REVIEW **Open Access**

Engineered biochar composites for improved adsorption stability and remediation of the wastewater

Awadhesh Kumar Verma[1], Tanya Singh[1], Ashab Noumani[2], Satyendra Singh[2], Olga Ergunova[3] and Neeta Raj Sharma[1*]

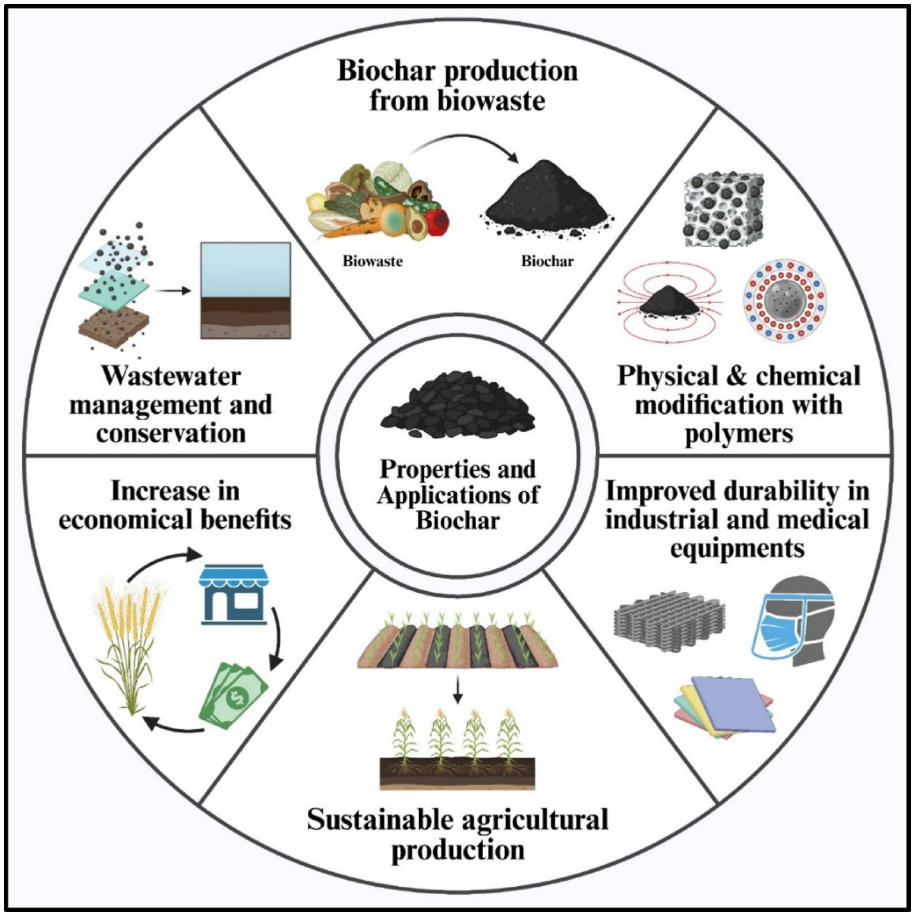
*Correspondence:
Neeta Raj Sharma
neeta.raj@lpu.co.in
[1]School of Bioengineering and Biosciences, Lovely Professional University, Jalandhar-Delhi, G.T. Road, Phagwara 144411, Punjab, India
[2]Special Centre for Nanoscience, Jawaharlal Nehru University, New Delhi 110067, India
[3]BRICS Women Scientists' Alliance, Russian Union of Young Scientists, Peter the Great St. Petersburg Polytechnic University, Vice-Chair, St. Petersburg, Russia

Abstract
Biochar, a carbon-dense substance utilized for environmental conservation, soil improvement, and carbon sequestration in sustainable farming, often faces challenges such as insufficient interfacial adhesion, thermal instability and leaching of toxic elements into groundwater, hindering its broader application. Employing and integrating polymers to enhance the structural integrity, surface compatibility, and adsorption effectiveness of biochar has shown to be a successful strategy for addressing these challenges. This review highlights the emergent application of polymer-coated biochar (PCB) to improve the functional efficacy of biochar obtained from organic waste via pyrolysis. Recent studies have focused on polymer-biochar composites, showcasing notable progress in grasping the physico-chemical interactions between polymers and carbon-rich matrices, while also revealing substantial gaps in understanding their long-term environmental effects and degradation processes. This comprehensive review investigates various polymer-coating methods and their effects on the physicochemical and functional properties of biochar, emphasizing enhanced pollutant adsorption, controlled nutrient release, and increased resistance to chemical and thermal degradation. The potential applications of PCB in sustainable waste management, pollution cleanup, and circular economy strategies are explored, emphasizing environmental benefits alongside possible ecological risks. Such analytical evaluation would integrate current studies to establish a foundation for future progress in PCB materials, providing crucial insights for researchers, practitioners, and policymakers seeking to align biochar innovation with global sustainability objectives.

Keywords Polymer-coated biochar, Wastewater management, Remediation, Biochar modification, Organic pollutant, Sludge-derived biochar, Carbon sequestration, Sustainability

Discover

Graphical abstract



1 Introduction

Although biochar is an effective technique for environmental remediation and carbon sequestration, its full potential is still unrealized. Enhancing the usefulness and usability of biochar made from organic wastes is made possible by the growing field of PCB [1]. Biochar is a carbon-rich substance produced by thermally burning organic feedstock with small amount of oxygen. It can be produced from a range of organic wastes, such as municipal solid waste and agricultural residues. However, wastewater treatment sludge is showing great promise as a feedstock because of its high carbon and nutritional content, which includes ammonia [2]. Biochar has historically attracted interest due to its favourable characteristics, which make it a strong contender for a range of environmental applications. These characteristics include a high carbon content, a large surface area, a high cation exchange capacity, and structural stability. The rise in published papers over the last 20 years demonstrates the growing importance of biochar in scientific literature and its promise for sustainable activities like wastewater treatment, soil improvement, and carbon sequestration [3]; wherein a global meta-analysis was carried out by Gross et al., in which they analysed the capability of biochar for carbon sequestration as a soil additive concerning various site and soil traits and the distinctions between laboratory experiments and field research, and discovered that biochar significantly enhances and stabilizes soil organic carbon (SOC) [4]. In another study, Kopecký et al. performed extraction of phosphorus from wastewater through a biochar filter to produce a soil enhancer with readily available phosphorus for plants. Through this method, they were able to conclude that such technology could be applied in agriculture and waste management [5]. However, existing studies often overlook crucial aspects, particularly the limitations posed by uncoated biochar. Common drawbacks include thickness swelling, thermal instability, and low interfacial bonding, which can hinder biochar's effectiveness in practical applications [6]. For instance, Das et al. conducted pioneering research that incorporated biochar derived from landfill pine wood into wood-plastic composites (WPCs), finding that while the addition of biochar improved interfacial adhesion and mechanical properties, issues related to material ductility arose at higher loading levels [7]. Such findings underscore the necessity of optimizing biochar properties to meet the demands of various applications.

Despite the progress made in the field, much of the literature has primarily focused on mechanical properties and the physical interactions of biochar without adequately addressing its environmental implications. For example, while Das et al. explored the mechanical advantages of biochar in composites, they did not investigate the environmental risks associated with potential leaching of harmful substances or the impacts on soil health [8]. Meanwhile, a review by Afshar et al. emphasizes on thorough environmental impact assessments that encompass the entire life cycle, addressing alterations in land use and carbon storage, should be a primary focus, along with assessing the real environmental impacts of biochar production and application necessitates carrying out this thorough assessment [9]. This paper aims to bridge these gaps by investigating the multifaceted benefits of PCB, particularly how polymer coatings can enhance biochar's properties and mitigate its limitations. Polymer coatings can improve stability, reduce dust and loss, facilitate controlled release capabilities, enhance compatibility, customize properties, and offer environmental protection compared to traditional biochar [10].

According to the main hypothesis of this study, PCB's customised features from polymer modification will enable it to perform better in a variety of applications. In particular, it is expected that adding polymers will improve biochar's adsorption capability for pollutants as well as its mechanical and thermal durability, making it a more useful instrument for environmental remediation [11].

1.1 Historical context of biochar

The usage of biochar dates back hundreds of years, when ancient societies realised how beneficial it was for improving soil fertility [12]. Nonetheless, its modern revival in research and application can be ascribed to heightened awareness of climate change, the necessity for sustainable waste management, and the quest for creative agricultural methodologies. Recent improvements in pyrolysis technology have enabled the effective generation of biochar from diverse organic sources, such as agricultural waste and municipal solid waste. The production process, generally entailing the thermal breakdown of biomass in low-oxygen environments, yields a stable carbon structure capable of sequestering carbon for prolonged durations [2, 13]. Biochar has been a hot topic in discussions about sustainable agriculture and climate change mitigation techniques because of its benefits, which include its capacity to enhance soil structure, boost nutrient retention, and reduce greenhouse gas emissions [3]. Traditional biochar applications have encountered difficulties with its physical characteristics and performance in particular environmental conditions, despite its advantages. Research has demonstrated, for instance, that the surface area, pore size distribution, and functional groups of biochar affect its ability to adsorb organic contaminants and heavy metals [14]. Depending on the feedstock and production, these characteristics might fluctuate greatly, resulting in inconsistent performance in various applications [15].

Although a great deal of study has been done on the characteristics and uses of biochar, little is known about the precise function of polymer coatings in improving biochar's performance. Many of the reviews that are now available concentrate on the production, alteration, or use of biochar without sufficiently discussing the possible advantages of mixing biochar with polymers [16]. This session offers a chance to learn more about how polymer coatings work in concert with biochar, especially with regard to mechanical performance, thermal stability, and environmental safety [17]. Investigations by prominent scholars have established a foundation for comprehending biochar's characteristics and uses; yet, constraints such as limited sample numbers, biases in feedstock selection, and insufficient comprehensive assessments impede the progress of the discipline. Some studies have demonstrated the effectiveness of biochar in mitigating soil pollutants; however, they frequently neglect to address the long-term environmental consequences of biochar application, such as the possible leaching of polycyclic aromatic hydrocarbons (PAHs) or metal ions [18, 19]. These disparities underscore the need for a more comprehensive strategy that blends the advantages of biochar with polymer technology to produce a more adaptable and efficient substance.

This research is crucial for informing policy and support systems aimed at promoting sustainable materials in environmental applications. This study offers important insights for those involved with agriculture, waste management, and environmental remediation by clarifying the advantages and disadvantages of PCB [20]. The results can be used by policymakers to create application recommendations for biochar that optimise its advantages while lowering any possible hazards. By advancing knowledge of how cutting-edge materials might be applied to urgent environmental issues, our research supports global sustainability goals.

2 Biochar properties and production

Produced by pyrolyzing biomass, biochar is a carbon-rich substance with special physical and chemical characteristics that are necessary for its use in agriculture and environmental management. The kind of biomass and the pyrolysis conditions have an impact on these characteristics. Figure 1 illustrates the general procedure for producing biochar.

