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Review

Biochar Production and Its Potential Application for Biocomposite Materials: A Comprehensive Review

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Abstract: Biochar, an organic, porous, and carbon-rich material originating from biomass via pyrolysis, showcases compelling attributes and intrinsic performances. Its appeal as a reinforcement material for biocomposites, as well as its auspicious electrical properties, has gained more attention, and makes biochar a versatile candidate for applications ranging from energy storage to catalytic devices. This scientific review undertakes a comprehensive exploration of biochar, spanning production methodologies, physicochemical intricacies, and critical process parameters. The focus of this paper extends to optimization strategies for biochar properties tailored to specific applications, with a dedicated inquiry into diverse production methods and activation strategies. This review's second phase delves into a meticulous analysis of key properties within biochar-based composites, emphasizing limitations and unique performance characteristics crucial for diverse applications. By synthesizing a substantial body of research, this review aims to catalyze future investigations by pinpointing areas that demand attention in upcoming experiments, ultimately emphasizing the profound potential of biochar-based materials across technical and scientific domains.

Keywords: biochar; pyrolysis; bio-based materials; metaphysical properties; electrical application

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1. Introduction

The escalating industrialization of recent years has precipitated a substantial surge in solid organic waste production [1], surpassing 3 million tons daily in 2017 [2,3]. Projections suggest a staggering global waste volume of 3.4 billion tons annually by 2050, more than doubling the population growth rate [4]. Contemporary waste management methods, notably the direct combustion in Combined Heat and Power (CHP) plants, offer expeditious waste valorization. However, this approach is marred by the consequential generation of environmentally detrimental Greenhouse Gases (GHGs) [5,6], including Carbone dioxide (CO_2), methane (CH4), and nitrous oxide (N_2O), contributing to the record-high global concentrations observed in 2019. Reaching 409.9 ppm, 1866.3 ppb, and 332.1 ppb, respectively, the highest recorded in the last 800,000 years [7], leading to an increase in the Earth's temperature. This is evident in the fact that the Earth's surface temperature over the last two decades (2000–2020) has been 0.99 °C higher than in the previous century [7], posing a significant threat to life and biodiversity [8].

However, in all scenarios, the temperature trend is upward. Even in the most optimistic scenario, such as SSP1-19 based on the Paris Agreement of 2015, which aims to achieve zero CO_2 emissions by 2050, we observe that the temperature will still rise to 1.5 °C. This underscores the urgent need to eliminate these gases or prevent their production.

In response to the imperative to curtail GHG emissions and mitigate climate change, thermochemical recovery methods such as pyrolysis emerge as potential alternatives [9–11].

Biochar, a notable byproduct of organic waste [12], stands out for its carbon-rich composition [13] and modifiable properties based on pyrolysis conditions, such as temperature, heating rate, medium, physico-chemical activation, composition, etc. [14–16], which makes it of great interest in many applications [17,18]. Its high surface area, carbon content, and porous structure make biochar an appealing candidate for bio-composite development [19], offering a sustainable avenue to replace petroleum-based plastics with biodegradable materials [20,21] and to address the increasing ocean pollution by the more than 8 million tons of plastics reaching the sea every year [22,23].

Even if biodegradable materials, such as biopolymers, have good characteristics and are already used in several fields [24–26] they are deficient in certain properties, and therefore need to be strengthened to improve and optimize the structure of these composite materials. The key sought-after properties are often associated with weight reduction, toughness, mechanical strength, chemical resistance, and the sports equipment and electronics industries [27].

With extensive experience in the use of carbonaceous materials in materials science [28], research indicates that carbonaceous fillers, in general, have a positive impact on the thermal, mechanical, and electrical properties of polymers [29,30]. Therefore, natural fibers and biochar are commonly utilized as reinforcements in biocomposites [31,32].

Comparatively, biochar offers more advantages than natural fibers when used as a filler in polymer composites. Biochar has better thermal stability that allows for the ability to work at temperatures above 200 °C [33]. It also can be modified to exhibit a hydrophobic nature and better compatibility with the polymer matrix, unlike natural fibers that are typically hydrophilic [19]. Moreover, the electrical properties of biochar contribute to the electrical conductivity of biocomposites, such that, in some cases, by adding activated biochar to biopolymer (PLA) in proportions of 50% to 85%, current measurements are, respectively, from 0.32 mA to 2.3 mA (milli ampere). This makes these materials suitable for applications in the electronics industry, smart food packaging [34], and personal protective equipment [35]. The wide range of applications for biochar-based biocomposites, which involve recycling waste materials in their production, adds to their economic viability when compared to carbon-based biocomposites [36].

This review is intended to highlight the utilization of biochar in bio-based materials and its wide range of applications. The first section delves into various techniques for producing biochar, exploring their physicochemical properties, and emphasizing the importance of considering critical process parameters. A comparative assessment of the impact of different production methods will be presented. Furthermore, the various activation strategies for biochar will be the subject of our investigation.

In the second section, we provide a comprehensive review of the primary properties of biochar-based composites. Special attention will be given to their limitations and the specific performance characteristics that render them suitable for a variety of applications. Through an examination of these aspects, this review will shed light on the potential of biochar-based materials across various fields.

2. Biochar Production

Biochar is a carbon-rich solid derived from the thermal stabilization of biomass or any other organic material [37]. In addition to (C), it includes ash, hydrogen (H), oxygen (O), nitrogen(N), and sulfur (S) [38,39]. Its richness, along with the abundance of functional groups such as phenolics, alcohols, and hydroxyls aromatics [40], contributes to its diverse characteristics, including alkaline pH, large specific surface areas, well-structured pores, tunable microstructure, good electrical conductivity, and high thermal and chemical stability, which make biochar attractive and useful in many fields [13,41,42]. Table 1 presents the properties of various biochar produced by pyrolysis at temperatures ranging from 400 °C to 900 °C.

Table 1. Properties of several raw biochar.

Raw Biochar Material	**T_{pyro} (°C)**	**S_{BET} (m^2/g)**	**V_p Cm^3/g**	**pH**	**EC (S/cm)**	**C %**	**O %**	**H %**	**N %**	**Ref.**
Wheat Straw	500	-	-	10.4	6.53×10^{-3}	67.4	7.3	1.0	1.4	[16]
Canola	600	<2	0.001	9.4	1.12×10^{-3}	77.5	12.3	2.3	7.6	[43]
Conocarp waste	600	-	-	12.2	9.03×10^{-3}	82.9	6.5	1.3	0.7	[44]
Alkaline lignin	900	27.0	-	-	0.002	64.0	21.3	0.7	0.8	[45]
Lignin-rich residue	700	14.3	0.029	-	0.050	70.2	28.2	1.0	0.6	[46]
Walnut shells	700	296.2	0.154	-	0.010	87.4	10.5	2.1	0.1	[46]
Sewage sludge	700	10.2	0.041	-	0.020	80.1	10.4	1.0	8.5	[46]
Bamboo	600	181.0	0.150	-	-	82.9	5.0	2.2	0.5	[47]
Bamboo	600	307.1	0.180	10.1	-	88.4	8.6	2.7	0.3	[42]
Bio solid	400	7.6	0.048	7.5	167×10^{-4}	21.4	20.4	0.9	3.3	[48]
Bio solid	600	32.0	0.058	11.3	406×10^{-4}	14.2	18.5	0.2	2.0	[48]
Safflower seed cake	500	4.2	0.008	9.44	-	71.37	21.76	2.96	3.91	[14]
Ulva flexuousa algae	450	1.2	-	8.0	0.0418	28.9	-	2.8	5.0	[49]
Bamboo	550	140.2	0.085	-	-	72.58	17.05	2.40	0.29	[50]
Rice husk biochar	600	297.4	0.152	-	-	51.02	----	1.67	0.52	[51]
Miscanthus	500	181.0	-	9.49	-	86.66	9.74	3.20	0.40	[52]
Banana pseudo-stem	500	1.078	0.005	10.16	-	43.23	36.81	0	19.96	[53]

Acronyms: (-) No data; Tpyro—Pyrolysis or carbonization temperature; SBET—Bruner, Emmett, and Teller, surface area; VP—Pore volume; EC—Electrical conductivity; C—Carbone; O—oxygen; H—hydrogen; N—nitrogen, wt.%.

