] and for heating purposes [20]. These applications do not exploit the full range of applications that biochar can be deployed for, especially with the ease of its modification by simple process adjustment [21].

Therefore, this paper aims to present a comprehensive overview of biochar applications in the non-agroforestry sector. The objectives include presenting a single useful medium to navigate the vast potential of biochar, establishing the feasibility of biochar as a potential substitute for conventional carbon materials and as a plausible alternative for high-tech materials. Recent relevant literature was summarized into four major sections dedicated to (i) catalysts synthesis, (ii) energy storage, (iii) environmental remediation, and (iv) composite materials production. It is anticipated that this review will provide more cognizance of the extensive potential of biochar.

2. Literature Survey Methodology

The literature review focused on works related to biochar production and mainly applications, especially in non-agroforestry systems. A systematic literature survey was carried out in Scopus, Elsevier, and ScienceDirect scientific databases, covering the majority of the peer-reviewed interdisciplinary publications. The obtained literature was evaluated utilizing the PRISMA-P (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols) [22]. The PRISMA-P workflow has a checklist that contains seventeen items geared towards preparing and presenting a powerful sequence for a systematic review. The search protocol was developed utilizing the following steps. A search query was carried out in line with the objectives of the review as highlighted in Table 1. Several eligibility criteria were applied during the search protocol: (1) Coverage period: the publication period of articles was unconstrained, (2) Search fields: title, abstract, or keyword of articles, (3) Document types: all types of documents were considered, (4) Language: considered literature was limited to only those published in English. The survey methodology was explicated, and thereafter, the literature was pooled, sorted, and appraised for eligibility to develop the most relevant literature.

Table 1. Outputs of literature search in scientific databases

Search strings	Number of publications found
Biochar production technologies	75
Biochar application in non-soil	275
Properties and uses of biochar	67
Biochar intrinsic properties	83

3. Technologies for Biochar Production

Biochar can be obtained using either of four major thermo-chemical technologies: (i) torrefaction, (ii) pyrolysis, (iii) hydrothermal carbonation, and (iv) gasification.

Torrefaction is a thermo-chemical process utilized for biomass densification to enhance their energy content [23]. It is done at low temperatures between 200 - 300°C and long residence time [24]. Torrefaction produces a high yield of solid residue products (biochar), with an average carbon content of about 55 wt.% [25], or 76 wt.% with microwave heating [26 -29].

Pyrolysis breaks down polymeric macro-molecules in biomass to produce compounds with lower molecular weight in the absence of oxygen [12,30]. Pyrolysis is done using different heating rates [31], reactor designs [32 – 35], and at temperatures between 300 - 800°C [36]. It yields different products (mainly bio-oil and biochar) of varying proportions.

Hydrothermal carbonization is a thermal decomposition of biomass (irrespective of the moisture levels) into bio-oil, gas, and solid residue (referred to as hydrochar) at moderate temperatures and elevated pressure [37] in a wet environment [38], a dry medium [39,40] or sub-critical medium [41]. The process can be carried out with or without a catalyst [40,42], and it has shown the capability to improve the properties of the products [43].

Gasification converts biomass into a mixture of gases commonly referred to as synthesis gas (syngas) in the presence of air, oxygen and/or steam [44 – 45], at elevated temperatures beyond 750°C with or without a catalyst [46]. Syngas is a mixture comprising carbon monoxide, carbon dioxide, methane, hydrogen, water vapour and tars. A major by-product of the process is biochar. Figure 1 highlights the different thermo-chemical treatments for obtaining biochar from biomass.

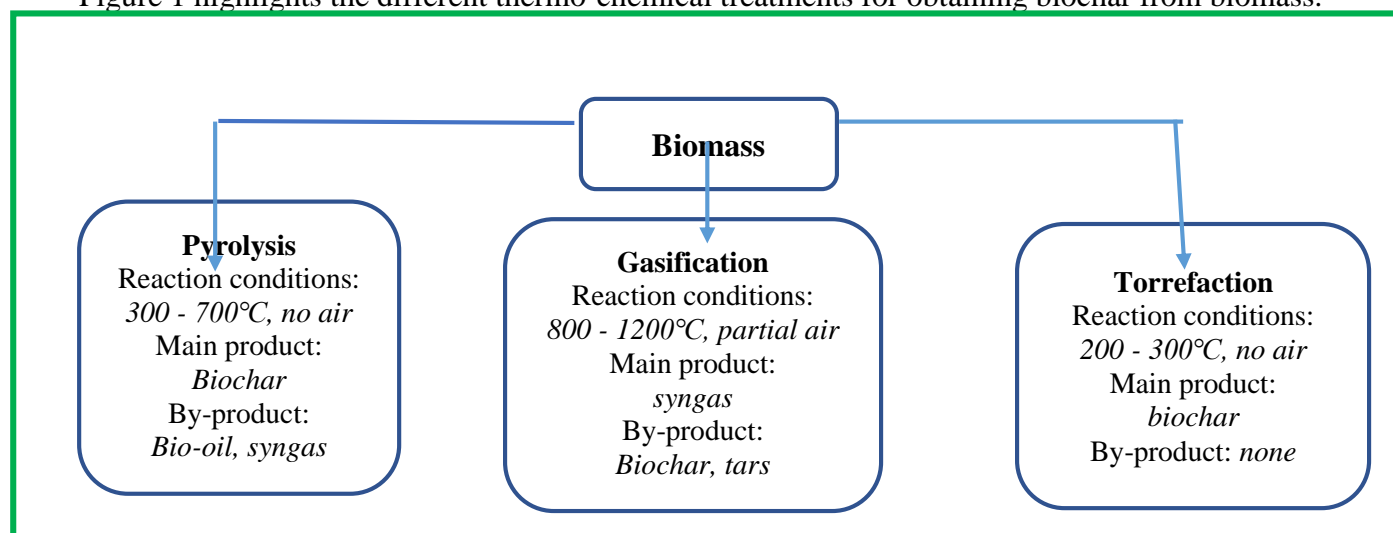


Figure 1. Thermo-chemical technologies for obtaining biochar from biomass.