2.1 Physical and chemical properties

Higher pyrolysis temperatures (≥ 600 °C) increase carbon content, structural organization, surface area, and porosity. At this temperature, amorphous carbon becomes graphitic [21]. Biochar has macropores, mesopores, and micropores, adsorption efficiency depends on micropores, while mesopores aid liquid-solid interactions. The higher temperatures increase micropore volume but decrease porosity [22]. Carbonization technique raises solid density but decreases bulk density, which is essential for agricultural applications [23]. Whereas chemical properties start with thermal decomposition and pyrolysis break down biomass components, influencing pH and cation exchange capacity (CEC), and high temperatures raise pH and diminish charcoal yield [24]. Pyrolysis

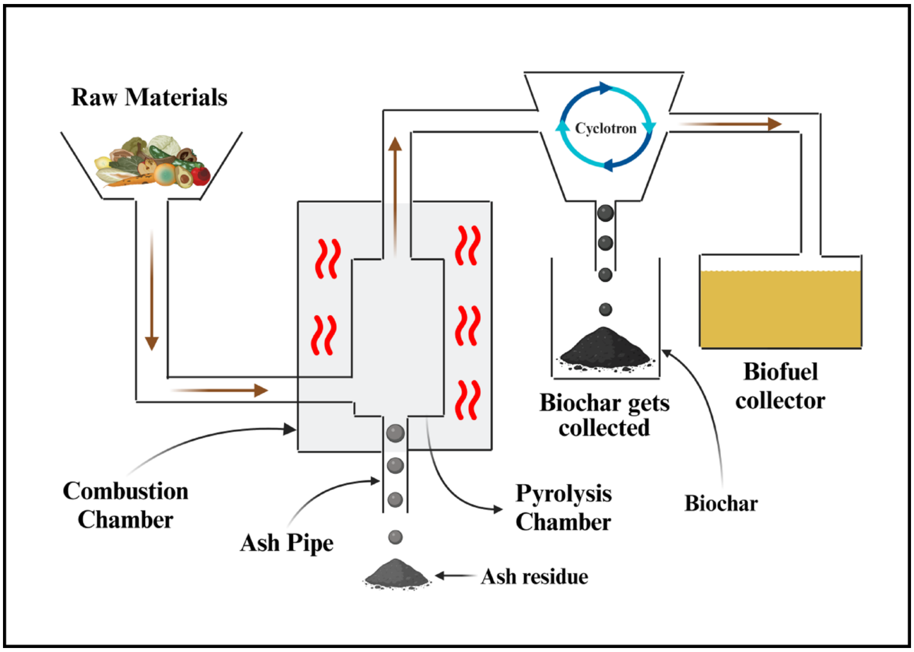


Fig. 1 Diagram explaining the general process of biochar production

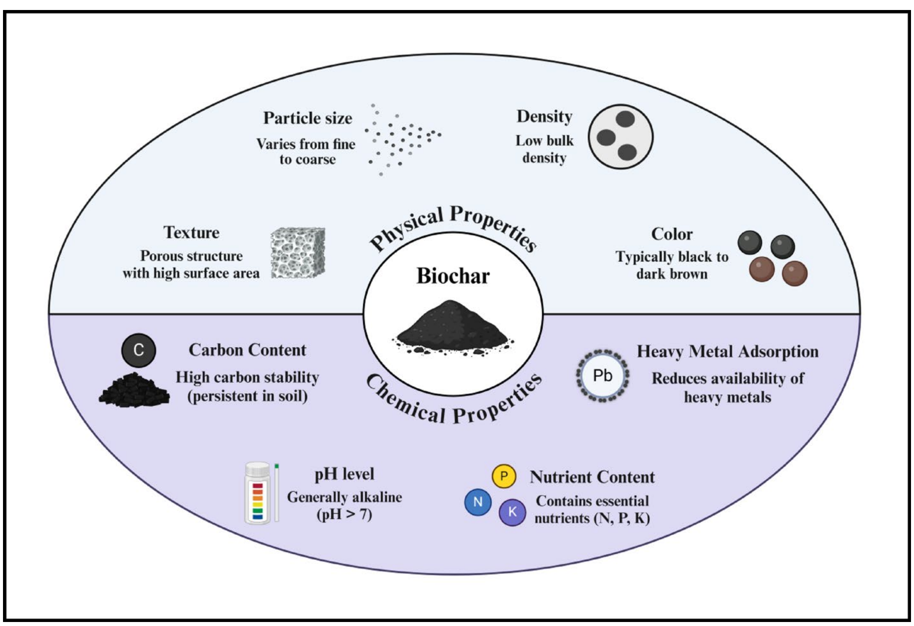


Fig. 2 An illustration demonstrating physical and chemical properties of Biochar

creates functional groups that improve chemical reactivity and pollutant adsorption. Due to mineral concentration and oxygen-containing functional groups, biochar from different feedstocks has variable CEC [25]. Surface characteristics, including the presence of heteroatoms, influence biochar's interactions with pollutants. Variability in chemical composition allows biochar to effectively adsorb contaminants [26]. The visual representation of physical and chemical properties of biochar is given in Fig. 2 below.

3 Production of biochar

Changes to biochar's physicochemical characteristics, such as surface area, functional groups, and pore structure, can maximise its adsorption capabilities for certain environmental applications. These qualities are improved via a variety of approaches, such as physical, chemical, and biological ones.

3.1 Physical modification methods

Physical modifications are cost-effective and do not introduce impurities. Common techniques include ball milling, where this process reduces particle size and increases surface area, improving adsorption for inorganic and organic ions [27]. A study by Zhao et al. demonstrated that ball milling biochar significantly enhanced its surface area, leading to improved adsorption capacity for heavy metals and organic pollutants [28]. Gas/Steam activation technique enhances porosity and surface reactivity while removing impurities, nearly doubling biochar's beneficial properties. However, it may reduce certain functional groups critical for metal remediation [29]. For instance, Olugbenga et al. reported that steam activation significantly increased the surface area of biochar but reduced its carboxyl group content, affecting its efficacy in heavy metal adsorption [11]. Microwave modification includes, microwave pyrolysis which produces biochar with greater surface area and functional groups, improving soil properties like water retention and cation exchange capacity. Research by Qiu et al. indicated that microwave-irradiated biochar had superior characteristics compared to conventionally produced biochar, enhancing its applicability in soil amendment [30]. Magnetic biochar incorporates magnetic materials, like iron oxides, facilitates easy separation after use in wastewater treatment, preventing secondary pollution. This modification can improve cation exchange and metal binding capacities. A study by Xiao et al. showed that magnetic biochar could be effectively removed from wastewater using magnetic forces, significantly reducing contamination levels [31]. These methods significantly enhance biochar's performance in pollutant removal and soil remediation.

3.2 Chemical modification techniques

Chemical modifications involve treating biochar with chemicals under inert gas atmospheres, enhancing micropores and functional groups. Common techniques include oxidizing modification which apply acids (e.g., H_2SO_4, HCl) or alkalis (e.g., KOH) either before or after pyrolysis enhances sorption capacity and metal uptake. Alkaline treatment improves surface electrostatic attraction, which is advantageous for a variety of contaminants, whereas acid treatment increases carboxyl groups, which improves metal adsorption [32]. A study by Wang et al. found that an increase in oxygen-containing functional groups in acid-activated biochar led to better adsorption of heavy metals like Copper and Lead [33]. Chemical impregnation/coating entails applying metal oxides or nanoparticles to biochar either during or following pyrolysis. Various methods create biochar-nanocomposites that exhibit improved surface area and adsorption properties [34]. For example, Liu et al. demonstrated that modified biochar enhanced removal efficiencies for organic contaminants compared to unmodified biochar [35].

3.2.1 Specific techniques in chemical modification

Nano-Metal Oxide/Hydroxide Composites, this is produced by pre-treating biomass with metal salts before pyrolysis, enhancing surface reactivity for better adsorption of heavy metals [36]. A study by Guo et al. reported that metal ion incorporation during pyrolysis significantly improved the biochar's adsorption capabilities [26]. Functional nanoparticles coating before or after pyrolysis, biochar can be coated with nanoparticles (such as graphene or chitosan) to enhance its adsorption capacity for a variety of contaminants [37]. Research by Wang et al. discovered that graphene-coated biochar showed improved methylene blue adsorption, proving the efficacy of this modification method [38]. Clay-coating techniques, the adsorption capacity of biochar is increased by adding clay minerals such as bentonite or kaolinite, especially for organic and inorganic contaminants. Clay-biochar composites can recover phosphates from wastewater, significantly enhancing biochar's effectiveness in contaminant removal [39]. Liang et al. demonstrated that magnesium-impregnated clay-biochar composites achieved high phosphate adsorption rates from wastewater [40]. All of these modification techniques are presented in Fig. 3.

Biochar offers significant advantages in environmental remediation, soil enhancement, and carbon sequestration; however, its effectiveness is often constrained by several inherent challenges. One primary limitation is the inconsistent performance attributable to the variability in feedstock types and production methods [41]. This inconsistency can lead to unpredictable adsorption capacities and reliability issues in different applications. There is a lack of comprehensive understanding regarding the interactions between biochar, various soil types, and a range of contaminants, which can result in uncertain outcomes in field applications [42]. Another concern is the potential for contaminant release under certain environmental conditions, biochar may discharge previously

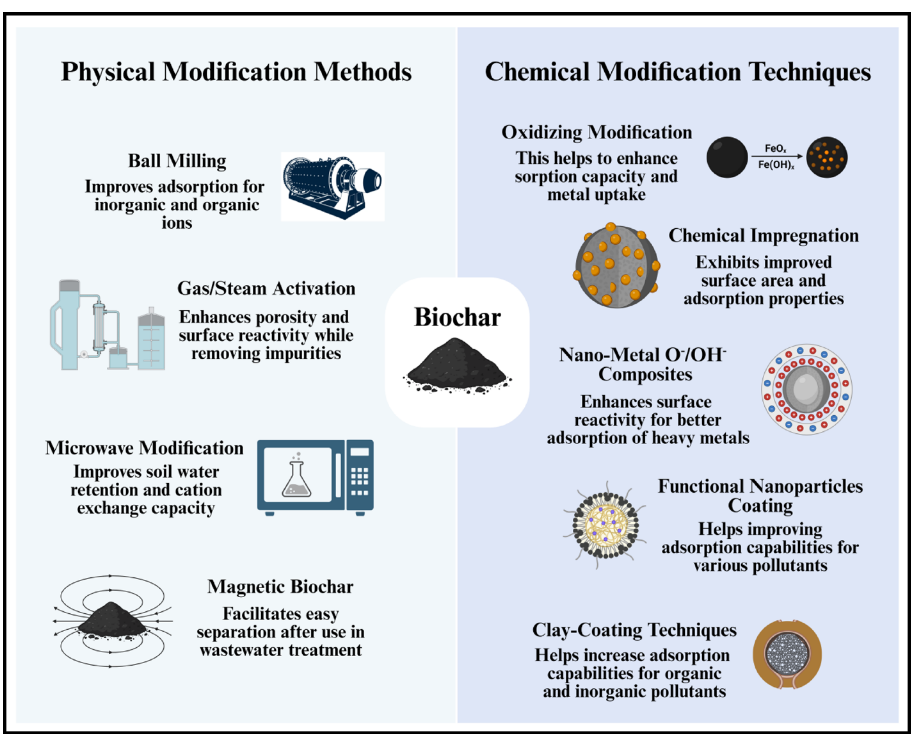


Fig. 3 An illustration discussing all the biochar modification techniques (physical and chemical)

adsorbed pollutants, creating additional environmental risks [43]. Also, producing high-quality biochar can be both costly and energy-intensive, which limits its scalability, particularly in resource-limited regions [44]. Improper management of biochar can also lead to nutrient imbalances, negatively affecting plant growth and soil health, and regulatory hurdles and public perceptions surrounding biochar production processes and its efficacy can further impede its broader acceptance and adoption [45].

4 Introduction to PCB

PCB is a major breakthrough in the use of biochar, utilising the special qualities of polymers and biochar to improve its effectiveness in a range of environmental applications [36]. The fundamental component of biochar is a high-surface-area porous carbon matrix that offers superior adsorption properties. But conventional biochar frequently has drawbacks, such as inconsistent adsorption effectiveness, poor nutrient retention, and leaching vulnerability. These drawbacks can be fixed by using a polymer coating, which will increase the biochar's usefulness and possible applications.

4.1 Benefits of PCB

The introduction of polymer coatings confers several advantages over traditional biochar which includes enhanced adsorption capacity. Biochar's surface chemistry can be altered by polymer coatings, which will increase its affinity for particular pollutants. For example, polymers with functional groups like amines or carboxylic acids can improve the adsorption of organic contaminants and heavy metals, increasing the effectiveness of PCB in processes like soil remediation and wastewater treatment [46]. It improved nutrient retention, PCB offers a more effective fertilisation method by retaining and releasing nutrients gradually due to the controlled release characteristics of polymers. In precision agriculture, where nutrient management is essential for crop output and environmental sustainability, this is especially advantageous [47]. Reduced leaching method acting as a barrier, the polymer layer can reduce the number of contaminants and nutrients that drain from the biochar. This characteristic lowers the possibility of groundwater pollution and lengthens the life of biochar in soil applications [48]. The protective polymer covering greatly increases PCB's longevity under challenging environmental conditions. This increased stability allows for longer-term application in soil and water remediation without the need for frequent reapplication [49]. It shows the versatility in applications, because polymer characteristics can be tuned, PCBs can be made specifically for uses including carbon sequestration, soil improvement, and pollutant removal. Various polymers can be chosen according to how well they work with the intended pollutants or soil types [50].

These benefits can be seen in the visual diagram as Fig. 4 given below.