Physico-chemical properties are affected by biochar productions conditions, particularly temperature [14]. Studies in the literature show that, due to dehydration and decarboxylation reactions, the carbon content in char decreases with increasing temperature. Indeed, under the effect of temperature, light organic compounds essentially volatilize into CO, CO_2, H_2O, and light hydrocarbons [15]. Also, unlike biochar produced from lignocellulosic biomass, in which constituents such as lignin are degraded, forming carbon-rich product ($T > 500$ °C) [54]. It has been shown that the heating rate during pyrolysis has no influence on pH, whereas temperature does. Indeed, the evolution of pH is proportional to the increase in temperature [16]. With increasing temperature, specific surface area and pore volume increase [55] in relation to the gradual development of the porous structure of biochar [48]. However, deformation of the pore structure has been observed at high temperatures greater than 500 °C [56]. Another property positively affected by pyrolysis temperature is the electrical conductivity [48]. Some authors link this behavior with the decrease in oxygen percentage [45], wile others attribute it to the increase in the content of soluble salts and the decrease in the amount of acidic functional groups in biochar as the temperature increases [57].

Due to its multiple and adaptable properties, biochar is increasingly being studied and tested for a wide range of applications, such as soil remediation [58,59], CO_2 capture [60,61], and the removal of organic [62,63], inorganic [64,65], and gaseous [66,67] pollutants. Moreover, biochar can be applied in the production of capacitors [68–70], batteries [71,72], composites (Y. Liu et al., 2022), and the reinforcement of bioplastics [73], among other uses [74,75].

2.1. Biochar Production Techniques

There are various thermochemical routes such as (I) torrefaction, (II) hydrothermal carbonization, (III) gasification, and (IV) pyrolysis that can produce biochar [74].

- Biomass torrefaction, also known as light pyrolysis, is a low-temperature (200–300 °C) heat treatment used as a pre-treatment of biomass to increase its calorific value and hydrophobicity [76,77]. During this process, hemicellulose and a portion of the cellulose undergo thermal decomposition, reducing the availability of hydroxyl groups. This prevents the formation of hydrogen bonds that would otherwise capture water molecules, making torrefied biomass more hydrophobic [78]. The process is conducted within a controlled environment under atmospheric pressure, with oxygen content below 21%, and residence times of biomass ranging from 5 to 120 min [79]. Torrefaction is further sub-classified based on the temperature range and medium used, and each sub-classification results in a product with distinct characteristics [80].
- Hydrothermal carbonization is a thermal depolymerization process that is used to convert wet biomass into crude oil, gas, and hydrochar [74]. This process is environmentally friendly, and uses moderate temperatures between 180 and 250 °C [81] under a saturated pressure of 2 to 20 MPa [82–84].
- Gasification is a thermochemical process in which the carbon content of biomass is converted onto a gaseous fuel in the presence of a gaseous medium such as oxygen, carbon dioxide, steam, or a mixture of these gases. This process takes place at a high temperature of between 700 °C and 900 °C [85–87]. When air or oxygen is used, gasification is considered to be a partial combustion process [88]. Gasification is also considered to be an efficient method of converting waste into energy, comprising various stages such as drying, combustion, pyrolysis, and the reduction zone, also known as the gasification zone [89]. The yield of biochar obtained by gasification is lower than that of pyrolysis [38], but the structural morphology of the biochar produced by the two processes is similar [90].
- Pyrolysis is a high-temperature (300–1300 °C) heat treatment that breaks down biopolymer macromolecules into lower molecular weight compounds under an inert atmosphere [37,42]. It is considered the most extensively studied thermochemical technique [91]. During pyrolysis, moisture and volatile compounds are released from biomass due to reactions such as dehydration, decarboxylation, volatilization, and polymerization. This process produces syngas, bio-oil, and biochar [92].

2.2. Types of Pyrolysis

Depending on operating conditions, pyrolysis can be classified into different subclasses. Each pyrolysis class has its advantages and limitations [93]. The various subclasses include fast, slow, flash, and intermediate pyrolysis, depending on temperature ranges, pressure range, heating rates, biomass, and steam residence time [42,93]. Other types of pyrolysis, such as vacuum pyrolysis and microwave pyrolysis, have also been reported in the literature [37,92].

- Slow pyrolysis (also known as conventional pyrolysis): This is the oldest method of charcoal production. It is characterized by a slow heating rate and a long residence time [88,93,94]. These conditions, regarding the temperature and slowness of the process, favor cracking and secondary reactions, which in turn lead to higher yields of biochar [38,95]. During this pyrolysis, a high production of quinone groups produced by the aromatic radicals of lignin is observed, which can be correlated with the complete carbonization of the material [96].
- Fast pyrolysis: This method is characterized by a high heating rate (10–200 °C/s) and a short residence time for vapor (0.5–10 s). The high heating rate involved in fast pyrolysis transforms the input biomass into a liquid product with a low exposure time to avoid cracking reactions that favor biochar formation [94]. The main product of fast pyrolysis is a liquid called bio-oil, which can find application as a liquid biofuel, or

from which valuable chemicals can be extracted [97]. The biochar produced by this type of pyrolysis has a higher porosity than that obtained by slow pyrolysis, which may be linked to a higher production of bio-oil [96].

- Flash pyrolysis: This is a variant of fast pyrolysis with higher heating rates and temperature (>900 °C) and shorter exposure time (<1 s) [93]. The combination of these two features results in a high yield of bio-oil and a low yield of biochar [10]. Some of the disadvantages of this process are illustrated by the thermal instability of the bio-oil composition and its low pH, which makes it corrosive. Also, fine particles can be entrained and find their way into the bio-oil [98].
- Intermediate pyrolysis: This type of pyrolysis is generally used to achieve a balance between liquid and solid products, i.e., between slow pyrolysis that gives high biochar yields, but relatively low liquid products [42], and fast pyrolysis [88,93].
- Vacuum pyrolysis: This is the thermal degradation of biomass under low pressure (0.001–0.02 MPa) in the absence of oxygen and without the need for a carrier gas to maintain the inert atmosphere [99]. This methodology is considered to be a promising technology for recovering energy from biomass, and has proved to be an alternative means of obtaining oils enriched with valuable fatty acids [9,100].
- Microwave-assisted pyrolysis: This uses microwave radiation as a heat source during pyrolysis, providing non-contact, rapid, selective, and energy-efficient heating. It also has a shorter processing time than the conventional technologies, using electrical energy as the heating source [92,101–103]. This type of pyrolysis has many advantages, but its industrialization is a challenge due to the complexity of reactor design, process control, and above all, safety. Furthermore, most studies have been carried out on a laboratory scale, which contracts with the growing need for large-scale systems [104]. The design of the microwave oven will depend on the final product [37,92]. For heating, microwaves penetrate the material forming a temperature gradient from the inside to the outside [11]. This type of pyrolysis promotes the development of porosity [37,102]. The operating conditions for the above mentioned pyrolysis process are illustrated in Table 2.