Figure 2 shows that biochar's carbon levels directly depend to a large extent on process operational temperature during production. Low values of hydrogen: carbon (H/C) and oxygen: carbon (O/C) ratios are an indication of effective carbonaceous structures, which could make biochar more appealing for electrical applications, as well as additive and adsorptive processes [47 – 48].

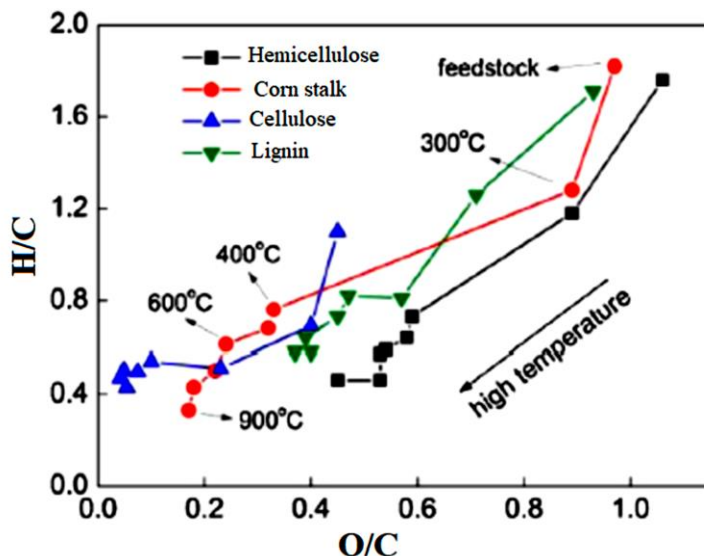


Figure 2. Hydrogen:carbon ratio vs oxygen:carbon ratio during the thermo-chemical conversion of corn stalk and its components [49].

4. Biochar Applications in Non-Agroforestry Sector

4.1. Biochar-based catalysts (Catalytic applications)

Biochar can function as support for catalysts, it can provide more active sites for catalytic reactions [50]. Biochar poses several inherent properties (derived from the original biomass) that make it distinctly propitious as a catalyst and/or catalyst support [51,52]. Properties such as large surface area, and ability to reorganize functional group composition are instrumental to its performance in varied catalytic applications. According to Buckner *et al.*, [53], biochar-based catalysts have notable attributes viz: (i) heterogenous; (ii) bi-functionality; (iii) recyclable; (iv) porous; and (v) does not crystallize at elevated temperatures. Biochar-based catalysts, unlike metal-based catalysts, are cheap, unarmful to the environment, easy to develop, recyclable, and bio-degradable. Specifically, biochar-based catalysts can be deployed in various sectors such as agriculture, environment, and energy, and for several purposes like biodiesel production, tar removal during synthesis gas production, waste management, chemical synthesis, and elimination of pollutants, among others [54,55].

Biochar is a remarkable catalyst with various beneficial attributes. Chen *et al.*, [56] reported that the presence of inorganic elements, like iron and potassium in biochar makes it potent for the catalytic cracking of tar. Biochar's surface functional groups allow its absorption of metal precursors thereby making it possible to develop biochar-supported metal catalysts [54,57]. Lignocellulosic biomass, being a renewable feedstock, is capable of synthesizing various products like biodiesel and biochemicals [58]. Figure 3 highlights such synthesis with the aid of biochar-

based catalysts. Biochar catalyst was observed to increase the hydrolysis rates of xylan about 15 times more than commercially available sulfonated macro-reticular resin. Despite its lower surface area, biochar converted more xylan (85%) during the hydrothermal treatment than activated carbon (57%) [59,60]. Biochar-derived sulfonic acids yielded about 28% HMF from cellulose [61].

According to Li *et al.*, [62], a mineral-impregnated biochar catalyst can remove about 30% of furfural from maize cob. Also, biochar acidified using Bronsted and Lewis acids is useful for catalytic valorization of biomass.

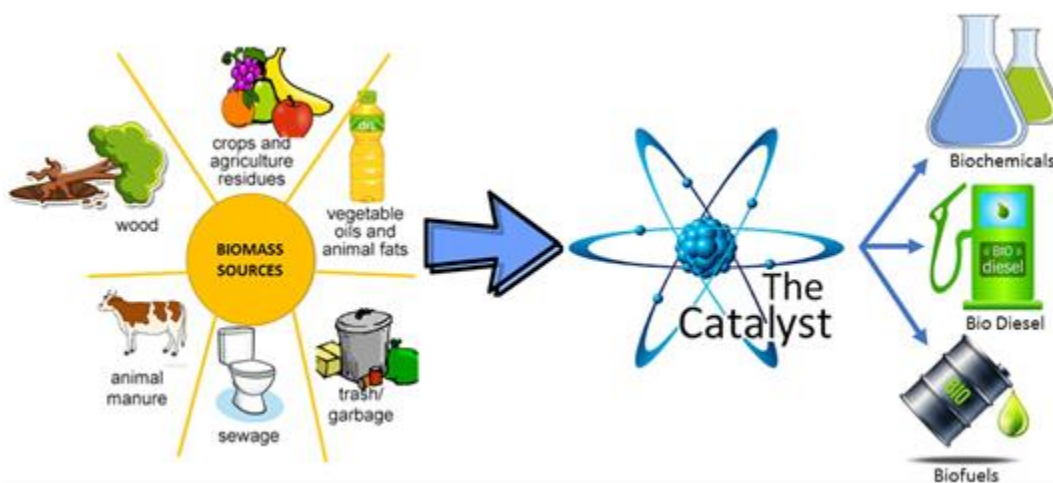


Figure 3. Biochar-based catalysts in biomass upgrading.

Biochar has a unique chemical structure, comprising a high surface area and peculiar surface functional groups, that presents a huge potential for use as flexible catalysts or catalytic support in several chemical reactions [63 – 65]. The presence of biochar in catalysts increases their uses and potential for developing new catalysts since biochar can easily be removed from catalysts to extract precious metals. Liu *et al.*, [66] investigated the conversion of synthesis gas to liquid hydrocarbons using biochar-based iron nanoparticles as catalysts. About 96% carbon monoxide conversion and about 67% liquid hydrocarbon yield were observed. Likewise, biochar activated by potassium hydroxide (KOH) and acidified with concentrated sulfuric acid (H₂SO₄) exhibited great isomerization in biodiesel production [67].