5 Mechanism of polymer coating on biochar

The polymer coating of biochar significantly enhances its functional properties for environmental remediation and agricultural applications. By selecting suitable polymers and employing effective coating techniques, improvements in stability, adsorption capacity, and safety can be achieved [51]. Understanding the mechanisms and chemistry of polymer coating not only optimizes biochar's properties but also aids in developing effective

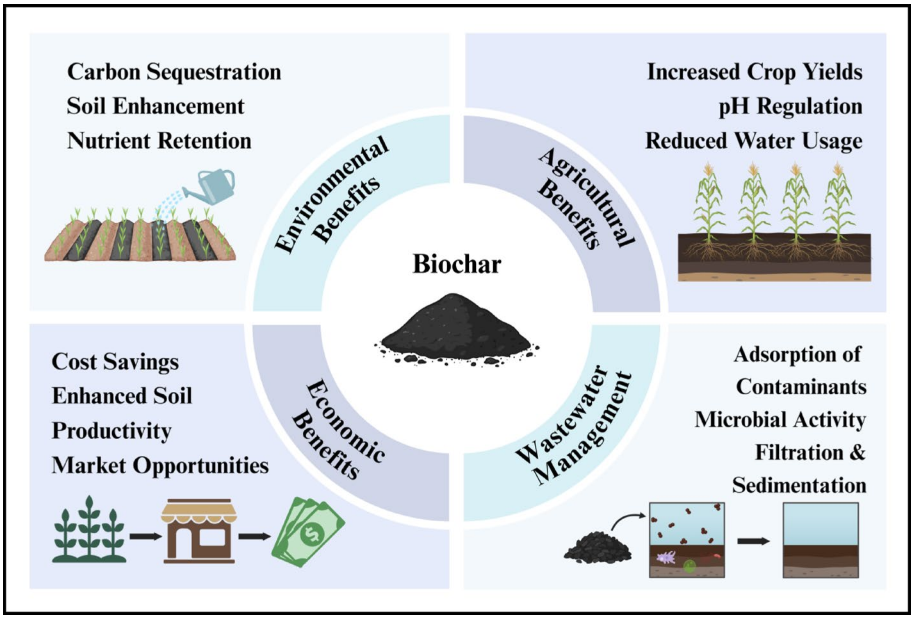


Fig. 4 An illustration showing applications and benefits of using biochar for soil enhancement

solutions for environmental challenges. This section explores the detailed mechanisms of polymer coating and its impact on the characteristics of biochar.

5.1 Mechanisms of polymer coating

The coating process typically involves the application of synthetic or natural polymers onto the surface of biochar. Common methods for polymer application include physical adsorption, involves hydrogen bonds and van der Waals forces to physically adsorb polymers onto the surface of the biochar. Although this method is approximately easy, it may result in a weak bond between the polymer and biochar, which could cause it to separate in some situations [52]. Using covalent bonding method, the surface of the biochar is chemically altered to provide reactive spots that can form covalent bonds with polymer chains. Covalent bonding improves the polymer coating's stability, longevity, and leaching resistance [53]. Another technique that is Layer-by-Layer (LbL) assembly, is the sophisticated technique allows for exact control over the thickness and makeup of the polymer layer by alternating the deposition of oppositely charged polyelectrolytes onto the surface of the biochar. LbL assembly can improve the coating's consistency and repeatability, which will boost its performance.

5.1.1 Polymer coating process

The polymer coating of biochar is typically achieved through several well-defined methodologies which include preparation of biochar, produced via pyrolysis, which involves thermochemical decomposition of biomass in an oxygen-limited environment. This process results in a highly porous, carbon-rich material with a complex surface structure characterized by various functional groups such as hydroxyl (-OH), carbonyl (C = O), and carboxyl (-COOH) groups [54, 55]. Polymer selection is one of very critical process in which the functional properties of the coated biochar are largely determined by the polymer selection. The selection of polymers is based on their chemical characteristics, biodegradability, environmental stability, and compatibility with biochar. Polyethylene, polystyrene, polyacrylic acid, and biodegradable substitutes such as chitosan and starch-based polymers are examples of frequently used polymers [56]. Coating techniques are employed for applying polymer coatings to biochar, that further includes solution coating. In this method, the polymer is dissolved in a solvent and mixed with biochar to allow for adhesion. The solvent then evaporates, leaving a thin polymer layer on the biochar surface [57]. Advanced techniques like electrospinning involves using an electric field to produce fine polymer fibers that coat the biochar. This allows for precise control over the thickness and morphology of the coating [58]. The process of in-situ polymerization occurs directly on the biochar surface, enabling strong adhesion through covalent bonding. This approach can enhance the coating's durability and stability under environmental conditions [53].

5.1.2 Underlying chemistry of polymer coating

The chemistry of polymer coating on biochar involves several critical interactions such as physical adsorption and initial interaction between the polymer. Biochar often involves physical adsorption mechanisms such as van der Waals forces, hydrogen bonding, and electrostatic attractions. These interactions depend on the surface chemistry of the biochar and the functional groups present in the polymer [51]. In covalent bonding, more robust attachment can occur through covalent bonding between the functional groups of the polymer and the reactive sites on the biochar surface. For instance, the carboxyl groups of biochar can react with amino groups in the polymer, forming stable amide linkages. This covalent interaction significantly enhances the coating's durability and reduces the risk of leaching in environmental applications [59]. Through hydrophobic and hydrophilic interactions, the polymer's chemical composition can modify the hydrophilicity or hydrophobicity of the coated biochar. Hydrophilic polymers increase the wettability of biochar, improving its dispersal in aqueous environments, while hydrophobic coatings may enhance the adsorption of non-polar organic contaminants [60]. To verify these interactions using techniques such as X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR), some case studies have been conducted in recent years. In one such study, He et al. had carried out an XPS analysis of the multi-layer enzyme coating on magnetic biochar nanoparticles to check the detection of bisphenol A in water, where it was confirmed the presence of C–O, C = O, and amide linkages between the enzyme-polymer layers and the biochar surface, validating the effective covalent immobilization and improved interfacial bonding stability, showing the linkage pattern for the stabilization of enzyme-polymer layer and biochar nanoparticle [61]. In another study, FTIR analysis demonstrated by Thinh et al. gave the findings that the produced composites preserved essential functional groups of the original biochar, exhibiting notable bands at 3440 cm^{-1} (O–H/N–H stretching), 1620 cm^{-1} (C = C stretching), and 2920–2851 cm^{-1} (C–H stretching). The distinct reduction of peaks at 1255 cm^{-1} and 1048 cm^{-1} (C–O and C–O–C bonds) suggested a structural change and the effective integration of graphitic carbon nanosheets and Fe_2O_3 onto the biochar surface. The spectral alterations demonstrated the chemical interaction among polyvinylpyrrolidone (PVP), iron oxide, and biochar, verifying that Fe–O bonds and left-over hydroxyl and amine groups play a role in hydrogen bonding and ligand exchange in adsorption processes [62].

6 Impact on biochar properties

The polymer coating substantially alters several key properties of biochar which enhances stability and durability, as the polymer layer protects biochar from degradation caused by microbial activity and environmental factors, such as moisture and temperature fluctuations [63]. This protection is particularly crucial for applications requiring long-term performance, such as in wastewater treatment and soil amendments [64]. Improved adsorption capacity, this modification of biochar's surface chemistry through polymer coatings allows for the introduction of specific functional groups, which can enhance the adsorption capabilities of biochar. For example, polymer coatings containing functional groups such as sulfonic (-SO_3H) or phosphonic (-PO_3H_2) acids can significantly increase the biochar's ability to adsorb heavy metals and organic pollutants [65]. Reduction of dust formation, conventional biochar can release fine particulate dust during handling, posing safety risks. The application of polymer coatings effectively reduces dust formation, enhancing the material's safety during transport and application, particularly in large-scale industrial scenarios [66]. Controlled release of substances, PCBs can be engineered for controlled release, which allows for the gradual release of adsorbed nutrients or contaminants. This feature is particularly advantageous in agricultural applications, where slow nutrient release can improve plant uptake and reduce leaching losses [67]. Environmental compatibility, use of biodegradable polymers can enhance the environmental sustainability of biochar applications. Biodegradable coatings can degrade over time, minimizing long-term environmental impacts and aligning with sustainable agricultural practices [68].

7 Comparative advancements and potentials of traditional biochar vs. PCB

Addressing the challenges regarding cost, utility and contamination caused by traditional biochar use in environmental settings is crucial to maximize the potential of biochar across various applications, and in response to these limitations, PCB has emerged as a promising alternative. To ensure stability of BC by PCB, application of polymer coatings helps in alleviation of biochar degradation and loss in aqueous solutions. This is critical for ensuring the long-term effectiveness of biochar in wastewater treatment and for soil amendment [69]. Increased adsorption capacity, polymer coatings enhance the surface chemistry of biochar, which allows for the controlled introduction of specific functional groups and improves the adsorption of targeted contaminants like heavy metals, pharmaceuticals, and organic dyes [70]. Dust reduction by PCB, in this process fine particulate dust generated from traditional can pose safety and health concerns. By this process PCBs can be made safer and easier to handle in large-scale industrial applications [71]. Adsorption and controlled release, certain PCBs can facilitate the gradual release of adsorbed nutrients and substances to enhance the utility of biochar in agricultural applications and controlled remediation efforts [19].

The exploration of biochar as an environmental solution has been pioneered by several researchers; Johannes Lehmann (Cornell University), often considered one of the most influential scholars in the biochar domain, whose seminal paper on biochar's role in sustainable agriculture and climate change mitigation titled, "Biochar for Environmental Management: Science and Technology" (2009), set the foundation for modern biochar research [2]. Lehmann's work illustrates biochar's potential in carbon sequestration, soil enhancement, and pollutant removal. A study conducted by Kumar et al. provided a systematic review for the modified biochars that enhance and improve contaminant sorption and their eco-friendly removal [72]. Bartoli et al. works explored the synergy between biochar and polymers, which highlighted how polymer coatings enhance the surface functionalities, pore structure, and chemical stability of biochar [1]. The comparison of properties related to Biochar and PCB are summarized in Table 1.

7.1 Issues and constraints of PCBs

Although polymer-coated biochars (PCBs) provide enhanced adsorption capacity, stability, and reusability, numerous challenges and limitations exist that could impact their environmental and economic feasibility. A significant issue is the possible leaching of polymers or leftover monomers due to varying pH, temperature, or microbial conditions, which could lead to the introduction of secondary contaminants into the environment [73]. Synthetic polymer coatings also can demonstrate inadequate biodegradability, resulting in prolonged accumulation and secondary microplastic generation if not appropriately handled [74]. From a techno-economic viewpoint, the processes involved in producing and altering PCBs, especially polymer synthesis, solvent application, and coating methods, can elevate production expenses and energy requirements, somewhat diminishing the sustainability advantages of biochar [75]. These compromises emphasize the necessity for additional investigation into biopolymer coatings and eco-friendly synthesis methods to reduce environmental hazards while maintaining the functional stability of PCBs. Although PCBs show significant enhancements in resilience and functionality, their life-cycle effects and disposal management require thorough assessment for sustainable use [76].

7.2 Impact of PCBs on the Sustainable Development Goals (SDGs)

Research and development of biochar have been closely linked to the United Nations Sustainable Development Goals (SDGs), and polymer-coated biochars (PCBs) further enhance these contributions. According to review works by Meftah et al., sustainable approaches like the use of biochar contributes directly to SDG 6 (Clean Water and Sanitation) by effectively eliminating heavy metals, dyes, and emerging pollutants, thereby guaranteeing safer water sources [77]. It supports SDG 3 (Good Health and Well-being) by minimizing human contact with harmful substances, and it advances SDG 12 (Responsible Consumption and Production) by transforming agricultural by-products and organic waste into valuable functional materials [77, 78]. Biochars with polymer

Table 1 Comparison of Biochar and Polymer-Coated Biochar

Property	Biochar	Polymer-Coated Biochar	References
Adsorption Capacity	High, but variable depending on feedstock and method	Superior, tailored functional groups enhance specificity up to 98%	[70]
Stability	Prone to degradation in some environments	Enhanced stability, resistant to environmental stressors	[69]
Surface Area	Large, but often reduced over time	Increased due to polymer modification	[46]
Ease of Use	Can generate dust during application	Reduced dust, more manageable for large-scale use	[71]
Cost and Complexity	Lower cost, simple production methods	Higher cost due to added steps, but more efficient long-term use	[44]
Potential Applications	Soil amendment, carbon sequestration, remediation	More specialized applications, such as high-efficiency wastewater treatment, advanced pollutant capture	[68]

coatings preserve these ecological and societal advantages while providing improved durability, potential for regeneration, and mechanical strength, which in turn decreases the need for replacements and waste production [79]. PCBs show adsorption efficiencies similar to activated carbon and exceed those of both raw and chemically altered natural adsorbents, providing enhanced economic, ecological, and sustainability outcomes [80]. Overall, incorporating polymeric features into biochar structures enhances the compatibility of these composites with SDGs 3, 6, and 12, fostering efficient water treatment methods that uphold the ideals of circular economy and sustainable innovation [78].