Table 2. Operating conditions for pyrolysis thermal conversion.

	Pyrolysis Type					
	Slow	**Fast**	**Flash**	**Intermediate**	**Microwave—Assisted**	**Vacuum**
Temperature °C	300–700	500–1000	800–1300	500–650	300–700	300–600
Heating rate (°C/s)	0.01–1	10–300	>1000	1.0–10	0.5–2	0.1–1.0
Vapor residence time (s)	Minutes to hours	0.5–10	<0.5	0.5–20	<30	0.001–1.0
Particle size (mm)	5–50	<1	<0.2	1–5	-	-
Pressure (MPa)	0.1	0.1	0.1	0.1	5–20	0.01–0.02
References	[10,70,88,93,105–107]	[10,70,88,93,101,104,105]	[10,88,93,105–107]	[88,93,106–108]	[10,92,106]	[99,104,107]

Acronyms: (-) No data.

Even though fast pyrolysis and flash pyrolysis are unfavorable for biochar production [10], the obtained biochar has a higher specific surface area than that derived from slow pyrolysis. Due to the shrinkage of the solid matrix at higher temperatures, the average pore diameter of biochar decreases, leading to the increase in specific surface area and availability of diffusion/reaction sites [109].

The effect of temperature, heating rate, and pyrolysis residence time has been studied by several authors in the literature [16]. In general, they have observed that biochar yield decreases with increasing pyrolysis temperature [110]. The amount of fixed carbon, pH, surface area, and pore diameter rise with temperature due to the thermal degradation of organic biomass [42]. The dominant functional groups of biochar, C-O and C-H, also decrease with higher heating temperatures due to more favorable dehydration [16]. At high temperatures, there are few hydrophilic functional groups available to establish a hydrogen bond with water [96]. Consequently, biochar produced at high temperatures has little affinity for water [111].

Another factor that has a significant effect on biochar properties is the way it is heated. The relatively high porosity of low-temperature biochar in Mw pyrolysis may be attributed to the heat and mass transfer mechanisms during microwave heating. Because Mw heating is volumetric with a slow-temperature front, volatile substances formed inside the particles can escape freely, leading to pore formation, resulting in a great advantage [37,56,112].

2.3. Biochar Activation

Even with precise control of pyrolysis parameters, the desired biochar properties may not be attained, necessitating activation. Among the most crucial properties of biochar are its porosity and surface area, which can be significantly altered through physical and/or chemical treatments [113]. These treatments are also valuable for modifying the functional groups within biochar. This adaptability renders biochar a versatile product suitable for various applications, as its properties can be tailored to enhance its performance [114]. Additionally, electrical properties may be potentially influenced after activation [34].

Chemical activation of biochar can be achieved through two processes: (i) Impregnating the raw biomass with a chemical agent and then subjecting it to heat treatment. During this process, the chemical agent dehydrates the sample and inhibits tar formation and the evolution of volatile compounds. This increases the efficiency of the carbonization process [115]. In this case, porosity and elemental composition depend on the distribution of chemical agents in the biomass and the activation parameters [116]. In the second process, (ii) the biochar is immersed in a solution of a chemical agent (acid, base, salt, etc.) at room temperature up to 120 °C for a set period [115,117,118], and then a secondary heat treatment is used to obtain the desired modified biochar [118,119].

Physical activation takes place in two stages. Firstly, carbonization is often carried out by pyrolysis in an inert atmosphere between 600 °C and 900 °C. Secondly, the activation of biochar by thermal treatment in an oxidizing medium such as water vapor, carbon dioxide, ozone, limited air, or moisture. The active oxygen in the activating agent is responsible for the combustion of the most reactive parts of the carbon structure and the tar retained in the porous structure [114,120]. The most common activating agent is steam [121]. The increase in porosity is more significant at higher temperatures [114]. Furthermore, high-temperature steam activation significantly mitigates the adverse impact of low-temperature pyrolysis on the surface and porosity of biochar [122].

Compared to physical treatment, chemical activation produces higher activity with greater total surface area and pore volume [123]. This activation can be carried out at relatively low temperatures. However, improved biochar activity and process efficiency are achieved with chemicals that are expensive, difficult to recover, and responsible for the corrosion of equipment, leading to various environmental problems [115].

3. Biochar Composites

Biochar composites and biocomposites have retained more attention in recent years, and exhibit excellent properties such as mechanical [124], thermal [125,126], and remarkable electrical conductivity [41,46,127]. The formulation of biochar composites is made by using synthetic polymers (PP, PVA, PC, etc.) or biopolymers (PLA, PBS, PHBV, etc.), as illustrated in Figure 1.