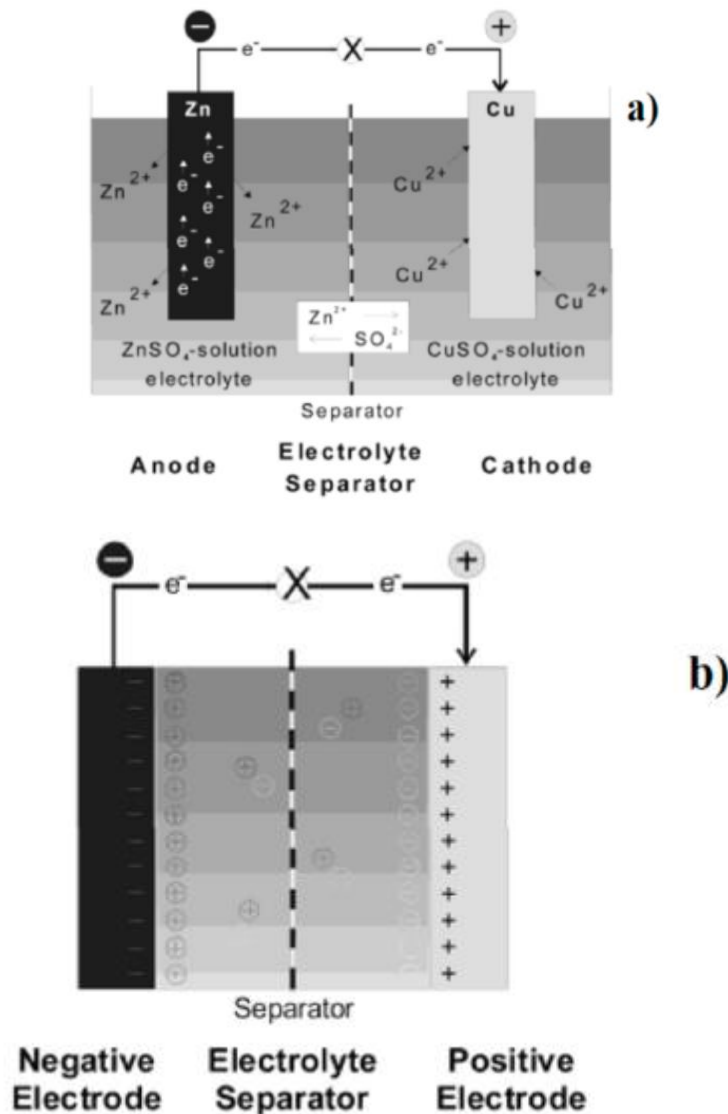
Catalysts have been of fundamental importance in the advancement of technology for the conversion of renewable and non-renewable carbonaceous feedstocks into valuable products such as biofuels and BTEX chemicals [68]. The global demand for catalysts is anticipated to grow by about \$34.3 billion by 2024 [69], while catalytic technologies will account for over 95% of industrial and over 35% of the Global Domestic Product (GDP). Biochar's attributes, such as high porosity and high carbon levels, present it as a potential substitute for conventional carbon-based solid catalysts, which are expensive and unhealthy to the environment. However, copious modifications, such as acid/base treatment or carbonization, might be necessary to improve the surface chemistry of biochar for it to be more attractive for catalytic processes [65]. Waste biomass has become a more prominent renewable feedstock for producing fuels and chemicals. The impact of biochar as a catalyst on biofuel production is highlighted in Table 2.

Table 2. Role of biochar on the production of biofuels.

Precursor	Biochar-based catalyst	% yield	Refs
Canola oil	Forest residues	45	[70]
Waste vegetable oil	Hard wood	82 – 89	[71]
Palmitic acid	Peanut hull	71	[72]
Oleic acid	Biochar	49	[73]
Waste cooking oil	Rice husk	87	[74]
Sunflower oil	Palm kernel shells	98	[71]

4.2. Energy Storage Applications

Energy is required for varied applications; its storage technology has become a major challenge of the 21st century [75]. In recent decades, diverse technologies have been advanced viz: fuel cells [76] and solar [77], well-functioning batteries [78], and supercapacitors [79], as shown in Figure 4.



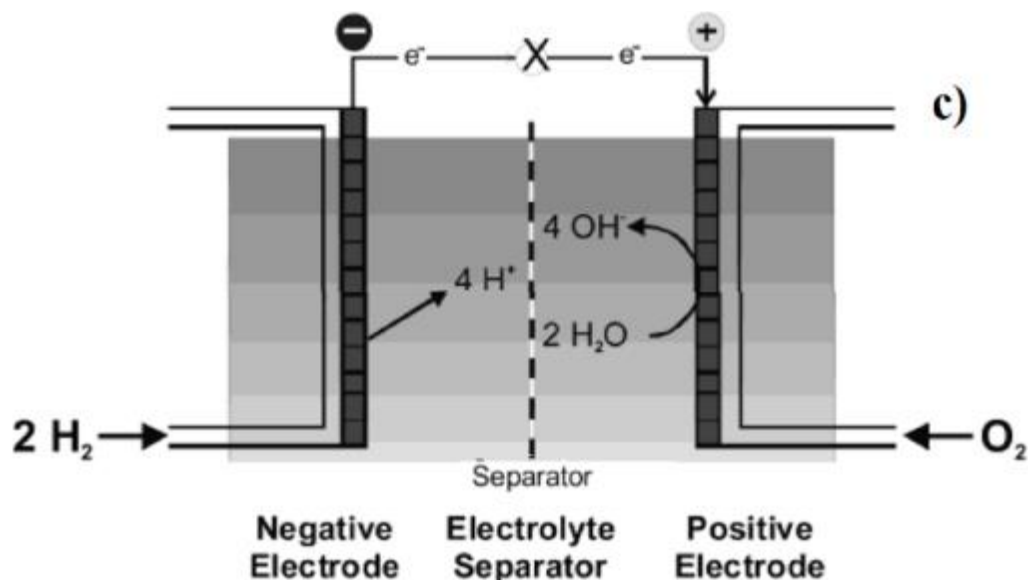


Figure 4. Schematics of (a) battery, (b) supercapacitor, (c) fuel cell [80].