8 Key theories and concepts in pcb technology

The application of polymer coatings to biochar is rooted in several key theories and concepts that guide its development and optimization [81]. These theories emphasize how polymer coatings can enhance biochar's functionality and address specific environmental and industrial needs. These theories and concepts are supported by recent studies that highlight the advancements in PCB technology and its potential applications in various environmental and industrial contexts.

8.1 Surface functionalization theory

According to this notion, biochar's chemical and physical characteristics can be considerably changed by applying polymer coatings to change the surface functional groups. The interaction between biochar and target pollutants can be improved by adding polymers with particular functional groups (such as carboxyl or hydroxyl), increasing the adsorption capacity and reactivity of biochar [82]. For instance, recent studies have shown that biochar coated with polyacrylic acid (PAA) exhibits increased affinity for heavy metals like lead and cadmium due to the presence of carboxyl groups [83]. Similarly, biochar functionalized with polydopamine (PDA) has demonstrated enhanced adsorption of organic pollutants, such as dyes and pharmaceuticals, owing to its increased surface reactivity and affinity [84]. This hypothesis emphasises how polymer coatings can be used to customise the characteristics of biochar for particular remediation activities.

8.2 Controlled release mechanism

In applications like soil remediation, where a gradual and controlled release of nutrients or pollutants can be advantageous, polymer coatings atop biochar can control the release of adsorbed materials. By acting as a barrier, the polymer layer controls how substances diffuse from the biochar into the surrounding environment. According to recent studies, biochar coated with polymers such as chitosan or alginate can provide regulated fertiliser release, improving soil nutrient availability over time [85]. This controlled release characteristic maximises the effectiveness of biochar in agricultural applications and reduces nutrient loss.

8.3 Encapsulation and barrier properties

The idea behind encapsulating biochar particles in a polymer matrix is to form a physical barrier that shields the biochar from deterioration in the environment. This barrier increases the stability and duration of biochar, increasing its efficacy for long-term uses including water treatment and carbon sequestration [86]. For example, biochar encapsulated in a polyurethane matrix, has demonstrated enhanced stability and tolerance to external conditions, increasing its efficacy in water purification procedures. The encapsulation also aids in preserving the structural integrity of biochar, guaranteeing its continued efficacy over time [64].

8.4 Compatibility and dispersibility enhancement

Biochar's compatibility and dispersibility in a variety of matrices, including soils and aquatic conditions, can be enhanced by polymer coatings. Depending on the desired use, polymers can increase the hydrophilicity or hydrophobicity of biochar by altering the surface chemistry [87]. Recent advancements have shown that biochar coated with hydrophilic polymers like polyethylene glycol (PEG) demonstrates better dispersion in aqueous systems, facilitating its use in water treatment applications [88]. In the same way, hydrophobic coatings such as those based on fluoropolymers enhance biochar's compatibility with organic solvents, making it suitable for applications involving non-aqueous environments [89].

8.5 Environmental safety and risk mitigation

The reduction of environmental hazards connected to conventional biochar applications is one of the main ideas of PCB. By covering biochar with polymers, it is possible to stop potentially hazardous materials like polycyclic aromatic hydrocarbons (PAHs) and heavy metals from leaking into the environment. According to recent research, polymer coatings can successfully lessen the harmful chemicals that biochar leaches, increasing its safety for environmental remediation [90]. This idea ensures that the advantages of biochar are fulfilled without creating additional hazards, which is in line with the larger objective of creating safer, more sustainable materials for environmental applications.

The different types of polymer-based fertilizers and their use in combination with biochar is described in Fig. 5.

9 Properties and applications of biochar-polymer composites

9.1 Polyolefins-based composites

Polypropylene (PP)-based composites biochar as an additive in wood-plastic composites markedly improves their mechanical properties, fire resistance, and crystallization behaviour. Ongoing investigation into the optimization of production and processing conditions, along with the examination of interactions between biochar and other additives, will be essential for enhancing the performance and applicability of these sustainable materials. Wood-plastic composites (WPCs) have attracted significant interest as sustainable substitutes for conventional materials owing to their advantageous characteristics, while encountering issues such as thickness swelling, thermal instability, and inadequate interfacial bonding [91]. In recent years, biochar (BC) produced from the pyrolysis of organic waste has surfaced as a possible solution to address these challenges. Innovative research by Das et al. emphasized the advantages of integrating biochar derived from landfill pine wood into wood-plastic composites (WPCs), illustrating that this incorporation markedly enhanced interfacial adhesion between wood and polypropylene (PP). The study reported that composites with 24 wt% biochar exhibited comparable tensile strength and modulus to traditional wood/PP composites while showing enhanced flexural properties [92]. However, a reduction in material ductility

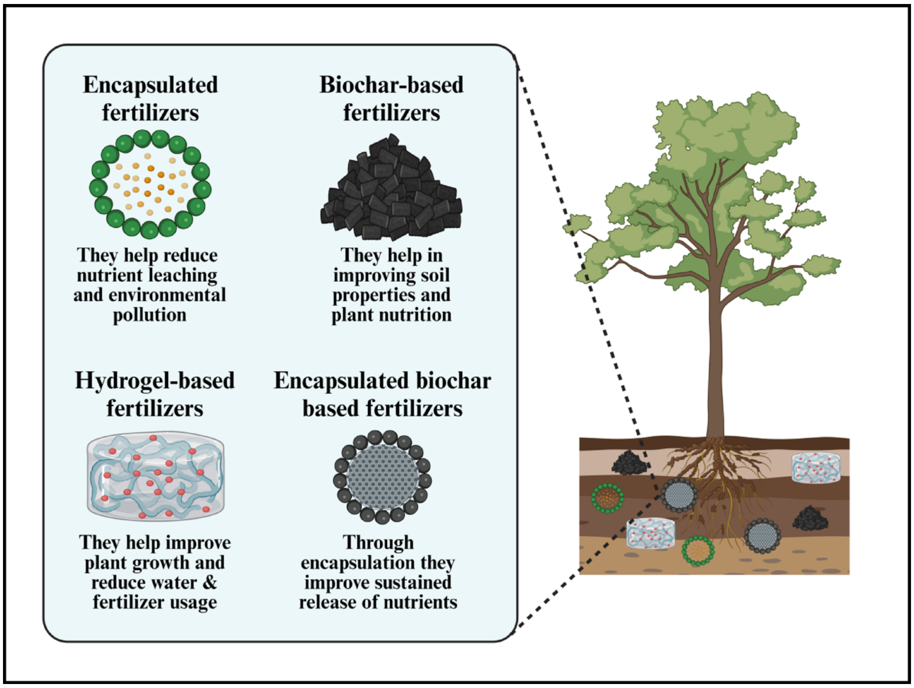


Fig. 5 Diagram showing use of polymer- and biochar-based fertilizers for efficient plant growth and nutrition

was observed at biochar loadings exceeding 15 wt%. To further investigate the influence of different waste feedstocks on the properties of biochar and its effects on WPCs, Das et al. analyzed six types of biochar from varied sources. Their findings revealed that biochar incorporation consistently enhanced the tensile and flexural moduli and strength of PP-based composites compared to those without biochar. Notably, higher carbon content and increased surface area in biochar correlated positively with improved mechanical properties. Composites containing biochar with elevated $CaCO_3$ levels also exhibited reduced heat release rates, suggesting enhanced fire retardancy [92].

Subsequent studies focused on optimizing biochar production parameters to enhance composite performance. For instance, biochar produced from landfill pine wood waste through pyrolysis at 500 °C, followed by activation at 900 °C, yielded composites with superior fire performance. This was attributed to the formation of a compact carbonaceous layer, which impeded oxygen transfer to the PP matrix, thereby reducing heat and smoke production rates [7, 92]. Higher biochar loadings facilitated an extended network of mechanical interlocking between the polymer matrix and filler, resulting in increased tensile and flexural moduli.

Moreover, research has revealed that biochar derived from pyrolysis processes serves as a versatile additive for enhancing the mechanical and fire-retardant properties of PP-based composites. Physical bonding resulting from polymer chain infiltration into biochar pores has been identified as a significant mechanism underlying the mechanical enhancements observed in PP composites. This infiltration reduces the need for coupling agents to improve interfacial adhesion between biochar particles and the polymer matrix [93]. The interplay between biochar and conventional flame retardants has also been examined, with findings indicating that while biochar enhances fire-retardant performance, its coexistence with flame retardants can negatively impact mechanical performance due to the trapping of flame-retardant particles within biochar pores, which hampers polymer chain flow and diminishes mechanical interlocking efficiency [94]. Das et al. further explored the potential of predicting the mechanical performance of PP-based composites containing biochar through nanoindentation studies, revealing that polymer chain infiltration into biochar pores significantly contributes to higher hardness values compared to unmodified biochar particles [95]. The effects of biochar pyrolysis conditions on composite properties have also been scrutinized, with varying feedstocks and pyrolysis temperatures leading to distinct mechanical performances. Biochar pyrolyzed at 700 °C achieved the best balance between stiffness and toughness due to its low polarity, reduced ash content, and optimized particle size compared to biochar processed at higher temperatures [96]. However, Ayadi et al. noted the limitations of high-temperature pyrolysis, which can decrease functional groups and limit strong interfacial interactions, despite enhancing dimensional stability and hydrophobicity [96].

Rheological characterization has provided insights into the distribution of fillers and polymer-filler interactions within the matrix. Poulose et al. studied PP composites with biochar derived from date palm waste, observing an extended filler-filler network formation, which restricted PP molecule movement. However, weak interactions between PP and biochar were indicated by minimal increases in storage modulus values compared to the unfilled matrix [97].

The incorporation of biochar within a PP matrix has been shown to significantly influence the crystallization behavior of the resulting composites, with biochar particles acting as nucleating agents that lead to higher degrees of crystallinity relative to unfilled PP matrices. Elnour et al. noted a progressive increase in crystallization temperature with increased biochar loading, which was attributed to the greater availability of nucleation sites [98]. They also observed a correlation between crystallization temperature and the pyrolysis temperature of biochar.

Further investigations by Alghyamah et al. into the crystallization behavior of PP-biochar composites, varying biochar loadings and pyrolysis temperatures, demonstrated that biochar enhanced overall crystallization processes, leading to increased nucleation and crystallization rates. The Avrami model analysis revealed distinct characteristics of biochar dependent on pyrolysis temperature: biochar produced at higher temperatures exhibited a porous structure and larger surface area, facilitating the growth of PP crystals into two-dimensional disk-like shapes, while biochar from lower temperatures promoted the formation of rod-like structures [99]. Evaluation of spherulitic growth at a crystallization temperature of 120 °C revealed a significantly higher number of smaller-sized PP spherulites in biochar-containing composites compared to unfilled PP, attributed to fast heterogeneous nucleation facilitated by biochar particles, which resulted in smaller-sized spherulites with imperfect morphologies [100]. Markos et al. seeks industrial applicability, where biochar was added to PP matrix materials at loadings of 2.0, 4.0, 6.0, 8.0, and 10.0 wt % to form reinforced composites. It was made from olive tree prunings. They have done total of fourteen tests assessed the thermal, structural, mechanical, morphological, and electrical aspects of additively created specimens. Adding 4.0 wt % biochar to polypropylene (PP) increased its tensile strength by 28.4% and modulus of elasticity by 24.3%. Tests showed that 6 wt % loading was best. The thermal stability of PP/biochar composites was much higher than pure PP. The PP/biochar composite's dc-conductivity increased by nearly 9 orders of magnitude at 8.0 wt % filler loading, demonstrating a percolation threshold beyond which the polymer composite becomes conductive. Biochar inclusion improved all evaluated parameters and showed its appropriateness as an eco-friendly additive manufacturing material [101]. Rayland et al. did their investigation of far infrared emission and UV protection properties of polypropylene composites embedded with candlenut-derived biochar for health textiles [102]. Venkata et al. in their study compare the surface roughness of pure polypropylene versus polypropylene blended with 10 wt% biochar after drilling. Experiments divide into Group 1 (pure polypropylene) and Group 2 (Biochar-filled polypropylene) were tested. Based on G-power calculations, 20 samples per group were selected. Samples were made using twin screw extrusion and injection molding. The surface roughness of drilled holes was measured and compared. The composite with biochar had a surface roughness of 2.05 µm, while pure polypropylene had 0.98 µm. Therefore, biochar increased polypropylene surface roughness by 27% [103].