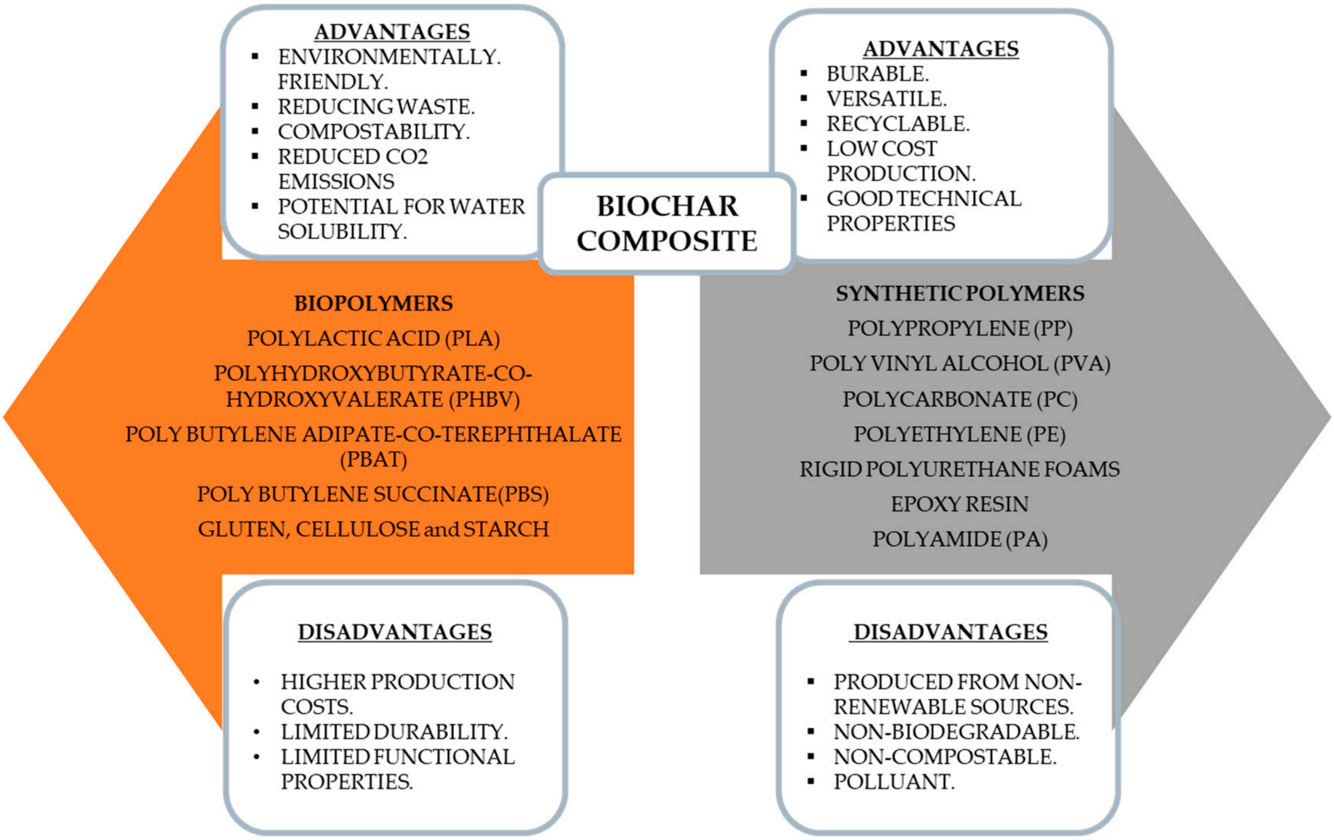

Figure 1. Illustration of different kinds of polymers used to formulate biochar-based composites.

Moreover, these materials demonstrate good degradability and compostability [128,129], as well as high-performance shielding against electromagnetic interference [130,131]. In addition, due to biochar's high CO_2 adsorption and retention capacity, it is also used to enhance the CO_2 sequestration capacity of certain composites [132]. Furthermore, the low density of biochar allows for the inclusion of a larger quantity of fillers in synthetic polymers, while significantly limiting the increase in the weight of the overall product. To illustrate, the final product weight of a composite containing 50% biochar (with a density of approximately 1.3–1.4 g/cm^3) in a PP matrix (~0.91 g/cm^3) is much lower than that of a composite containing talc (~2.7–2.8 g/cm^3) and carbon black (1.8–2.1 g/cm^3) with the same filler content [133]. The utilization of biochar as reinforcement in biocomposites is highly versatile and diverse. Biochar can be used as a standalone reinforcement [29,133,134], or can be effectively combined with various materials, including wood fibers [135], cellulose [136,137], glass fibers [125], and more. Its applications extend across a wide spectrum of matrix groups (as illustrated in Figure 2). It is also employed in composites with cementing matrices [138,139], and with polymer matrices such as PE [51], PLA [140], PP [141], nylon [142], rigid polyurethane foams [143], PC [144], Epoxy Resin [134,145], etc.

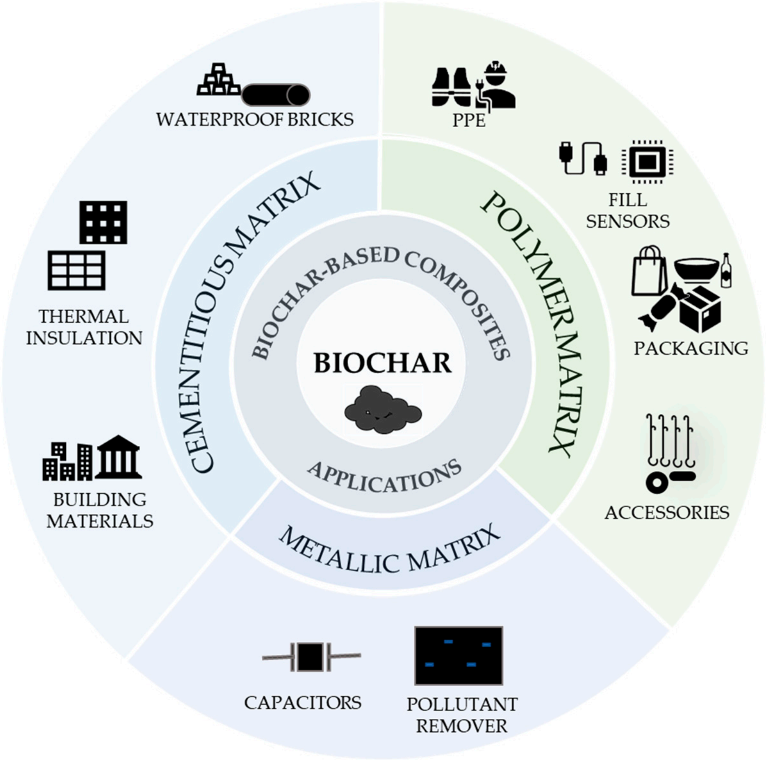

Figure 2. Main application fields of composites reinforced with biochar.

3.1. Cementitious Matrix-Based Biochar Composites

Industrialization and rapid technological progress have led to chemical contamination of water, affecting the environment and the health of living organisms. As some pollutants do not degrade and accumulate within living organisms, new alternatives have been sought. One alternative is the use of biochar-based composites to ensure the product's biodegradability. As shown in the study by Jinchuan Yan et al. [146], the biochar-supported nanoscale zerovalent iron composite was employed for trichloroethylene removal. Also, Zhang et al. [147] used chitosan-modified magnetic biochar to enhance Cr(VI) removal from an aqueous solution. The maximum adsorption capacity increased from 75.8 mg/g for the magnetic biochar to 127 mg/g for the modified magnetic biochar. Other examples are highlighted by L. Liang et al. [65], who reported different methods of producing magnetic biochar composites to remove inorganic contaminants such as acid orange 7(AO7), Ni(II), Cr(VI), Pb(II), Cu(II), Cd(II), Zn, etc., and organic pollutants such as dyes, phenol, pesticides, and antibiotics.

Silva et al. [148] show the potential application of waste-based magnetic biochar/titanium dioxide (BC/TiO_2) composite materials in the photocatalytic removal of antibiotics from aquaculture effluents. In their study, the authors evaluated the photodegradation of two widely used aquaculture antibiotics, sulfadiazine (SDZ) and oxolinic acid (OXA). The observed removal rates were 87% for SDZ and 98% for OXA when using 100 mg L-1 of the BCMag_TiO_2 composite.

The properties of biochar-based composites extend beyond water decontamination; they also find applications in building materials using clay as a matrix [149], concrete [150], and cement [151] (as depicted in Figure 1). The use of biochar is seen as a potential solution for improving the properties of cementitious composites. The addition of mixed wood feedstock biochar significantly improves the mortar's waterproof, compressive strength, and flexural strength. In addition, it promotes waste recycling and carbon sequestration [141]. Gupta and Kashani [152] found that adding 3% of pyrolyzed peanut shell biochar at 500 °C to cement matrix reduces its workability; however, it increases the setting speed of cement by 30%, increases hydration by 23%, improves compressive strength by 20%, and can reduce CO_2 equivalent emissions due to net carbon sequestration of the biochar. Similar results were obtained by K. Tan et al. [153] by studying the effect on certain properties when replacing some portions (0%, 1%, 3%, 5%, and 10%) of cement with pyrolyzed wood biochar obtained at different temperatures (between 400–700 °C). They also found that the albedo (the fraction of light that is reflected by an object) and the thermal conductivity of the mortars decreased linearly with the biochar content.