A battery is a system made up of several electrochemical cells placed in contact with each other to provide electrical energy. Solid-state batteries are mainly comprised of lithium and sodium ions [81,82]. Supercapacitors are types of electrochemical energy storage systems that have appreciable energy density and specific capacitance. It is capable of releasing energy with high density within a short time. A fuel cell is a type of electrochemical system that generates electrical energy from the redox reaction between a fuel and an oxidant. It is highly efficient and has no emissions. The fuel is hydrogen [83], carbon [84], or methanol [85] and the oxidants are oxygen or hydrogen peroxide.

4.2.1. Supercapacitors

A vital requirement necessary for the production of high-performing supercapacitors is a large surface area where the double ionic layer will be formed. This makes activated biochar an appealing resource for the production of supercapacitor electrodes [86].

Chemical activation interposes functional groups on biochar's surface, thereby improving its electrochemical properties and capacitive performance [87]. Nevertheless, Gabhi *et al.* [88] observed the impact of monolithic biochar on capacitive performance. They established a correlation between the conductivity of activated biochar and biochar production temperatures and reported an increase in biochar conductivity up to about 344S/m when carbon levels increased from approximately 87 to approximately 94wt.%. This observation was adduced to the formation of graphite nanocrystals in the main structure of the biochar during production. Luo *et al.* [89] reported that biochar activated with ammonia gave a capacitance of up to $40\mu F/m^2$. Jin *et al.* [87] observed the capacitive performance of a biochar (with high ash levels) that was chemically activated using potassium hydroxide at $900^\circ C$ and thereafter, with nitrous acid at $150^\circ C$. The activated biochar exhibited a large surface area of about $2000m^2/g$ and a specific capacitance of about $260F/g$.

Qu *et al.* [90] produced biochar from corncob and activated it by treating it with steam, acid, and alkali. The activated biochar exhibited a good surface area of about $120m^2/g$, a capacitance of

about 314F/g, and remarkable stability after 105 cycles in a uniform cell. Chen *et al.* [91] used fast pyrolysis and alkaline chemical activation to convert food waste into activated biochar. They revealed that the obtained biochar offered a capacitance of 488 F/g. Biochar from herbaceous biomass has also been investigated as a possible material for the production of electrodes and the realization of supercapacitor production [92 – 94]. Surface morphology is very crucial in biochar-based supercapacitors [95 – 97]. Macroporous biochar was observed to exhibit inferior performance in comparison with biochar having micro and mesoporous, with microporous biochar offering more current density (about 1.3A/g) than the other forms [98]. Activated biochar attributes can also be modified through plasma treatment, as demonstrated by Gupta *et al.* [99]. The authors revealed that the surface area of biochar obtained from yellow pinewood was increased when it was subjected to low-temperature plasma treatment, and consequently enhanced its capacitance from 14 to 174F/g. In addition, non-lignocellulosic biomass can be carbonized for capacitive purposes. For instance, algae mixed with keratin was pyrolyzed to produce biochar, activated using heteroatom doping. The activated biochar had a reasonable surface area and significant capacitive values [100]. Pontiroli *et al.* [101] produced biochar by pyrolyzing poultry dung. On activation, the biochar exhibited high porosity, a remarkable surface area (about 3000m²/g), and significant capacitance (about 230F/g).

4.2.2. Batteries

Several studies have investigated the potential of biochar as electrode material in battery production. The focus has been on lithium-ion batteries due to their widespread usage. For instance, Dai *et al.* [102] deployed biochar produced from sewage sludge pyrolysis as anode material in a lithium-ion battery. The authors reported that the anode had a notable discharging capacity of about 1200mA-h/g. However, biochar with low porosity has displayed lower performances [103]. The authors reported that biochar obtained from pyrolysis of spent coffee exhibited a capacity of about 360mA-h/g. Zhang *et al.* [104] confirmed this pattern. They observed a discharging capacity of about 600mA-h/g using a microporous biochar. In contrast, Benitez *et al.* [105] observed a discharging capacity of about 920mA-h/g and a current density of about 100mA/g, on deploying biochar with low porosity as a cathode in a lithium–sulfur battery. Doping with nitrogen could stabilize and improve the activity of low porous biochar. Chen *et al.* [106] demonstrated that nitrogen doping enhanced the activity of biochar, obtained from pomegranate residues pyrolyzed at about 700°C, up to about 550mA-h/g. Using heteroatom-doped biochar as a cathode, Chen *et al.* [107] reported a discharging capacity of about 1050mA-h/g.

Biochar from non-lignocellulosic biomass has shown impressive potential as a material for battery production. For example, Magnacca *et al.* [108] showed that biochar obtained from chitin pyrolyzed at a moderate temperature had acceptable performance when used to produce a low-cost lithium–sulfur battery. Also, tailoring biochar could further improve its performance. Pan *et al.* [109] doped biochar obtained from silk with ZnCo₂O₄ nanocubes and used it to produce anode material that exhibited a flexible performance. Li *et al.* [110] revealed that pericarp-derived biochar tailored with iron oxide nanoparticles reached a capacity of about 640mA-h/g. Salimi *et al.* [111] produced an electrode material using algae-derived biochar tailored with iron oxide nanoparticles. The material exhibited a discharging capacity of about 740mA-h/g and satisfactory cyclic stability.

Alternatively, Saavedra-Rios *et al.* [112] deployed biochar from varied biomass as precursors for anode materials for developing sodium-ion batteries.