Biochar plastic composites are being researched to reduce plastic pollution. Yunpeng et al. in their study creates biochar/polypropylene composites (BPCs) using waste polypropylene (PP) and reed charcoal (RC), using γ-aminopropyl triethoxysilane (KH550) as an interface modifier to improve compatibility between the two materials. Due to the coupling effect of KH550, K-RC/PP composites have higher tensile and bending strengths than RC/PP. With 2.4 wt% KH550, K-RC/PP has 22.77 MPa tensile and 49.6 MPa flexural strengths. The interfacial modification also improves composites' thermal stability and hydrophobicity, reducing fire risks and increasing durability. This work presents a method for making biochar/plastic composites with improved mechanical characteristics and fire safety [104]. Yang et al. investigated a mask recycling technology for high-value secondary applications. Disassembled polypropylene waste masks were merged with Enteromorpha clathrate biochar (AC) to generate mask-biochar packages (M-AC) for methylene blue (MB) wastewater treatment. Mask-biochar packages (M-AC) removed MB solution 18.50% faster than AC alone. Mask-biochar packages (M-AC) were pyrolyzed at 550 °C to produce hydrocarbon-rich bio-oil and composite biochar. Compared to MAC alone, M-MAC increased MB removal by 10.16%. The composite biochar has an adsorption capacity of 820.925 $mg{\cdot}g^{-1}$ without activator or acid washing. Hydrocarbon-rich bio-oil has 55.31% hydrocarbon content. This study produced strong experimental evidence that biomass and masks work synergistically in waste treatment and biochar formation [105].

9.2 Polyethylene (PE)-based composites

Ultra-high molecular weight polyethylene (UHMWPE) has emerged as a viable matrix for the fabrication of conductive polymer composites, with biochar investigated as a sustainable and economical filler to improve electrical and mechanical properties. Composites based on UHMWPE are preferred due to their segregated microstructure, which significantly decreases interfacial electrical resistance between the filler and polymer matrix, hence enhancing electrical conductivity [106]. Conductive polymer-based materials provide a broad spectrum of electrical conductivity, frequently favored over metallic conductors due to their reduced expense. Although carbon-based fillers such as graphene and carbon nanotubes have historically been utilized in UHMWPE-based composites, their cost and lack of sustainability have prompted a growing interest in biochar as an alternative. Composite systems based on polyethylene containing various types of biochar have been developed to assess their impact on electrical and mechanical properties. Incorporating biochar into UHMWPE results in composite materials with high mechanical properties and electrical conductivity [106]. Li et al. prepared highly filled composites (up to 80 wt%) using commercial biochar particles derived from Bamboo charcoal via melt extrusion. Given UHMWPE's high viscosity, a blend of UHMWPE and linear low-density polyethylene (LLDPE) was utilized as the matrix [107]. Electrical property evaluation revealed well-established biochar conductive pathways at filler loadings beyond 60 wt%, with electrical conductivity increasing progressively with biochar loading. The composite with 80 wt% biochar exhibited exceptional conductivity (107.6 S/m), attributed to electron transfer between biochar particles through direct physical contact or tunneling phenomenon.

Moreover, high BC loadings effectively provided ample free electrons for electromagnetic radiation attenuation, with the 80 wt% BC composites demonstrating remarkable electromagnetic interference (EMI) shielding effectiveness. This underscores BC's potential as a filler for conductive polymer-based composites in diverse engineering and electrical applications [108]. Biochar (BC) has emerged as a multifaceted filler for improving the characteristics of polyethylene-based composites, particularly Ultra-High Molecular Weight Polyethylene (UHMWPE) and High-Density Polyethylene (HDPE), in many applications. Li et al. exhibited the fabrication of flexible UHMWPE/BC composites with adjustable conductivity and favorable mechanical properties. By utilizing BC particles derived from pine, apple, and bamboo charcoal via pyrolysis at different temperatures, they achieved uniform dispersion within UHMWPE matrices, establishing strong polymer/filler interfacial interactions [109]. Increasing pyrolysis temperature transitioned BC from insulating to conductive, leading to composites with high electrical conductivity, particularly at 70 wt% BC loading. Another study by Li et al. highlighted the attainment of low electrical percolation thresholds in UHMWPE-based composites with segregated morphology. Utilizing a combination of high-speed mechanical mixing and hot compaction, BC particles were distributed only at the interface between polymer granules, forming a segregated conductive network. This method yielded composites with enhanced thermal stability, tensile strength, and reduced electrical percolation thresholds, making them suitable for industrial applications [109]. For orthopedic applications, UHMWPE-BC composites containing BC from commercial bamboo charcoal particles pyrolyzed at different temperatures were proposed. Composites exhibited improved hardness and tensile modulus, with BC pyrolyzed at higher temperatures enhancing mechanical properties, while lower temperatures improved wettability and friction coefficient, highlighting their potential for orthopedic applications. In HDPE-based composites, BC derived from agricultural wastes was utilized as a reinforcing filler. Zhang et al. demonstrated enhanced tensile properties, creep resistance, and flame retardancy with increasing BC loadings [110]. Pyrolysis conditions of BC particles significantly influenced mechanical properties, with higher treatment temperatures leading to improved compatibility and mechanical properties. Rheological analyses by Arrigo et al. revealed slowed relaxation dynamics of polymer chains in HDPE-BC composites, indicative of strong polymer/BC interactions [111]. Carbon-based adsorbent materials made from sewage sludge and plastic debris were tested by Ashraf et al. to know ability to reduce water ciprofloxacin concentrations. Each formulation has 20% or 50% polyethylene (PE) or polyethylene terephthalate. Specific surface area increased to 194.7 m2/g in the PET—50% composite. It was found that ciprofloxacin (CPX) adsorption was efficient at pH 5 at 113.97 mg/g(qms). Pollutant elimination after 12 h was due to generated π–π interactions, electrostatic, and hydrophobic surface contacts, highlighting the importance of chemosorption. Alkaline pH decreased adsorption capacity significantly. SS-PET showed a considerable increase in active sites, indicating a robust interaction with ionized CPX molecules and increased sorption efficiency through the unique material combination. Four continuous cycles of regenerative experiments showed considerable adsorption. For successful CPX-contaminated wastewater management and plastic pollution reduction, this study provides critical knowledge and practical insights [112]. Arrigo et al. examined the structure-property interactions in polyethylene-based composites infused with BC sourced from discarded coffee grounds. This research entails the incorporation of BC derived from waste coffee grounds into high-density polyethylene (PE) through melt mixing. The data indicate that the integration of BC particles into PE-based composites improved thermo-oxidative stability, significantly elevating the breakdown temperatures of PE [111].

9.3 Polyamide-based composites

Biochar (BC) has emerged as a promising reinforcing filler for polyamide (PA) composites, primarily PA6 and PA6,10, with various studies exploring its impact on mechanical and thermo-mechanical properties. Ogunsona et al. investigated the effect of BC pyrolysis conditions on PA6-based composites using pyrolyzed miscanthus fibers. Composites with low-temperature pyrolyzed BC exhibited increased tensile and flexural strength compared to those with high-temperature pyrolyzed BC, attributed to better interfacial adhesion between BC and PA6 [113]. Similarly, Watt et al. analyzed the influence of corn cob BC pyrolyzed at different temperatures on commercial PA 4,10. SEM analyses revealed particle encapsulation at the polymer interface with low-temperature pyrolyzed BC, resulting in improved rheological properties and mechanical performance [114]. Further research by Ogunsona et al. focused on the effect of BC particle size on PA6,10 composites, demonstrating that smaller BC particles led to increased heat deflection temperature (HDT) and impact strength [115]. Conversely, larger BC particles reduced impact strength due to decreased ductility and hindered polymer chain dynamics. Studies also explored the impact of high BC concentrations on PA6 composites. Zhang et al. demonstrated acceptable properties in PA6-BC composites with BC loadings of 30 to 40 wt%, including strength, toughness, and processing fluidity. Accelerated thermo-oxidative aging studies revealed similar mechanical properties between BC-PA6 and talc-filled PA6 composites, with BC-filled composites being less dense. However, BC-filled composites exhibited more significant degradation after aging, attributed to the physical structure of BC [116].

9.4 Polyester-based composites

Biochar (BC) has gained attention as a reinforcing filler for various polyester matrices, including polylactic acid (PLA), poly(butylene terephthalate) (PBT), poly(trimethylene terephthalate) (PTT), and poly(ethylene terephthalate) (PET). These composites offer improvements in mechanical and thermo-mechanical properties, extending their potential applications across different industries [117]. Polylactic Acid (PLA), PLA–BC composites have been extensively studied to enhance PLA's poor crystallization property, thermal stability, toughness, and brittleness. While the incorporation of BC generally increases the elastic modulus, it often leads to a decrease in tensile strength, elongation at break, and impact strength due to stress transfer inefficiencies and uneven dispersion of BC particles [118]. However, optimization of BC loading and surface modifications can mitigate these drawbacks, resulting in enhanced mechanical properties. Chemical modifications, such as grafting maleic anhydride onto PLA and thermal esterification of BC particles, have shown promising results in improving interfacial bonding and composite properties. Moreover, BC incorporation in PLA affects thermal properties by reducing thermal stability and glass transition and melting temperatures while enhancing the mobility of PLA macromolecular chains, inducing a plasticization effect. In addition, BC improves abrasion resistance, wear resistance, and flammability of PLA composites, making them suitable for various applications [119]. Polyesters (PBT, PTT, PET), BC-reinforced PBT, PTT, and PET composites have also been investigated for their mechanical and thermo-mechanical properties. PBT composites containing BC showed increased tensile and flexural modulus after thermo-oxidative aging, although BC-filled composites exhibited a greater decrease in mechanical strength compared to talc- and glass fiber-filled counterparts [114]. In PTT composites, BC significantly improved heat deflection temperature (HDT) and stiffness while reducing impact strength and yield elongation. The addition of a chain extender further enhanced mechanical properties, with optimal composite formulations achieving balanced properties [120]. PET composites containing BC, recycled PET, and a chain extender demonstrated synergistic effects on stiffness, tensile strength, and impact toughness, highlighting the potential of these materials for various applications. Two biodegradable mixtures and charcoal were tested by Jurczyk et al. in composites, one being mechanical evaluation of PBAT/PLA/BC and PLA/P(3HB-co-4HB)/BC composites with 0, 10, 15, 20, and 30 wt% biochar, amd other being filler content changed composite properties in testing. PBAT/PLA and PLA/P(3HB-co-4HB) matrix composites with 30 wt% biochar had 100% higher tensile modulus and lower elongation at break than empty matrices. PBAT/PLA and PLA/(3HB-co-4HB) composites with 30 wt% biochar had 50% and 65% lower break elongation than empty matrices. The tensile strength of PLA/P(3HB-co-4HB) matrix composites decreased from 35.6 MPa for unfilled matrix to 27.1 MPa for BC30 composites as filler content increased. In the Charpy impact test, composites with more filler were brittle regardless of matrix. The impact strength of PLA/P(3HB-co-4HB) composites decreased from 4.47 kJ/m² for the matrix to 1.61 kJ/m² with 30 wt% biochar. PBAT/PLA composites with 10 wt% biochar exhibited somewhat lower impact strength than the empty matrix, and 30 wt% had 30% lower. Complex viscosity was increased by filler. All composites on both polyester matrices became less viscous with rotation [121]. Polymer composites were made from sugarcane waste biochar at 5, 10, and 15 wt% with varied treatment durations in polyester matrix by Sundarakannan et al.., where by ASTM protocol, mechanical and thermal properties of sugarcane biochar polyester (SBPE) composite was tested. They demonstrated that the composite tensile strength decreased with sugarcane weight. Morphological metrics of tensile fractured specimens showed a superior interfacial transmission zone in a 10 wt% sugarcane biochar polyester matrix composite. One-hour polyester composites with 10 wt% sugarcane biochar showed little erosion at 90° impact [122].