This trend in physical properties and environmental benefits was also presented by Roychand et al. [154] when studying the recycling of bio-solids as cement composites. They compared the properties of three composites: (I) composites with cement and biosolids in raw form; (II) composites of cement and biochar from bio-solids pyrolyzed under nitrogen at 600 °C for 1 h; and (III) finally, composite cement and ash produced from bio-solids calcined at 550 °C for 15 h. They observed that adding 10% biosolids to the cement compound increased its total porosity by more than 21 times and decreased its compressive strength by 80% at 28 days of curing. On the other hand, adding the same percentage of biochar enhanced its mechanical resistance by ~278% and reduced its total porosity by ~87% compared to that of cement compounds mixed with biosolids. Finally, replacing 10% cement with bio ash showed a ~66% reduction in total porosity and an 11% reduction in compression strength at 28 days compared to cement specimens mixed with biochar. In contrast, Laili et al. [155] have shown that using oil palm empty fruit bunch biochar as cement reinforcement has no effect on the compressive strength, but positively affects water resistance. Cement specimens reinforced with more than 8 wt.% biochar were found to be water resistant, while specimens that contained less than a percentage of biochar failed the water resistance test employed.

It should be noted that the particle size of the biochar used plays an important role. Inadequate particle dispersion leads to various defects in composite materials and decreases the reinforcing impact of the particles [156,157].

Gupta and Kua. conducted a study investigating the effect of particle size and biochar dosage on the fresh and hardened properties of cement mortar [139]. The findings revealed that both coarse biochar (2–100 µm) and fine biochar (0.10–2 µm) expedite cement hydration, leading to higher early strength development compared to control samples. Additionally, the authors noted a significant reduction in early-age (1-day) water permeability by approximately 50% with the addition of 0.50 wt.% coarse and 1 wt.% fine biochar. This reduction was attributed to the pore refining and densification effects of biochar in the cementitious paste. However, it is important to note that the rugged texture of biochar adversely affects the workability and rheology of cementitious mixes, while the fine particles of biochar enhance water tightness in cementitious materials through pore compaction and blocking [158].

3.2. Polymeric Biochar-Based Composites

Biocomposites and biodegradable polymers offer an alternative to the ecological crisis and plastic pollution. They are already used in a wide range of applications. However, they have certain weaknesses in terms of mechanical, electrical, and thermal properties. Consequently, biochar has been used to improve their physical behavior and increase their biodegradability. Table 3 illustrates mechanical and thermal properties of biochar-based composites.

Table 3. Illustrates the mechanical and thermal properties of biochar-based composites.

Polymer or Biopolymer	**Raw Biochar**	**Biochar Temperature (T_{pyro} °C)**	**Biochar Load (wt.%)**	**T_C (°C)**	**T_m (°C)**	**T_S (MPa)**	**T_M (GPa)**	**Ref.**
PP	Date palm	900	0	120.9	165.7	35.0	1.10	[19]
			5	123.2↗	165.2↘	34.5↘	1.12↗	
			15	123.1↗	166.6↗	34↘	1.36↗	
PLA	Coffee powder waste	700	0	129.3	153.4	52.5	2.50	[159]
			5	128.3↘	152.8↘	51↘	2.70↗	
			7.5	126.6↘	150.2↘	50.1↘	2.75↗	
PLA	Bamboo	-	0	129.1	159.8	34	2.80	[160]
			7.5	135.1↗	156.6↘	40.74↗	3.70↗	
PLA	Cotton fibers	1000	50	-	151↘	47.56↗	-	[161]
PA 4,10	Corn cob	500	10	247.3	225.9	68	3.10	[162]
			20	248.4↗	224.9↘	66↘	3.4↗	
PP	Starch	1100	0	113.2	159.7	21.73	0.38	[163]
			0.50	113.5↗	160.2↗	36.56↗	0.56↗	
			1	121.3↗	162.9↗	36.89↗	0.65↗	
PLA/PBAT 75/20 70/20	Coconut shell	800	5	99.0	176.7	28.2	2.51	[35]
			10	98.0↘	176.8↗	24.6↘	2.54↗	
UHMWPE	Bamboo	1000	60	134.3	121.7	94.5	1.39	[164]
			70	133.9↘	122.4↗	128.9↗	2.03↗	
			80	132.8↘	122.8↗	95.0↗	2.1↗	
PBS	Miscanthus	~500	0	91.2	115.7	41.5	0.80	[165]
			10	89.4↘	115.2↘	42.5↗	1.06↗	
			15	89.8↘	115.8↗	42.5↗	1.18↗	
			20	88.4↘	115.5↘	43↗	1.25↗	
			25	87.9	115.6↘	44↗	1.26↗	
Nylon	Miscanthus	650	20	196.4	222.3	81	2.51	[142]
PHBV	Miscanthus	650	0	124	174	38.3	3.50	[166]
			10	121↘	175↗	32.2↘	3.74↗	
			20	122↘	174≡	33.1↘	4.69↗	
			30	124≡	174≡	32.8↘	5.24↗	

Acronyms: (-) No data; Tpyro—Pyrolysis or carbonization temperature; TC—Crystallization temperature; Tm—Melting Temperature; TS—Tensile Strength; TM—Tensile Modulus; PLA—polylactic acid; PP—polypropylene; PA—polyamide; PBAT—poly butylene adipate-co-terephthalate; UHMWPE- Ultra high modular weight polyethylene; PBS—Poly (butylene succinate); PHBV—poly (3-hydroxybutyrate-co-3-hydroxyvalerate). ↘—diminution, ↗—Increase, ≡—no or very little variation from reference.

Several studies have shown that the addition of biochar to PLA promotes crystallization and increases its biodegradability. This addition can also result in a composite material that is recyclable, compostable, and can be used to manufacture agricultural accessories, such as branch separators or tomato supports [126,167]. This is because modified PLA presents good mechanical properties and thermal stability compared to PLA alone [168]. Das et al. [169] exposed that adding 24 wt.% of biochar to a wood-polypropylene biocomposite increases its tensile modulus from 3.1 to 3.5 GPa, and Flexural Modulus from 2.3

to 3.4 Gpa, approximately. Papadopoulou et al. [129] studied biocomposites of butylene succinate with varying biochar content (1%, 2.5%, and 5% by weight). They found that the inclusion of 2.5 wt.% miscanthus straw biochar, compared to butylene succinate alone, resulted in notable enhancements: around 19% in tensile strength, 19% in Young's modulus, and 39% in impact resistance. Moreover, they observed an increase in crystallization, diffusivity, and thermal conductivity. In addition, Cooper et al. [165] added miscanthus biochar to a bio-sourced poly(butylene succinate) matrix to improve the thermomechanical properties of the bioplastic. They observed that biocomposites filled with 25% biochar showed improvements of 57%, 13%, and 32% in tensile modulus, thermal deflection temperature, and thermal expansion, respectively.