4.2.3. Fuel Cells

Biochar is increasingly being used as a fuel in direct carbon fuel cells [113 – 115], indicating a direct correlation between its properties (such as carbon and ash levels, surface area, and energy content) and its performance as fuel. A direct relationship between the thermal decomposition of biomass and its performance in carbon fuel cells was undoubtedly established by Xu *et al.* [116] by comparing thermogravimetric data with empirical data. Qiu *et al.* [117] investigated the performances of biochar obtained from wheat straw, bagasse, and corncob respectively as fuel in a direct carbon solid oxide fuel cell. They revealed that the fuel cell performed with high efficiency producing optimal power densities of 260mW/cm² at 800°C. Kacprzak *et al.* [118 – 120] carried out a detailed investigation on the use of biochar in direct carbon fuel cells. They initially compared graphite rod and apple tree biochar in a molten salt mixture of sodium hydroxide and potassium hydroxide. They observed peak operating conditions at 400°C and a sodium hydroxide to potassium hydroxide ratio of 1, whereby outputs from using biochar were comparable with those obtained using pure graphite. Additional investigation revealed that using biochar also generates outcomes comparable to outcomes from using coal. The obtained results in both scenarios were about 36mW/cm².

Ali *et al.* [121] evaluated the use of biochar produced from walnut shells and almond shells as fuel in a direct carbon fuel cell having anodes that contain titanate. The authors observed an output power of about 78mW/cm². Similarly, using only almond shell biochar as fuel, Elleuch *et al.* [122] obtained an output power of about 130mW/cm².

Another potential application of biochar is as electrodes in microbial fuel cells. Huggins *et al.* [123] demonstrated that using wood biochar as electrodes in microbial fuel cells significantly reduced costs and carbon footprints. They reported an output power of about of 532mW/m² and a power cost of \$7/Watts. This was about 90% cheaper than graphene electrodes, which have a cost of about \$402/W. Better outputs (606 mW/m²) were obtained by using biochar doped with manganese oxide as electrodes [124]. Khudzari *et al.* [125] used a granular biochar anode in a rice-paddy microbial fuel cell to produce bioelectricity. The authors revealed that the use of biochar reduced methane emissions without adverse effects on the plant yield. Biochar has also been used as cathodes in microbial fuel cells. Li *et al.* [126] reported a maximum power output of about 459 mW/m² when corncob-derived biochar pyrolyzed at 650°C was used in air-cathode microbial fuel cells. The biochar was deployed as a catalyst. Similarly, Yuan *et al.* [127] obtained an output power of about 550 mW/m² using biochar obtained from sewage at 900°C.

Biochar can also be used in the development of membranes. Chakraborty *et al.* [128] built a novel, low-price proton exchange membrane (PEM) for use in microbial fuel cells. They used activated biochar obtained from high-temperature pyrolysis of food residues. The membrane performed optimally exhibiting a proton conductivity of 0.07S/cm, a transference number of 0.891, and an oxygen diffusion coefficient of about 6.5×10⁻⁹m²/s. In Comparison, the biochar-based membrane performed better than membranes comprising other materials like Nafion.

4.3. Environmental Remediation

Environmental pollution poses a great threat to the world, and its proportion is increasing daily at an alarming rate attributable to rapid urbanization, massive industrialization, and growing dynamism in people's lifestyles. Consequently, the provision of clean water and safe environments for people has become a huge challenge. Specifically, the global demand for water for human activities is on the increase annually, and so is the resulting quantity of wastewater [129]. Sustainable management of wastewater has become a major priority for every urban community [130], and it involves varied biological and chemical treatments [131] before it can be reused for domestic and industrial applications.

Water pollution has become a huge global menace that is menacing the environment and impacting negatively the lives of millions of people [132,133]. Several technologies have been deployed for water purification including filtration [134], adsorption [135], or degradation [136] technologies. Many studies have claimed to achieve water purification efficiency of about 99%, however, this can only be at ideal conditions of pH, contaminant levels, and other operation parameters [137]. In addition, many of these methods, for example, ion exchange resins, are aimed at eliminating one category of contaminant per time [138], making them less effective for treating environmentally polluted waters, where several classes of contaminants are always present at the same time. This makes purification methods like adsorption and degradation more attractive for real scenarios.

Biochar presents a revolutionary material that is capable of eliminating both organic and inorganic pollutants using adsorption and degradation methods. Additionally, biochar has the potential to clean up air by removing harmful gases including carbon dioxide and hydrogen sulphides.

4.3.1 Adsorbent

A principal application of biochar is for environmental remediation. Biochar has received considerable attention in wastewater treatment processes [139]. Several contemporary studies have described biochar as a potent, eco-friendly, and relatively cheap adsorbent. As stated earlier, biochar's effectiveness in varied applications is ascribed to its notable properties, which include large surface area, great porosity, impressive cation and anion exchange capacity, ability to retain water, copious minerals, and surface functional groups. These intrinsic properties, sequentially influence biochar's adsorption capability through several physisorption and chemisorption mechanisms, thereby making biochar an attractive adsorbent [140 – 142]. Biochar properties, pivotal for the elimination of pollutants, are habitually impacted by temperature and biomass type during production [143]. Biochar obtained from forest residues and agro-residues has a larger surface area than residues from municipalities and livestock. Other variables such as pH, duration of contact, application rate, and type of contaminants also influence biochar's remediation capability [144]. Remarkable studies have been conducted to investigate the capability of biochar to remediate copious industrial organic and inorganic chemicals [145], as highlighted in Table 3.

4.3.2. Wastewater treatment

Biochar's high porosity and large surface area, make it a potentially attractive material for wastewater treatment [142]. Biochar was proven to be an outstanding material for absorbing nutrients from effluent [146]. It is accredited with an increasing ability to constantly remove pollutants from wastewater due to its high porosity and adsorption ability, which enable toxic

substances to accumulate on its surfaces, resulting in an immaculate discharge [147]. Carbonaceous materials are quite potent in detoxifying water sources, and biochar presents an inexpensive alternative. Many studies have investigated the ecological and economic implications of using biochar and activated carbon to eliminate deadly contaminants. Huggins *et al.* [148] compared the performance of granulated wood-derived biochar and granulated activated carbon materials for treating wastewater streams. The treatment was done in both batch and continuous systems, and it was observed that biochar was more potent than activated carbon in reducing ion concentrations and total chemical oxygen demand (COD) in the wastewater. Gwenzi *et al.*, [149] demonstrated that although the large surface area of activated carbon promotes toxin adsorption through pore filling, surface functional groups are mainly responsible for biochar's effective removal of toxic heavy metals from wastewater. In addition, the production of activated carbon consumes more energy (97 MJ/kg) and emits more greenhouse gases than the production of biochar (6.1 MJ/kg) [150]. Hence, in terms of greenhouse gas emissions, energy consumption, and costs, biochar is more efficient than activated carbon in eliminating pollutants from wastewater. Several resources consulted for this section and their findings on biochar's potential to remove various harmful pollutants from water and wastewater by biochar are summarized in Table 4.