9.5 Other thermoplastic-based composites

Research into the use of biochar (BC) as a filler in engineering polymers has yielded diverse findings across various polymer matrices, including polycarbonates (PC), polyvinyl alcohol (PVA), starch, polycaprolactone (PCL), and polyhydroxyalkanoates (PHA). For polycarbonates (PC), limited interest has been observed in utilizing BC alone for modifying PC due to its tendency to intensify hydrolytic degradation, compromising thermo-mechanical stability. However, combining BC with recycled carbon fibers (CF) has shown promise. Andrzejewski and colleagues demonstrated that BC-CF composites improved the mechanical properties of PC significantly. The addition of acrylonitrile butadiene styrene (ABS) to the PC matrix further mitigated hydrolytic degradation, enhancing the overall performance of PC-BC-CF blends [123]. For polyvinyl alcohol (PVA), Nan et al. investigated BC-PVA composite films for electrical conductivity and mechanical properties. They found that increasing BC loading improved conductivity and piezoresistive effect in PVA sensors [124]. Bartoli et al. had also achieved high conductivity in BC-PVA composites derived from waste cotton, making them suitable for applications requiring conductivity under pressure [1]. Starch and polycaprolactone (PCL), BC has been mixed with starch mainly for biomass densification purposes. PCL-starch-BC composites, incorporating BC from waste coffee grounds, exhibited increased elastic modulus with 10 wt% BC loading, suggesting potential applications in biodegradable products like coffee cup lids [125]. Polyhydroxyalkanoates (PHA) PHA, specifically poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), has been explored as a matrix for BC composites to improve mechanical properties. PHBV filled with miscanthus biochar (PHBV/MB) showed increased elastic and flexural modulus but decreased tensile and flexural strength and elongation at break with any biochar loading [126]. However, the addition of biochar enhanced dimensional stability and heat deflection temperature (HDT) of PHBV composites.

Figure 6 Graphically shows the properties and applications of biochar-polymer composites listed in the context above

Table 2 here shows summary of polymer-based applications of biochar.

9.6 BC composites: thermosetting matrices

9.6.1 Epoxy resin-based composites

Epoxy resins, widely used in industries like aeronautics and automotive sectors, often benefit from reinforcement with high-tech fillers such as carbon nanotubes (CNTs) or carbon and glass fibers [139]. Recent studies have explored the potential of using biochar (BC) as a filler in epoxy resins, aiming to achieve comparable performance to traditional fillers. Khan et al. compared the mechanical performance of epoxy composites containing CNTs and maple-derived BC. They found that BC concentrations of up to 2 wt% improved mechanical behavior, even outperforming CNTs in certain aspects [140]. Furthermore, BC at 20 wt% displayed higher electrical conductivity than 4 wt% of CNTs. Giorcelli et al. filled epoxy with coffee-derived BC, achieving a high conductivity of 36 S/m, surpassing carbon black. However, high filler loading led to decreased elongation at break and increased Young's modulus, attributed to limited matrix mobility [141]. For the effect of BC properties, Bartoli et al. investigated the influence of BC feedstock on stress-strain curves, noting variations in stiffness and elongation at break [1]. Different BC types induced varied mechanical behaviors due to differences in particle size

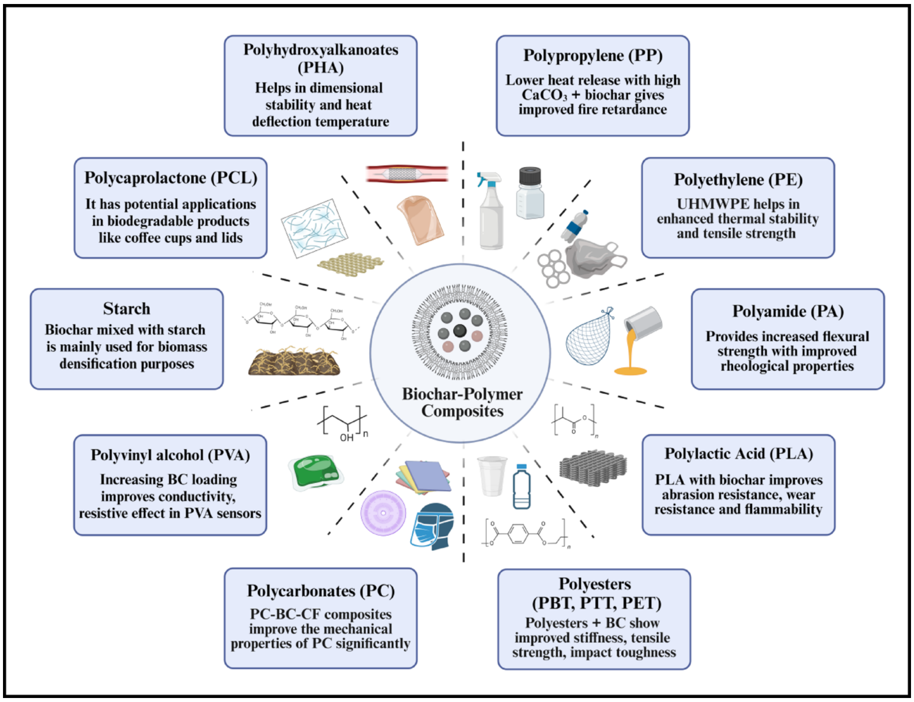


Fig. 6 Diagram illustrating types of different polymer composites and their applications when combined with biochar (BC)

Table 2 Table summarizing the polymer used and related applications of PCB

Biochars	Polymers	Applications	References
Magnetic activated biochar-zeolite composite	Polyethyleneglycol (PEG) and Polyethylenimine (PEI)	Adsorption of microplastics from sea water, tap water and wastewater effluent.	[127]
Fe_3O_4-based biochar	Surface-imprinted polymer	Salicylic acid removal from wastewater	[128]
Banana leaf sheath	Urea	Slow-Release fertilizers for crop production and soil management	[129]
Lignocellulosic Biochar	Alginate & chitosan	Remove heavy Metal Chromium VI during water treatment	[130]
Corncob biochar	Pure PDMS	Antifouling with improved long-term release in water-body aquatic systems.	[131]
Curcumin grafted biochar	Poly acrylic acid	Removal of cationic dye from industrial wastewater	[132]
Corncob	Carboxymethyl cellulose sodium	Adsorption of heavy metals and controllable release of soil fertilization for soil management in agriculture	[133]
Cardanol oil and cassava peel biochar	Quick-set Araldite epoxy resin LY556	Structural application in electrical appliances, industrial, automotive, aircraft, cold storage units, and defense applications	[134]
Alfa fibers	Methyl 2-hydroxyethyl cellulose	Slow-Release Phosphate Fertilizers in agricultural land use	[135]
Cow dung-derived	N-Halamine	Antibacterial agents for bacterial decontamination in wastewater management	[136]
Oat hull	Cellulose acetate, Ethyl cellulose and Sodium alginate, Formamide	Urea controlled-release fertilizer for crop production	[137]
Rice biochar	Polyvinyl alcohol	Slow-release fertilizer for crop production and soil management	[138]

distribution and surface roughness. Studies delved into the impact of BC particle shape, revealing differences in mechanical properties. BC spheres exhibited better dispersibility and less reduction in elongation at break compared to rods, attributed to a network formed by rods reducing macromolecular chain mobility [142]. The temperature and ramp rates during BC production significantly affected epoxy composite properties. Lower pyrolysis temperatures promoted hydrogen bond formation, enhancing particle-matrix adhesion, while higher temperatures increased aromatic domain formation, influencing stiffness and elongation [143]. For toughening agent for fibrous composites, BC showed promise for fibrous epoxy composites, where incorporating BC into glass or carbon fiber-reinforced epoxy matrices increased storage modulus, ultimate tensile stress, and strain, thereby improving interfacial properties between fibers and the polymer. Matykiewicz demonstrated increased storage modulus with BC addition to carbon fiber-based epoxy composites [144]. Zuccarello et al. reported enhanced ultimate tensile stress and strain with BC in agave fiber epoxy composites, attributing improvements to better fiber-polymer interaction [145].

9.6.2 Unsaturated polyester resin-based composites

Unsaturated polyester resins, commonly used in construction materials, have been subject to investigation regarding the incorporation of biochar (BC) as a filler, aiming to improve various mechanical and tribological properties [146]. In the case of estimating impact strength and hardness, Akaluzia et al. explored the effect of incorporating hardwood BC into unsaturated polyester resin at varying loadings (5 to 30 wt%). They observed a 15% increase in impact energy and a remarkable 100% increase in hardness [147]. Sundarakannan et al. conducted a detailed study using cashew nutshell BC as a filler for unsaturated polyester resin, at loadings from 5 to 15 wt%. They reported significant improvements in hardness, tensile, and impact strength, with increases of 37%, 21%, and 41% respectively compared to the unfilled matrix. The maximum flexural strength was achieved with a BC loading of 15 wt%, attributed to the high uniform distribution of BC particles [148]. Richard et al. conducted a tribological study on BC-based unsaturated polyester resins, aiming to correlate tribological behavior with BC particle size distribution. They found that the specific wear rate and friction coefficient decreased with increasing BC loading and decreasing particle size. The best results were achieved with 2.5 wt% of BC with an average size of 45 nm, reducing the friction coefficient and wear rate by 56% and 46% respectively [149]. This lubricant effect of BC was comparable to that of other carbonaceous fillers such as nanographite or graphene. Richard et al. achieved similar results using finely milled red mug-derived BC in unsaturated polyester resin [150].

9.6.3 BC-rubber composites

Researchers have investigated innovative uses of biochar (BC) in rubber composites, both as an independent filler and in conjunction with other materials, to improve mechanical and electrical qualities. Peterson et al. investigated the use of BC mixed with nanosilica as a filler for poly(styrene)-poly(butadiene) rubber, aiming to replace carbon black in tire formulations. BC derived from maple pyrolysis initially showed lower properties compared to commercial carbon black due to larger particle sizes (> 10 μm). However, reducing the filler size led to overall improvements in mechanical features.

The authors reported a 31% increase in elongation at break and a 24% increase in toughness without sacrificing tensile strength compared to carbon black-based composites. This improvement was attributed to the good dispersion and sub-micrometric size of BC particles [151]. Giorcelli et al. utilized BC derived from olive pyrolysis, thermally annealed at 1500 °C, as a highly conductive filler for silicone rubber composites. The BC filler exhibited fully reversible elastic deformation under pressure strain up to 40 MPa, indicating its potential for applications requiring high conductivity and mechanical flexibility [152]. These studies demonstrate the versatility of BC as a filler for rubber composites, offering opportunities to enhance mechanical properties, electrical conductivity, and elastic deformation behavior. By optimizing particle size and dispersion, BC shows promise for various applications in rubber manufacturing, including tire production and flexible electronic devices [79].

Table 3 gives a comprehensive review of the composite types and their applications with biochar.

10 Conclusion

The integration of polymer coatings with biochar (PCB) represents a notable advancement in enhancing biochar's functionality and versatility across diverse applications. In this study, it was found that PCB distinguishes itself from conventional biochar due to its tailored surface properties, which improve adsorption capacity and reactivity towards pollutants. This enhancement is crucial for environmental remediation efforts, where effective interaction with contaminants like heavy metals and organic compounds is essential. The application of polymer coatings introduces controlled release mechanisms that allow for the regulated delivery of nutrients or adsorbed substances, making PCB particularly suitable for soil remediation and sustainable agriculture. PCB could effectively release nutrients over an extended period, thus enhancing soil fertility. The encapsulation and barrier properties of the polymer layer also protect biochar from environmental degradation, thereby extending its operational lifespan in applications such as carbon sequestration and wastewater treatment. In comparison to uncoated biochar, PCB exhibits improved compatibility and dispersibility, which facilitates its integration into various matrices. This versatility ensures optimal interaction within target environments, thus enhancing performance in diverse settings.

The environmental safety and risk mitigation offered by polymer coatings are essential factors in PCB development. Studies demonstrate that PCB can inhibit the leaching of potentially hazardous compounds, corresponding with the increasing demand for safer and more sustainable materials in environmental applications. Ongoing investigation into the optimization of polymer varieties, coating techniques, and application tactics will be essential for achieving the complete potential of PCB. Recent studies underscore the distinctive advantages of PCB, positioning it as a viable alternative for tackling urgent environmental issues and promoting sustainable practices.