The addition of biochar to some polymers has beneficial effects concerning the heat release rate. The high thermal stability of the biochar contributes to reducing it. Das et al. [29] show that adding 35%wt pine wood biochar to Polypropylene reduces in around 54% Peak heat release rate (PHRR).

In some cases, it is possible to obtain biocomposites reinforced with biochar derived from the same material. For instance, in the research conducted by Das et al. [170], three different charcoals 6 wt.% (gluten char, pine bark char, and carbon black) were used to make a composite with wheat gluten plastic. They found that the addition of this biochar to gluten significantly enhanced its properties. However, among all the composites, the one with gluten char was found to have the best mechanical and water-resistant properties, with a substantial reduction in water uptake by 38% and an increase in indenter-modulus by 1525%.

The manufacturing capability of biochar-based composites is diverse and highly applicable, for example, PLA reinforced with biochar from wheat stalks pyrolyzed at 800 °C used for 3D printing [171], or a composite of thermoplastic polyurethane (TPU) and digitalis purpurea biochar produced at 450 °C for 3D printed film [172]. Other examples include BIOPLAST GS2189 reinforced with 2.5% and 5% wood biochar pyrolyzed at 550 °C for the manufacture of agricultural accessories, such as biodegradable supports to avoid breaking tomato stalks [126], as well as a 50/50 blend of starch and polycaprolactone reinforced with various fillers (10%, 20%, and 30%) of biochar pyrolyzed at 800 °C from coffee grounds to produce thermoformed containers [128]. Other research has highlighted the interest in biochar-based biocomposites for lightweight automotive parts due to their light weight and low cost [173].

3.3. Factors Affecting the Properties of Biochar-Based Biocomposites

The properties of biochar-based composites are influenced by several factors, including the textural and structural characteristics and the dispersion of biochar added [168]. Additionally, the use of coupling agents plays an important role. The proper dispersion of biochar particles has been shown to improve the mechanical properties and rheology of biocomposites [174]. In some cases, the addition of biochar severely increased the zero-shear viscosity from approximately 160 Pa·s to over 5000 Pa·s. However, reducing the particle size significantly reduced it to approximately 260 Pa·s [175]. To achieve this, various techniques are used, such as ball milling, which reduces the size of biochar particles. However, this reduction can sometimes lead to a decrease in functional properties like electrical conductivity [176]. Richard et al. [177] studied the effect of loading and particle size on the tribological properties of polymer composites reinforced with biochar particles. They found that increasing the content rate with biochar particles reduces the coefficient of friction and wear rate of the composite compared to the neat polymer.

Zhang et al. [51] emphasized the significance of a well-structured porous surface. They revealed that increasing the pyrolysis temperature reduces the number of functional polar groups in biochar, increasing the affinity between biochar and non-polar groups of the polymer. However, it is important to note that the porous structure of the biochar, which facilitates strong physical and mechanical bonding within the bio-composite, has a more pronounced impact on mechanical properties than this affinity. The authors highlight that better mechanical properties of the bio-composite were reached with biochar pyrolyzed at 500 and 600 °C, which exhibited the best pore structure. This impact was also observed by Nizamuddin et al. [178].

In some cases, coupling agents such as maleic anhydride grafted polypropylene (MAPP), have been used to improve the interfacial bonding of components in composites. The use of MAAP can potentially improve the mechanical and water absorption properties, as well as the dimensional stability of the composites [179,180]. By adding 9 wt.% MAPP to the bamboo–polypropylene composite, the flexural, tensile, and impact strengths increased by 22.9, 29.6, and 1.92%, respectively, compared to the base composite [181]. Other studies have shown that the use of MAPP in biochar-wood-polymer composites improves the materials due to the reaction of the MAAP carbonyl group with the hydroxyl group of the wood or natural fiber [30,182].

3.4. Biocomposites Based on Activated Biochar

The surface of biochar can be readily modified to improve its compatibility with polymers, and thus obtain composites with better properties. For this purpose, some authors have chosen to use plasma-retreated biochar or activated carbon to ensure a better interface between filler and polymer [163].

A study conducted by Zhang et al. [137] showed that the incorporation of active biochar into MCC/PLA composites had the effect of stimulating an early exothermic crystallization, increasing the glass transition temperature and melting temperature, and retarding composite degradation. With the addition of biochar, certain mechanical properties were improved, notably (i) tensile strength, (ii) flexural strength, and (iii) impact strength. The stiffness, elasticity, creep resistance, and anti-stress relaxation capacity of the composite were also improved.

Another study, conducted by Lan et al. [183], showed that using chemically modified tree bark biochar to prepare polydimethylsiloxane composite membranes improved the overall performance of the membranes. The modified particles were well dispersed in the polymer matrix, resulting in enhanced mechanical properties. However, it should be noted that while the activation of biochar can improve many mechanical properties, the activation method used can have an impact on the electrical properties of composites. Some studies show that KOH activation tends to attack the structural domains of the carbon matrix, resulting in a highly porous and disordered structure, with poor electrical conductivity [184].

Ho et al. [160] observed that the tensile and flexural strengths, and also the ductility index of PLA/bamboo biochar composites, increased with the percentage of biochar. The latter reached maximum values when the bamboo biochar charge was at its optimum at around 7.5%. This improvement was attributed to a good dispersion of biochar particles in the polymer matrix. Similarly, Pudełko et al. [126], who used biochar derived from wood and sewage sludge (10–20%) as reinforcement in polylactic acid (PLA) and BIOPLAST GS2189, found a decrease in the mechanical properties of the composites due to the agglomeration of the biochar particles. This observation underlines the importance of good dispersion to improve the mechanical properties of biochar-based composites.

In summary, as explained by Das et al. [36], the use of activated carbon in composites has several advantages. First, it promotes sustainable and cleaner production by using waste. Second, higher surface area, carbon content, hardness, and stiffness of the active biochar improve the performance of biocomposites. In addition, adding active biochar to the bio-composite could reduce manufacturing costs, as less MAPP can be used to maintain comparable mechanical and flammability properties.

3.5. Fire-Resistant Biocomposites

Although biochar is used as a fuel, it is also useful to improve the fire resistance of biocomposites. Choi et al. [185] reported that creating a block with corn cob powder mixed with 10% biochar improves the thermal stability by 27.6%. In a recent study, Shah et al. [186]

evaluated the fire-retardant properties of rice husk biochar-reinforced recycled high-density polyethylene. Using different loads of biochar 10 to 40 wt.%, the authors observed that the flammable properties improved with biochar rate content, and affirmed that at a high content (40 wt.%), the rice husk biochar-reinforced recycled PE exhibited the best thermal stability, the lowest burning rate, the highest limited oxygen index (LOI), and displayed the best fire-retardant properties.

The trend of reduced flammability in composites due to the presence of biochar has been observed by Das et al. [187], who also observed that, in biochar-based wood/polypropylene composites, a higher proportion of biochar and less wood are beneficial in reducing flammability. The stability of biochar contributes to the formation of effective carbon to limit the transfer of oxygen gas to the polymer. This also compromises tensile and flexural strength, as when biochar pores are filled with flame-retardant substances, polymer infiltration into the biochar becomes ineffective, and thus limits physical adhesion.