Table 3. Efficiency of various biomass-derived biochar to remediate organic and inorganic pollutants.

Pollutants	Adsorbate	Adsorbent	Biochar loading (%)	Remediation efficiency (%)	References
Organic	Polyaromatic hydrocarbons	Shrub	10	32	[151]
	Polychlorinated dibenzo-p-dioxins	Paper mill waste	5	38	[152]
	Perfluoro octane sulfonate	Wood chips	1	40	[153,154]
		Maize Stover	1	52	[155,156]
		Sallow	0.12	41	[157]
		Maize straw	0.12	70	[158]
	Atrazine	Ecological waste	1	19	[159]
	Carbofuran	Wood chips	1	51	[160]
	Trifluralin	Wheat straw	1	13	[161]
	Simazine	Ecological waste	2	95	[162]
	Phenanthrene	Wood	0.1–5	50	[163,164]
	Pentachlorophenol	Rice straw	2	95	
	Trichloroethylene	Peanut shells	0.03	70	
	Isoproturon	Soybean, Stover, Wood	0.03	67	[165 – 167]
	Inorganic	Cd ²⁺		2	49.8
Rice straw, Tree bark, Wheat			20	97.1	[168]
Straw, Sludge			10	99	[169]
Pb ²⁺			40	94	
		Rice straw	5	100	[158,170]
		Chicken manure, Soybean Stover, Sugarcane, straw	5	94	[165 -167, 171]
Zn ²⁺		Sludge	20	90	[172]
Cr		Sugar beet tailings	5	51.2	[172]
As			0.8	89	[158]
		Shrub	47	0	[163]
U	Switchgrass	0.5	90	[149]	

Table 4. Removal of pollutants from wastewater using different biomass-derived biochar.

Pollutants	Adsorbate	Adsorbent	Remediation efficiency (mg/g)	Refs.
Heavy metals	Hg (II)	Spent malt rootlets	103 130	[173,174]
	Cr (VI)	Waste glue	326	[175]
	Ni (II)	Lotus stalks	62	[176]
	Cd ²⁺ , Pb ²⁺ , Cu ²⁺	Bamboo, bagasse, hickory wood, peanut hull	14	[177]
Dyes	Reactive Red 141	Pecan nutshell	130	[178,179]
	Hydroquinone	Sewage sludge	220 and 202	[180]
	Orange lanasyn and gray Lanasyn	Bamboo, cane	2600	[181]
Phenols and PAHs	Naphthalene and 1-naphthol	Orange peel	81 (naphthalene) and 187 (1-naphthol)	[182]
Pesticides	Deisopropylatrazine	Broiler litter	83.3	[68]
	Atrazine and simazine	Maple, elm, oak woodchips and barks	451- 1158 (atrazine) & 243 -1066	[176]
	Thiacloprid	Maize straw and pig manure	8	[68]
Inorganic ions	Dibromo chloropropane	Almond shell	102	[163]
	NH ₄ ⁺	Bamboo	6.4	[183]
	NO ₃ ³⁺		5 – 9	[184]
	PO ₄ ³⁺	Walnut shell and sewage sludge	303	[185]
	PO ₄ ³⁺	Wood and rice husks	25 - 28	[185]
	F ⁺	Spruce wood	13.6	[176]

4.3.3. Carbon sequestration

Carbon sequestration is a process whereby carbon is captured and stored, probably in soil, consequently increasing soil carbon sink [186]. Biochar has been globally endorsed as a potential carbon sequestration medium for building carbon sinks in soils. This is because biochar can highly resist soil chemical and biological decomposition due to the recalcitrance and stability of its carbon acquired during its production processes [187]. In addition, the improved chemical stability of biochar is accredited to its dense aromatic contents [188 – 189]. According to Wang *et al.* [190], the labile fraction of biochar has an average chemical half-life of about 556 days, while Graber and Hadas [191] and Gwenzi *et al.* [192] reported that about 63 per cent of the carbon in biochar is sustained on an anhydrous basis. Therefore, the application of biochar can potentially sequester carbon in the soil for centuries, probably because; (1) biochar application in soil may inhibit the mineralization of endemic soil organic carbon (SOC) indelibly [190 - 193], and reduces significantly the amount of dissolved organic carbon (DOC) in soil due to its adsorption onto the surface of biochar [194, 195], (2) Biochar application in soil can boost microbial carbon and decrease their metabolic quotient due to its influence on availability of carbon and nitrogen [195]. Generally, biochar transmutes labile carbon from the active carbon pool to the passive pool, and its application could advance carbon sequestration and soil management practices [192].

4.4. Biochar-Based Composites Production

Composite materials are becoming a major player in the global materials market as presented in Figure 5. Carbon-containing composites constitute a major aspect of the global markets, boosting a healthy estimate of about 151 kilotons per year in 2018 [196]. As highlighted in Figure 6, about 70% of all carbon-based composites are characterized by host polymeric materials, of which about 49.10% are thermoset and about 20.50% are thermoplastic polymers. Among the polymeric family, carbon fibre-reinforced epoxy resins constitute a higher portion thanks to vast applications in crucial intricate industries (like aeronautics, aerospace, etc.) [197]. Carbon-based inorganic composites are majorly ceramics [198] and cement [199], but their combined production is much less than polymers. In this case, biochar still finds application, despite its use will be justified by its production flexibility and its adjustable properties [200].