Table 3 Description of different composites with their biochar source/preparation and applications

Composite Type	Biochar Source/Preparation	Properties and Applications	References
Polyolefins-Based Composites			
Polypropylene (PP)-Based Composites	BC from landfill pine wood, varying pyrolysis conditions	Mechanical Properties: Enhanced tensile strength and modulus, improved flexural properties with 24 wt% BC; reduced ductility beyond 15 wt% BC.	[153]
		Fire Performance: Lower heat release rates with high $CaCO_3$ BC, improved fire retardancy.	[154]
		Crystallization: Higher crystallinity, increased crystallization temperature with BC loading.	[99]
		Interactions: Improved interfacial bonding, reduced impact from flame retardants.	[154]
Polyethylene (PE)-Based Composites	BC from bamboo charcoal, various pyrolysis temperatures	Mechanical and Electrical Properties: High mechanical properties and electrical conductivity with up to 80 wt% BC.	[155]
		Electromagnetic Interference: Enhanced EMI shielding with high BC loadings.	[155]
		Orthopedic Applications: Improved hardness, tensile modulus; variations in properties with BC pyrolysis temperature.	[156]
Polyamide (PA)-Based Composites	BC from miscanthus fibers, corn cob	Mechanical Properties: Enhanced tensile and flexural strength with low-temperature pyrolyzed BC; reduced impact strength with larger BC particles.	[157]
		Processing: Improved HDT and toughness; effects of BC concentration and size on water uptake and aging properties.	[158]
Polyester-Based Composites			
Polylactic Acid (PLA)	BC with various surface modifications	Mechanical Properties: Increased elastic modulus, decreased tensile strength and impact strength; optimization can enhance properties.	[159]
		Thermal Properties: Reduced thermal stability and glass transition temperatures; improved abrasion and wear resistance.	[160]
Poly(butylene terephthalate) (PBT)	BC from various sources	Mechanical Properties: Increased tensile and flexural modulus after aging.	[117]
		Performance: Enhanced stiffness and heat deflection temperature; effects of chain extenders.	[161]
Poly(trimethylene terephthalate) (PTT)	BC from various sources	Mechanical Properties: Improved HDT and stiffness; reduced impact strength.	[162]
		Performance: Enhanced properties with chain extenders.	[163]
Poly(ethylene terephthalate) (PET)	BC, recycled PET, chain extenders	Mechanical Properties: Synergistic effects on stiffness, tensile strength, and impact toughness.	[164]
Other Thermoplastic-Based Composites			
Polycarbonates (PC)	BC combined with recycled carbon fibers	Mechanical Properties: Improved with BC-CF composites; reduced hydrolytic degradation with ABS addition.	[165]
Polyvinyl Alcohol (PVA)	BC from waste cotton	Electrical Properties: Improved conductivity and piezoresistive effect; high conductivity in pressure applications.	[166]

Table 3 (continued)

Composite Type	Biochar Source/Preparation	Properties and Applications	References
Starch and Poly-caprolactone (PCL)	BC from coffee grounds, biomass	Mechanical Properties: Increased elastic modulus with 10 wt% BC; potential for biodegradable products.	[167]
		Properties: Decreased Young's modulus with starch-BC composites.	[168]
Polyhydroxyalkano-ates (PHA)	BC from miscanthus fibers	Mechanical Properties: Increased elastic and flexural modulus; decreased tensile and flexural strength.	[169]
		Performance: Enhanced dimensional stability and heat deflection temperature.	[170]
Thermosetting Matrices			
Epoxy Resin-Based Composites	BC from maple, coffee, various feedstocks	Mechanical Properties: Improved behav-ior with up to 2 wt% BC; higher electrical conductivity at 20 wt% BC.	[171]
		BC Properties: Variations in stiffness, elongation, and impact with different BC types and production conditions.	[172]
		Toughening Agent: Increased storage modulus and ultimate tensile stress in fibrous composites.	[173]
Unsaturated Poly-ester Resin-Based Composites	Hardwood BC, cashew nutshell BC	Mechanical Properties: Increased impact energy and hardness; significant improve-ments in hardness, tensile, and impact strength.	[174]
		Tribological Behavior: Reduced friction coefficient and wear rate with optimal BC loading and particle size.	[175]
Rubber Composites			
Poly(styrene)-Poly(butadiene) Rubber	BC from maple, nanosilica	Mechanical Properties: Improved elonga-tion at break and toughness compared to carbon black; better dispersion and size effects.	[176]
Silicone Rubber Composites	BC from olive pyrolysis	Mechanical Properties: Enhanced performance with specific BC types and loadings.	[177]

Abbreviations

PCB	Polymer-Coated Biochar
BC	Biochar
PAHs	Polycyclic Aromatic Hydrocarbons
CEC	Cation Exchange Capacity
H_2SO_4	Sulphuric Acid
HCl	Hydrochloric Acid
KOH	Potassium Hydroxide
Cu	Copper
Pb	Lead
LbL	Layer-by-Layer
SO_3H	Sulphonic Acid
PO_3H_2	Phosphonic Acid
PAA	Polyacrylic Acid
PDA	Polydopamine
PEG	Polyethylene Glycol
PP	Polypropylene
WPCs	Wood-Plastic Composites
$CaCO_3$	Calcium Carbonate
UV	Ultraviolet
BPCs	Biochar/Polypropylene Composites
RC	Reed Charcoal
AC	Enteromorpha clathrate biochar
M-AC	Mask-Biochar Packages
MB	Methylene Blue
UHMWPE	Ultra-High Molecular Weight Polyethylene
LLDPE	Linear Low-Density Polyethylene

HDPE	High-Density Polyethylene
EMI	Electromagnetic Interference
PE	Polyethylene
CPX	Ciprofloxacin
SS	Sewage Sludge
PLA	Polylactic Acid
PBT	Polybutylene Terephthalate
PTT	Polytrimethylene Terephthalate
PET	Polyethylene Terephthalate
PA	Polyamide
PC	Polycarbonates
PVA	Polyvinyl Alcohol
PCL	Polycaprolactone
PHA	Polyhydroxyalkanoates
HDT	Heat Deflection Temperature
PBAT	Poly(1,4-butylene adipate-co-1,4-butylene terephthalate)
P(3HB-co-4HB)	Poly[(R)-3-hydroxybutyrate-co-4-hydroxybutyrate
ASTM	American Society for Testing and Materials
SBPE	Sugarcane Biochar Polyester
CF	Carbon Fibers
ABS	Acrylonitrile Butadiene Styrene
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)
PEI	Polyethylenimine
Fe_3O_4	Iron(III) Oxide
CNTs	Carbon Nanotubes
PDMS	Polydimethylsiloxane
SOC	Soil Organic Carbon
PVP	Polyvinylpyrrolidone
XPS	X-ray Photoelectron Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy

Acknowledgements
The authors sincerely acknowledge support from the Department of Biotechnology and Bioinformatics, School of Bioengineering and Biosciences, Lovely Professional University, Punjab, India. The authors are also thankful to Special Centre for Nanoscience, Jawaharlal Nehru University, New Delhi, India, along with Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia for their help in compiling and reviewing our work.

Author contributions
AKV, NRS and AN led the development of the methodology, data extraction, study quality assessment, conceptualization, study identification, analysis, and manuscript writing. TS created the graphics under the supervision of AKV. TS edited the whole draft and did the referencing. SS provided detailed reviews of the manuscript drafts and analyses, OE conducted overall review and editing of the manuscript, and NRS delivered crucial critical feedback. The final manuscript, reflecting these collective contributions, has been approved by all authors.

Funding
Declaration.
No funds were procured or were applicable to write this review.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not Applicable.

Consent for publication
Not Applicable.

Dual publication
The authors also declare that the results/data/figures in our submission have not been previously published, and are not under consideration for publication elsewhere.

Competing interests
The authors declare no competing interests.

Received: 21 October 2025 / Accepted: 12 March 2026
Published online: 16 March 2026

References

1. Bartoli M, Arrigo R, Malucelli G, Tagliaferro A, Duraccio D. Recent Advances in Biochar Polymer Composites. Polym (Basel). 2022;14:2506.

2. Lehmann J, Joseph S. Biochar for environmental management: An introduction. Biochar for environmental management. Science and technology. Earthscan Publ Ltd (2009).
3. Sohi SP, Krull E, Lopez-Capel E, Bol RA. Review of Biochar and Its Use and Function in Soil. in 47–82 (2010). https://doi.org/10.1016/S0065-2113(10)05002-9
4. Gross A, Bromm T, Glaser B. Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. Agronomy. 2021;11:2474.
5. Kopecký M, et al. Modified Biochar—A Tool for Wastewater Treatment. Energies. 2020;13:5270.
6. Fang Q, et al. Application of layered double hydroxide-biochar composites in wastewater treatment: Recent trends, modification strategies, and outlook. J Hazard Mater. 2021;420:126569.
7. Das O, Sarmah AK, Bhattacharyya D. Biocomposites from waste derived biochars: Mechanical, thermal, chemical, and morphological properties. Waste Manag. 2016;49:560–70.
8. Das O, et al. An Attempt to Find a Suitable Biomass for Biochar-Based Polypropylene Biocomposites. Environ Manage. 2018;62:403–13.
9. Afshar M, Mofatteh S. Biochar for a sustainable future: Environmentally friendly production and diverse applications. Results Eng. 2024;23:102433.
10. Ahmad M, et al. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere. 2014;99:19–33.
11. Samuel Olugbenga O, Goodness Adeleye P, Blessing Oladipupo S, Timothy Adeleye A. Igenepo John, K. Biomass-derived biochar in wastewater treatment- a circular economy approach. Waste Manag Bull. 2024;1:1–14.
12. Kabir E, Kim K-H, Kwon EE. Biochar as a tool for the improvement of soil and environment. Front Environ Sci 11, (2023). https://doi.org/10.3389/fenvs.2023.1324533 https://doi.org/10.3389/fenvs.2023.1324533
13. Amalina F, Krishnan S, Zularisam AW, Nasrullah M. Recent advancement and applications of biochar technology as a multifunctional component towards sustainable environment. Environ Dev. 2023;46:100819.
14. Hossain MZ, et al. Biochar and its importance on nutrient dynamics in soil and plant. Biochar. 2020;2:379–420.
15. Zhang P, Sun H, Min L, Ren C. Biochars change the sorption and degradation of thiacloprid in soil: Insights into chemical and biological mechanisms. Environ Pollut. 2018;236:158–67.
16. Kumar A, Saini K, Bhaskar T. Hydochar and biochar: Production, physicochemical properties and techno-economic analysis. Bioresour Technol. 2020;310:123442.
17. Aboughaly M, Babaei-Ghazvini A, Dhar P, Patel R, Acharya B. Enhancing the Potential of Polymer Composites Using Biochar as a Filler: A Review. Polym (Basel). 2023;15:3981.
18. Li D, Su P, Tang M, Zhang G. Biochar alters the persistence of PAHs in soils by affecting soil physicochemical properties and microbial diversity: A meta-analysis. Ecotoxicol Environ Saf. 2023;266:115589.
19. Haider FU, et al. Biochar application for the remediation of trace metals in contaminated soils: Implications for stress tolerance and crop production. Ecotoxicol Environ Saf. 2022;230:113165.
20. Subramaniam MN, Wu Z, Goh PS, Zhou S. The state-of-the-art development of biochar based photocatalyst for removal of various organic pollutants in wastewater. J Clean Prod. 2023;429:139487.
21. Mukherjee S, et al. Biochar-microorganism interactions for organic pollutant remediation: Challenges and perspectives. Environ Pollut. 2022;308:119609.
22. Tan X-F, et al. Role of biochar surface characteristics in the adsorption of aromatic compounds: Pore structure and functional groups. Chin Chem Lett. 2021;32:2939–46.
23. Tomczyk A, Sokołowska Z, Boguta P. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Rev Environ Sci Bio/Technology. 2020;19:191–215.
24. Yaashikaa PR, Kumar PS, Varjani S, Saravanan A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnol Rep. 2020;28:e00570.
25. He D, Luo Y, Zhu B. Feedstock and pyrolysis temperature influence biochar properties and its interactions with soil substances: Insights from a DFT calculation. Sci Total Environ. 2024;922:171259.
26. Guo S, et al. Recent advances in biochar-based adsorbents for CO2 capture. Carbon Capture Sci Technol. 2022;4:100059.
27. Zou H, et al. Ball milling biochar iron oxide composites for the removal of chromium (Cr(VI)) from water: Performance and mechanisms. J Hazard Mater. 2021;413:125252.
28. Zhao S-X, Ta N, Wang X-D. Effect of Temperature on the Structural and Physicochemical Properties of Biochar with Apple Tree Branches as Feedstock Material. Energies. 2017;10:1293.
29. Yameen MZ, Naqvi SR, Juchelková D, Khan M. N. A. Harnessing the power of functionalized biochar: progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability. Biochar. 2024;6:25.
30. Qiu M, et al. Biochar for the removal of contaminants from soil and water: a review. Biochar. 2022;4:19.
31. Xiao B, et al. A review on magnetic biochar for the removal of heavy metals from contaminated soils: Preparation, application, and microbial response. J Hazard Mater Adv. 2023;10:100254.
32. Abegunde SM, Idowu KS, Adejuwon OM. Adeyemi-Adejolu, T. A review on the influence of chemical modification on the performance of adsorbents. Resour Environ Sustain. 2020;1:100001.
33. Wang Y, et al. Effect of different production methods on physicochemical properties and adsorption capacities of biochar from sewage sludge and kitchen waste: Mechanism and correlation analysis. J Hazard Mater. 2024;461:132690.
34. Damahe D, Mayilswamy N, Kandasubramanian B. Biochar/metal nanoparticles-based composites for Dye remediation: A review. Hybrid Adv. 2024;6:100254.
35. Liu Z, et al. Modified biochar: synthesis and mechanism for removal of environmental heavy metals. Carbon Res. 2022;1:8.
36. Chausali N, Saxena J, Prasad R. Nanobiochar and biochar based nanocomposites: Advances and applications. J Agric Food Res. 2021;5:100191.
37. Arabzadeh Nosratabad N, Yan Q, Cai Z, Wan C. Exploring nanomaterial-modified biochar for environmental remediation applications. Heliyon. 2024;10:e37123.
38. Wang Y, et al. Preparation of novel biochar containing graphene from waste bamboo with high methylene blue adsorption capacity. Diam Relat Mater. 2022;125:109034.
39. Han H, et al. A critical review of clay-based composites with enhanced adsorption performance for metal and organic pollutants. J Hazard Mater. 2019;369:780–96.