In other studies, biochar is used to host a naturally flame-resistant material, such as lanosol. Perroud et al. [73] Studied the effects of lanosol-doped biochar on the mechanical and fire resistance properties of bioplastics. To manufacture the composite, 4 wt.% of lanosol was initially doped into 6 wt.% of biochar using various techniques: mechanical (dry mixing), chemical, and thermal doping. Subsequently, this biocarbon, doped with lanosol, was blended with 65 wt.% wheat Gluten and 25 wt.% glycerol. The study revealed that all bioplastics incorporating the doped biocarbon exhibited enhanced flame retardancy compared to the bioplastic alone. Notably, the composites utilizing lanosol thermally doped in biochar demonstrated superior mechanical resistance compared to the other two composite variations.

3.6. Electrical Characteristics of Biochar-Based Biocomposites and Their Practical Applications

Due to their inherent properties, natural polymer compounds typically exhibit electrical non-conductivity [188]. However, the use of biochar, with the appropriate physicochemical properties [31], could be a cost-effective and environmentally friendly alternative for manufacturing biocomposites with enhanced electrical conductivity (Table 4).

Table 4. Electrical conductivity of certain composites and their possible applications.

Polymer or Biopolymer	Raw Biomass	Biochar Temperature (T_{pyro}(°C))	Biochar Load (%)	Electrical Propriety	Possible Applications	Ref.
70PLA/20PBAT	Noix coco	800	10	1.03×10^{11} ohm/sq	Packaging. Personal protective equipment.	[35]
UHMWPE	Apple	900	70	8.2×10^{-2} S/cm	Antistatic materials. Electronic circuit.	[41]
UHMWPE	Bamboo	1000	80	0.53 S/cm	Antistatic materials. Shielding against electromagnetic interference.	[164]
UHMWPE	Bamboo	1100	70	0.39 S/cm	Antistatic materials. Electronic circuit.	[41]
PLA	Corn Cane	Activated at 800	50	0.32 mA	Biosensors for smart food packaging.	[34]
			85	2.3 mA		
PVA	Leaf mixture	-	6	0.23816×10^{-6} S/cm	Electronic devices. Anti-static materials.	[189]
			10	1.833×10^{-6} S/cm		
PVA	Cotton	1000	10	1 mS/m	Piezoresistive sensors. Impact detectors.	[190]
			20	2.90 S/m		
			30	7.5 S/m		

Table 4. *Cont.*

Polymer or Biopolymer	Raw Biomass	Biochar Temperature (T_{pyro}(°C))	Biochar Load (%)	Electrical Propriety	Possible Applications	Ref.
PVA	Sugar cane bagasse	800	12	2.38×10^{-2} S	Electronic devices.	[191]
PVA	Sugar cane bagasse	1000	5	1.91×10^{-2} S	Resistive piezo materials.	[191]
Epoxide Resin	Coffee	1000	15	35.96 S/m	Electronic devices.	[127]
Epoxide resin	Miscanthus	650	20	0.20 S/m	Sensors.	[31]
		700		1.88 S/m		
		750		2.75 S/m		

Acronyms: BC—Biochar; PLA—polylactic acid; PP—polypropylene; PA—polyamide; PBAT—poly butylene adipate-co-terephthalate; UHMWPE—ultra high molecular polyethylene; PVA Poly (vinyl alcohol); Electrical propriety may be resistance, conductance, or electrical conductivity.

Ahmed et al. [191] indicated that 5 wt.% biochar is the minimum required amount to make an electrically conductive Sugarcane Bagasse Biochar/Polyvinyl Alcohol Biocomposite Film. Unterweger et al. [192] analyzed the properties of Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) and biochar derived from carbonized wood dust and cellulose fibers at temperatures ranging from 900 to 2300 °C. They observed a significant improvement in mechanical performance and electrical conductivity. The latter improved by increasing the biochar charge, reaching 1.7 S/cm when the biochar load was 15 to 20% by volume.

This behavior of conductivity as a function of biochar loading has also been demonstrated by Umerah et al. [193], who showed that the conductivity of biochar composites from coconut shell waste and PLA increases with the increment of biochar load. Their results suggest that it is possible to create polymer nanocomposites with high mechanical, thermal, and electrical properties, suitable for use in 3D printing, biomedical, and food packaging applications. These applications have also been highlighted by George et al. [35]. On the other hand, Jasim et al. [194] found that, due to the electrical and hydrophilic properties of biochar, PLA/Thymol/biochar composites can be used in antistatic packaging to dissipate static charges.

The electrical conductivity of biochar is influenced by the composition of biomass. Indeed, high lignin content gives a biochar with better conductivity in comparison with low lignin biomasses [45]. However, the electrical conductivity of biochar is mainly influenced by the pyrolysis temperature, as indicated by previous studies [46]. High pyrolysis temperatures increase the biochar aromatization [195] and enhance the specific surface area and carbon content, with a notable impact on the quantity of sp2 hybridized carbon. This specific type of carbon significantly contributes to the electrical conductivity exhibited by the produced biochar [19,35,196]. Therefore, the higher the pyrolysis temperature, the higher the conductivity. Table 4 illustrates the electrical conductivity properties of composites based on biochar as an effective filler to enhance functional properties. Some possible applications are also indicated.

Al-Wabel et al. [44] show that, in the biochars produced from conocarpus residues and pyrolyzed at temperatures ranging from 200 °C to 800 °C, the conductivity varies from 0.76 ± 0.004 to 10.26 ± 0.04 dS/m, which may be due to the presence of salts and high carbonization. Conductivity is strongly dependent on the degree of carbonization, with high carbon content resulting in high electrical conductivity. Gabhi et al. [197] found that bulk conductivity increased from 2.5×10^{-4} to 399.7 S/m when carbon content rose from 86.8 to 93.7% wt. This information coincides with the idea that the electrical properties of biochar composites are enhanced by the presence of highly purified carbon, low functional group content, and small particle size [35]. Furthermore, the electrical conductivity of biochar is also affected by compression, which is described by the phenomenon of elastic electrical conductivity behavior. According to this phenomenon, the conductivity of biochar increases with compression load and decreases to the previous compression level when the load is released [197]. This phenomenon was also observed by Giorcelli et al. [31], who explained that it is due to the compaction process of biochar powders. As pressure increases, air is expelled from the pores and the void between particles decreases. As a result, the structure of biochar particles becomes deformed, increasing the effective contact between the biochar particles, and thus their conductivity. Biochar-polymer composites possess properties that enable them to be used as three-point bedding strain sensors with high sensitivity of electrical conductivity towards the applied strain [198,199].

To adapt biochar for specific applications that require enhanced conductivity, it often undergoes pre- or post-treatments. In the case of electromechanical detection, biochar is often impregnated with conductive materials, such as Cu^{2+}/Cu^{+}, which has been used in conjunction with biochar to manufacture an ultra-sensitive enzyme-free electrochemical glucose sensor [200] and the ultra-sensitive electrochemical detector of nitrite in water [201].