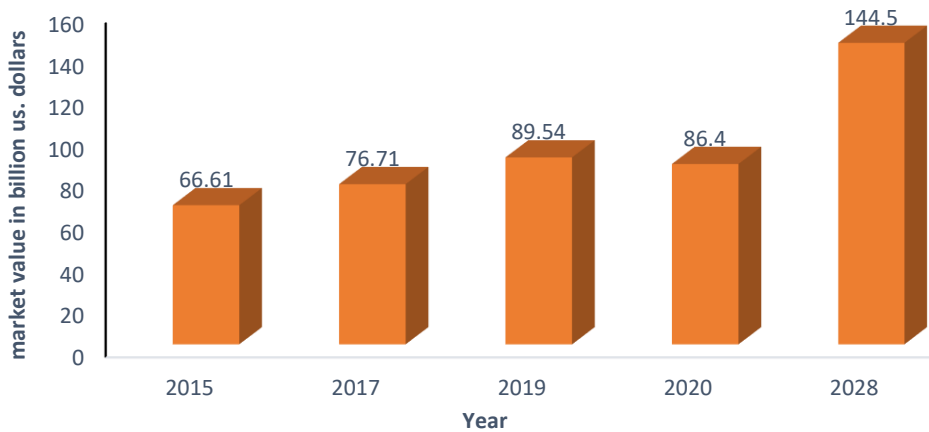


Figure 5. Market value of composite materials worldwide from 2015 to 2028 (in billion U.S. dollars) [201].

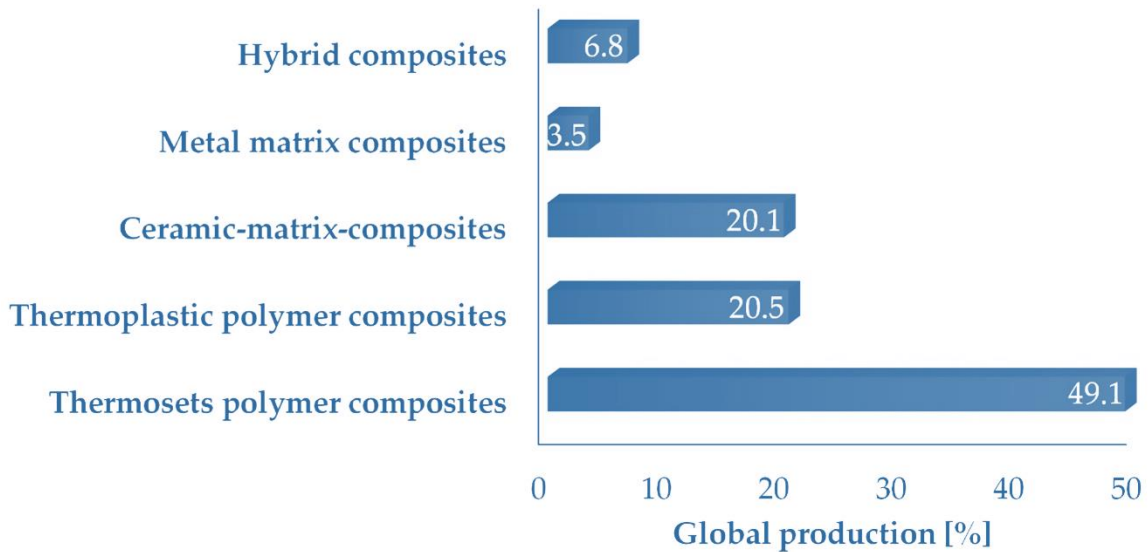


Figure 6. 2018 global production of carbon-containing composites [196].

4.4.1. Inorganic-Based Composites

As of 2018, the global rate of cement production was over 3 gigatons per year [202]. Historically, several additives have been invented and deployed to enhance the mechanical properties and durability of cement-containing composites such as polymers, carbon nanotubes, graphene and carbon fibres [203 – 207]. Although biochar application as an additive has equally been widely investigated, it is yet to be commercialized

Cosentino *et al.* [208] comprehensively studied the influence of certain biochar properties (such as particle size, carbon levels, and operation temperature) on the mechanical properties of biochar-based cement composites, using biochar obtained from the UK Biochar Research Centre. The authors having considered the impact of the biochar properties on the bending strength and fracture energy of the composites, reported unsatisfactory results compared to results observed by preceding researchers [209]. Gupta *et al.* [210] provided more insight into biochar-based cement composites by conducting a comprehensive investigation into how the particle sizes and surface morphology of biochar impact the rheology, strength and permeability of cement mortar in wet and dry curing conditions. They revealed that particle sizes of biochar did not influence the hydration process, which occurred speedily in every experimental run. Small particle sizes (<2 µm diameter) enhanced initial strength and hydration better than macroporous particles (>2 µm). Mo *et al.* [211] mixed biochar and magnesium oxide to reduce the intrinsic contraction of cement materials. Muthukrishnan *et al.* [212] observed a similar occurrence using biochar from pyrolyzed rice husks. Gupta *et al.* [213] examined the effect of adding biochar particles. They observed a decline in absorptivity and level of water perforation of about 60%. Another attractive matrix that could accommodate biochar is concrete, which is a more intricate material than ordinary cement. Cement's content varies widely and could partially or completely be substituted with biochar, according to Dixit *et al.* [214]. They expounded on biochar's potential to substitute cement in extreme concrete aggregate. Initially, a scanning electron microscope was used to study the interactions at the biochar–cement interphase. The authors observed that biochar surface porosity allowed cement hydrates to deposit inside the pores of biochar, which lends credence to biochar's efficacy in enhancing hydration.

Gupta *et al.* [215] showed that biochar from pyrolysis (at 550°C) enhanced the ability of concrete to withstand high temperatures, and increased concrete's strength by about 20%. Biochar-based concrete composites exhibited impressive sound absorption ability between 200 - 2000 Hz, as revealed in multiple literatures [216,217]. One of the most prominent findings was contained in the publication by Kua *et al.* [218]. The authors studied the utilization of composites comprising biochar, immobilized bacteria, and poly (vinyl alcohol) fibres for the development of self-repairing fibre-reinforced concrete. They reported a self-repairing ability for cracks bigger than 600µm.

Besides cement and concrete, biochar has been hosted in many other inorganic matrixes. Mu *et al.* [219] delineated the potential of carbon-clay composites as effective building materials. Lee *et al.* [220] used a composite material made from a blend of biochar and clay to insulate the building envelope. They observed better water vapour resistance at 23wt.% biochar. Yang *et al.* [221] examined several mechanical properties of biochar-clay composites, using biochar obtained from rice husks, coconut shells, and bamboo. They observed that the composite made from 10wt.% bamboo biochar and clay were stronger and exhibited better thermal performance.