For use in the material's production, Giorcelli et al. [202] annealed (thermally activation) olive biochar at 1500 °C to achieve a good degree of graphitization. This yielded an electrical conductivity of 103 S/m, enabling them to produce a fully reversible silicon-rubber piezoresistive material. In the case of Siobhan et al. [34], they used steam-activated biochar at 800 °C to fabricate a biosensor from 85%wt activated biochar (ABC)/PLA-based composite. This biosensor exhibited good electrical conductivity compared to PLA alone, as well as high NH3 sensitivity, and was suitable for smart food packaging.

As mentioned above, it is possible to create supercapacitors based on a biochar with excellent electrochemical performance, promising specific capacitance, and high energy [203]. Thomas et al. [204] produced a banana-stem biochar pyrolyzed at 500 °C composite with polyaniline. They made several mixtures (polyaniline 3–6 mmol and biochar 0.2–1 g), and observed that the compound of 0.6 g biochar and 4 mmol of polyaniline had the best electrical conductivity of 4.1 $S.cm^{-1}$. This composite exhibits a capacitance of 57.5 $F\ g^{-1}$, which means better electrochemical performance compared to various biochar-based electrode materials reported in the literature, such as the BC-NiO nanocomposite [205] and modified tea waste biochar [206].

4. Conclusions

In conclusion, this comprehensive review underscores the substantial potential of biochar as a reinforcement in biobased materials, unlocking a multitude of applications with profound environmental and economic implications. The surge in solid organic waste production, exacerbated by rapid industrialization, requires innovative approaches for waste valorization and sustainable material development. Biochar, emerging as a versatile byproduct of thermochemical recovery, stands out for its carbon-rich composition, modifiable properties, and diverse applications.

Firstly, Biochar's inherent properties, including a large specific surface area, high porosity, thermal stability, and electrical conductivity, position it as an exceptional reinforcement material. Its potential applications cover multiple useful performances and span a wide spectrum, encompassing energy storage, electromagnetic shielding, catalytic devices, sensors, and the pivotal realm of biodegradable biocomposites (Figure 3).

One of the significant challenges addressed in this review is the agglomeration and poor dispersion of biochar within biopolymer matrices, which can compromise the mechanical and electrical performance of biocomposites. The exploration of various biochar production techniques, along with an in-depth analysis of physicochemical properties and critical process parameters, has laid the groundwork for understanding the nuances of biochar utilization.

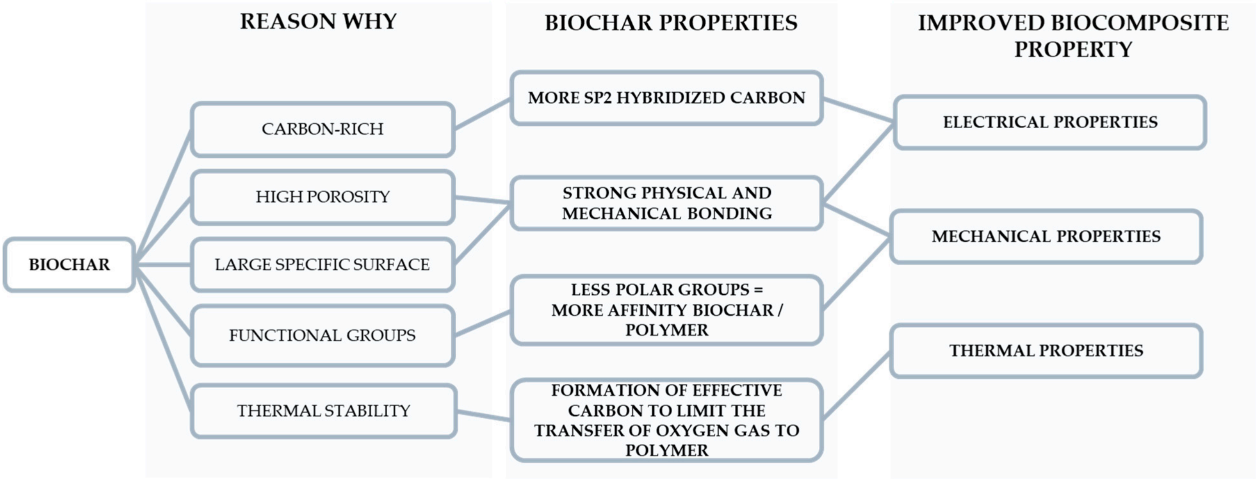

Figure 3. Summary of the causal effect between biochar properties and final properties of the biocomposite performances.

In the second part of the review, a thorough examination of key properties in biochar-based composites sheds light on their limitations and specific performance characteristics, offering a roadmap for tailored applications. The significance of weight reduction, toughness, mechanical strength, and chemical resistance in biodegradable materials, such as biopolymers, is highlighted. Biochar's superiority over natural fibers as a filler in polymer composites, owing to its enhanced thermal stability and hydrophobic nature, is emphasized. Moreover, the pivotal role of biochar in influencing the electrical properties of biocomposites opens avenues for applications in electronics, smart packaging, and personal protective equipment. However, as mentioned above, a high biochar content causes an increase in the viscosity of the composite, which makes it difficult to mold, and causes problems during processes such as injection molding. Another limitation is that biochar-based composites are prone to particle agglomeration, which hurts the properties and appearance of the biocomposite; therefore, the importance of good dispersion was emphasized in Section 3. Another limitation is the inconsistency in the properties, as mentioned in Section 2, as the properties of biochar vary depending on many factors, which can lead to inconsistencies in the properties of the biocomposite.

As we navigate the evolving landscape of sustainable materials, this review serves as a comprehensive guide, illuminating the transformative potential of biochar in revolutionizing the biobased materials sector and in fostering a more sustainable and resilient future. Further research is needed to improve the electrical performance of biocomposites and explore new applications. Future lines of research could focus on developing new processing techniques to improve dispersion and reduce agglomeration. Optimizing biochar properties for specific applications and exploring new biopolymer matrices and composite architecture are also important to investigate. In addition, further studies are needed to investigate the long-term stability and environmental impact of biochar-based biocomposites.

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Abbreviations

ABC	Activated Biochar
BC	Biochar
C	Carbone
CH4	Methane
CHP	Combined heat and power
CO_2	Carbone dioxide
EC	Electrical conductivity
GHG	Greenhouse gas
H	Hydrogen
MAPP	Maleated polypropylene
MCC	Microcrystalline cellulose
Mw	Microwave
N	Nitrogen
(N_2O)	Nitrous oxide
O	Oxygen
PA	Polyamide
PBAT	Polybutylene adipate-co-terephthalate
PBS	Poly(butylene succinate)
PC	Polycarbonate
PE	Polyethylene
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxy valerate)
PLA	Polylactic acid
PP	Polypropylene
Ppb	Parts per billion
PPE	Personal protective equipment.
ppm	Parts per million
PVA	Poly (vinyl alcohol)
SBET	Brunauer, Emmett, and Teller surface
TC	Crystallization temperature
Tm	Melting temperature
TM	Tensile Modulus
Tpyro	Pyrolysis or carbonization
TS	Tensile strength
UHMWPE	Ultra high molecular weight polyethylene
VP	Pore volume
XPS	X-ray photoelectron spectroscopy

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