Dahal *et al.* [222] deployed biochar as a filler in glass–fibre composites. They observed that, in contrast to using glass fibres alone, biochar loading of 10wt.% resulted in lowering the damping ratio, increasing the storage modulus, and improving the stiffness of the composite material.

4.4.2. Reinforced-Plastics Production

Carbon-based reinforced thermoset plastics are generally dispersed materials that integrate disparate matrixes [223 – 225]. Epoxy matrix has been extensively investigated and universally utilized over the years. Hence, the possibility of replacing conventional carbon fillers with biochar has instigated enormous attraction. Khan *et al.* [226] investigated the mechanical and di-electrical attributes of biochar-epoxy composites. a filler concentration of 0.5 to 20wt.% was used and the biochar was obtained from maple annealed at high temperature. They observed that when 4 wt.% annealed biochar was used, there was a significant increase in all mechanical properties, and at 20 wt.% biochar obtained dielectric properties were similar to when carbon nanotube resins were used. A relationship between biochar particles' surface morphology and mechanical properties of correlated composites was established by Bartoli *et al.* [227] at 2 wt.% biochar. Obtained results revealed a maximum expansion of 40% and an increase in Young's modulus when biochar from rhizomatous grass and wheat straw were used respectively. They hypothesized that smooth surfaces can ease mobility within the epoxy matrix, but surfaces with high porosity cannot. This manifested in the distinct behaviours noticed when biochar obtained from varied feedstocks and under similar pyrolysis conditions was used.

Reactor temperatures considerably influence the interactions between biochar particles and epoxy resins. Giorcelli *et al.* [228] utilized biochar produced from maple trees at temperatures between 600 and 1000°C. They observed about a fivefold improvement in maximum elongation compared with neat resin.

Biochar produced at high temperatures is likely a strong alternative for developing epoxy composites with high conductivity. Giorcelli *et al.* [229] showed that biochar converted to graphite by heating exhibited a strong direct current conductivity. This impacted their ability to better absorb microwave radiation when compared with multi-layered carbon nanotubes [230], or thin films [231]. In addition, biochar obtained from the pyrolysis of waste cotton fibres and modified into carbon fibre shapes demonstrated an improvement in the properties of the epoxy-resin host matrix [232,232].

Polyolefins-based biochars have been the most produced reinforced thermoplastics. Arrigo *et al.* [234] evaluated biochar-based polyethylene using biochar obtained from coffee. They observed that the polymer chains were restrained at the filler porous surface, which culminated in the reduction in the dynamics of the host polymer matrix. However, the well-immersed biochar particles enhanced the stability of the obtained polyethene composites during thermal oxidation. Zhang *et al.* [235] examined the impact of temperature on high-density biochar-polyethylene composites. It was reported that the biochar particles did not affect the microcrystalline structure of the polymer matrix. However, biochar-based polymers exhibited better mechanical properties than virgin polymers, with the biochar-based polymers exhibiting enhanced ability to withstand bending and impact. Li *et al.* [236] investigated the behaviour of polyethene heavily loaded with biochar obtained from bamboo pyrolyzed at 1100°C. At 80 wt % biochar loading, the authors

observed a high-performance shield against electromagnetic interference and a conductivity of about 108 S/m. In addition, Bajwa et al. [237] demonstrated that biochar obtained from wood can be combined with polyethene for the production of high-density polymer composites with significant thermal stability.

Poly(propylene) is another polyolefin type that has been widely investigated for the production of quality biochar-containing composites. Das *et al.* [238] conducted an economic analysis of using biochar instead of the usual carbon fillers. The authors revealed that the reduction in the cost of biochar-containing composites with similar attributes as non-biochar-containing ones was about 3 wt.% as a result of the reduction in the compatibilizer, with cost savings amounting to 18 wt.%. Biochar's low price influenced the research done by Behazin *et al.* [239], focusing on the use of biochar from pyrolyzed perennials as fillers in the production of polypropylene/polytene-ethylene composites. Biochar amounts of 10 and 20% were used respectively. Rheological analysis showed an enhanced linkage between the biochar and polymer matrix. A detailed investigation of polypropylene-biochar interactions was done by Das *et al.* [240 – 242]. They concluded that biochar application generally improved the mechanical and thermal properties of biochar-based polypropylene composites and their ability to retard flames.

Furthermore, Das *et al.* [243] produced a bio-composite with remarkable properties using polymer and wood-derived. Similarly, Poulouse *et al.* [244] immersed particles of biochar obtained from date palms into a polypropylene matrix. and reported that biochar addition of up to 15% had an insignificant impact on the composite's storage modulus. Other polyolefin matrices widely deployed for the development of piezo sensors are polyvinyl alcohol [245,246] and polyacrylonitrile [247]. Ogunsona et al. [248] impregnated polyesters with biochar particles. Nylon 6 was filled with biochar obtained from pyrolyzed Miscanthus at temperatures between 500 and 900°C. Obtained results revealed that high-temperature biochar was beneficial while low-temperature biochar was detrimental to the composite. In recent times, biochar has been utilized for the production of bio-polymer composites (such as starch [249] and gluten [250], consequently realizing the goal of absolute bio-sustainable production.

5. Conclusions

This review has provided a comprehensive update on the burgeoning field of biochar applications in the non-agroforestry sector, emphasizing recent advancements in areas beyond traditional soil amendment. We have highlighted numerous studies delving into the remarkable adsorptive capacity of biochar for both ions and organic molecules, alongside its promising electrochemical properties. These characteristics offer significant potential in the context of clean energy generation and storage, paving the way for a more sustainable future.

Furthermore, we have extensively explored the possibility of utilizing biochar as a viable substitute for normal fillers in both inorganic and organic composite materials. This potential for widespread application across diverse sectors highlights the feasibility of biochar as a strong alternative to both conventional and next-generation materials. The unique polyhedral structure of biochar further reinforces its advantage as a versatile material within the realm of material science. We firmly believe that this insightful summary of recent literature will serve as a springboard for groundbreaking research endeavours, unlocking the vast potential of biochar and biochar-based materials across various scientific and technological frontiers.

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