40. Liang H, et al. Porous MgO-modified biochar adsorbents fabricated by the activation of Mg(NO3)2 for phosphate removal: Synergistic enhancement of porosity and active sites. Chemosphere. 2023;324:138320.
41. Bo X, et al. Benefits and limitations of biochar for climate-smart agriculture: a review and case study from China. Biochar. 2023;5:77.
42. Masud MA, Al, et al. A critical review of sustainable application of biochar for green remediation: Research uncertainty and future directions. Sci Total Environ. 2023;904:166813.
43. Ndirangu SM, Liu Y, Xu K, Song S. Risk Evaluation of Pyrolyzed Biochar from Multiple Wastes. *J. Chem.* 2019, 1–28 (2019).
44. Campion L, Bekchanova M, Malina R, Kuppens T. The costs and benefits of biochar production and use: A systematic review. J Clean Prod. 2023;408:137138.
45. Osman AI, et al. Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. Environ Chem Lett. 2022;20:2385–485.
46. Raji Z, Karim A, Karam A, Khalloufi S. Adsorption of Heavy Metals: Mechanisms, Kinetics, and Applications of Various Adsorbents in Wastewater Remediation—A Review. Waste. 2023;1:775–805.
47. Wang C, et al. Biochar-based slow-release of fertilizers for sustainable agriculture: A mini review. Environ Sci Ecotechnology. 2022;10:100167.
48. Rombel A, Krasucka P, Oleszczuk P. Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. Sci Total Environ. 2022;816:151588.
49. Gole P, Raut K, Kandasubramanian B. Polymer-based biochar materials for environmental remediation: A review. Hybrid Adv. 2024;6:100267.
50. Tao Y, et al. Utilization of cotton byproduct-derived biochar: a review on soil remediation and carbon sequestration. Environ Sci Eur. 2024;36:79.
51. Dong X, et al. Mechanisms of adsorption and functionalization of biochar for pesticides: A review. Ecotoxicol Environ Saf. 2024;272:116019.
52. Zhang C, et al. Experimental and Theoretical Studies on the Adsorption of Bromocresol Green from Aqueous Solution Using Cucumber Straw Biochar. Molecules. 2024;29:4517.
53. Gęca M, et al. Surface Treatment of Biochar—Methods, Surface Analysis and Potential Applications: A Comprehensive Review. Surfaces. 2023;6:179–213.
54. Criado-Gonzalez M, Mijangos C, Hernández R. Polyelectrolyte Multilayer Films Based on Natural Polymers: From Fundamentals to Bio-Applications. Polym (Basel). 2021;13:2254.
55. Awasthi MK. Engineered biochar: A multifunctional material for energy and environment. Environ Pollut. 2022;298:118831.
56. Yarahmadi A, Dousti B, Karami-Khorramabadi M, Afkhami H. Materials based on biodegradable polymers chitosan/gelatin: a review of potential applications. Front Bioeng Biotechnol 12, (2024).https://doi.org/10.3389/fbioe.2024.1397668 https://doi.org/10.3389/fbioe.2024.1397668
57. Mohammadi R, Hezarjaribi M, Ramasamy DL, Sillanpää M, Pihlajamäki A. Application of a novel biochar adsorbent and membrane to the selective separation of phosphate from phosphate-rich wastewaters. Chem Eng J. 2021;407:126494.
58. Huang C, Thomas NL. Fabrication of porous fibers via electrospinning: strategies and applications. Polym Rev. 2020;60:595–647.
59. Abel SB, Frontera E, Acevedo D, Barbero CA. Functionalization of Conductive Polymers through Covalent Postmodification. Polym (Basel). 2022;15:205.
60. Zhang M, et al. Surface Hydrophobic Modification of Biochar by Silane Coupling Agent KH-570. Processes. 2022;10:301.
61. He L, et al. Multi-layered enzyme coating on highly conductive magnetic biochar nanoparticles for bisphenol A sensing in water. Chem Eng J. 2020;384:123276.
62. Van N. Coconut biochar doped with graphitic carbon nanosheets and α-Fe2O3 shows high adsorption rate for multiple toxic elements in contaminated water. Clean Technol Environ Policy. 2025;27:4471–82.
63. Mo H, Qiu J. Preparation of Chitosan/Magnetic Porous Biochar as Support for Cellulase Immobilization by Using Glutaraldehyde. Polym (Basel). 2020;12:2672.
64. Bolan S, et al. The potential of biochar as a microbial carrier for agricultural and environmental applications. Sci Total Environ. 2023;886:163968.
65. Yang X, et al. Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy metals from aqueous solutions: A critical review. Chem Eng J. 2019;366:608–21.
66. Gelardi DL, Li C, Parikh SJ. An emerging environmental concern: Biochar-induced dust emissions and their potentially toxic properties. Sci Total Environ. 2019;678:813–20.
67. Govil S, Van Duc Long N, Escribà-Gelonch M, Hessel V. Controlled-release fertiliser: Recent developments and perspectives. Ind Crops Prod. 2024;219:119160.
68. Phiri R, Mavinkere Rangappa S, Siengchin S, Oladijo OP, Dhakal HN. Development of sustainable biopolymer-based composites for lightweight applications from agricultural waste biomass: A review. Adv Ind Eng Polym Res. 2023;6:436–50.
69. K E MR, Anil A, Maria HJ, Nzihou A, Thomas S. Recent Advances in the Application of Engineered Biochar for Wastewater Treatment. in 45–69 (2024). https://doi.org/10.1021/bk-2024-1478.ch003
70. Dzoujo HT, et al. Recent advances in metal oxide-biochar composites for water and soil remediation: A review. Hybrid Adv. 2024;7:100292.
71. Jatav HS, et al. Sustainable Approach and Safe Use of Biochar and Its Possible Consequences. Sustainability. 2021;13:10362.
72. Kumar A, et al. Biochar Modification Methods for Augmenting Sorption of Contaminants. Curr Pollut Rep. 2022;8:519–55.
73. Saud A, et al. Progress in the Sustainable Development of Biobased (Nano)materials for Application in Water Treatment Technologies. ACS Omega. 2024;9:29088–113.
74. Chandrika KSVP, et al. Porous crosslinked CMC-PVA biopolymer films: Synthesis, standardization, and application in seed coating for improved germination. Carbohydr Polym Technol Appl. 2025;11:100900.
75. Alkhaldi H, et al. Sustainable polymeric adsorbents for adsorption-based water remediation and pathogen deactivation: a review. RSC Adv. 2024;14:33143–90.
76. Gallego-Ramírez C, Chica E, Rubio-Clemente A. Life Cycle Assessment of Raw and Fe-Modified Biochars: Contributing to Circular Economy. Mater (Basel). 2023;16:6059.
77. Meftah S, et al. Heavy metal polluted water: Effects and sustainable treatment solutions using bio-adsorbents aligned with the SDGs. Discov Sustain. 2025;6:137.

78. Meftah S, et al. The versatility and effectiveness of bio-adsorbents in the removal of chemical pollutants from water: adsorption mechanisms, optimization by ANN and RSM, SWOT analysis, and contribution to the 3rd and 6 th Sustainable Development Goals. Discov Sustain. 2025;6:971.
79. Tengku Yasim-Anuar TA, et al. Emerging application of biochar as a renewable and superior filler in polymer composites. RSC Adv. 2022;12:13938–49.
80. Das C, Tamrakar S, Kiziltas A, Xie X. Incorporation of Biochar to Improve Mechanical, Thermal and Electrical Properties of Polymer Composites. Polym (Basel). 2021;13:2663.
81. Divyangkumar N, Panwar NL. Standardization, certification, and development of biochar based fertilizer for sustainable agriculture: An overview. Environ Pollut Manag. 2024;1:186–202.
82. Zhu Z, et al. Stability of Functionally Modified Biochar: The Role of Surface Charges and Surface Homogeneity. Sustainability. 2023;15:7745.
83. Zhang L, et al. Highly efficient and selective capture of heavy metals by poly(acrylic acid) grafted chitosan and biochar composite for wastewater treatment. Chem Eng J. 2019;378:122215.
84. Zhang D, et al. Ball-milled biochar incorporated polydopamine thin-film composite (PDA/TFC) membrane for high-flux separation of tetracyclic antibiotics from wastewater. Sep Purif Technol. 2021;272:118957.
85. Sim DHH, Tan IAW, Lim LLP, Hameed BH. Encapsulated biochar-based sustained release fertilizer for precision agriculture: A review. J Clean Prod. 2021;303:127018.
86. Li S, Tasnady D. Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspectives. *C* 9, 67 (2023).
87. Wang X, Guo Z, Hu Z, Zhang J. Recent advances in biochar application for water and wastewater treatment: a review. PeerJ. 2020;8:e9164.
88. Wu H, et al. Polyethylene glycol-stabilized nano zero-valent iron supported by biochar for highly efficient removal of Cr(VI). Ecotoxicol Environ Saf. 2020;188:109902.
89. Barthwal S, Uniyal S, Barthwal S. Nature-Inspired Superhydrophobic Coating Materials: Drawing Inspiration from Nature for Enhanced Functionality. Micromachines. 2024;15:391.
90. Eldos HI, Zouari N, Saeed S, Al-Ghouti MA. Recent advances in the treatment of PAHs in the environment: Application of nanomaterial-based technologies. Arab J Chem. 2022;15:103918.
91. Xu K, Wang H, Liu T. Co-Extruded Wood-Plastic Composites: Their Structure, Properties, and Applications. in *Fiber-Reinforced Composites - Recent Advances, New Perspectives and Applications*IntechOpen, (2024). https://doi.org/10.5772/intechopen.1005662
92. Das O, Sarmah AK, Bhattacharyya D. A novel approach in organic waste utilization through biochar addition in wood/polypropylene composites. Waste Manag. 2015;38:132–40.
93. Mohammed Z, Jeelani S, Rangari V. Effective reinforcement of engineered sustainable biochar carbon for 3D printed polypropylene biocomposites. Compos Part C Open Access. 2022;7:100221.
94. Mensah RA, et al. Influence of biochar and flame retardant on mechanical, thermal, and flammability properties of wheat gluten composites. Compos Part C Open Access. 2022;9:100332.
95. Das O, Kim NK, Kalamkarov AL, Sarmah AK, Bhattacharyya D. Biochar to the rescue: Balancing the fire performance and mechanical properties of polypropylene composites. Polym Degrad Stab. 2017;144:485–96.
96. Ayadi R, et al. Effect of the Pyro-Gasification Temperature of Wood on the Physical and Mechanical Properties of Biochar-Polymer Biocomposites. Mater (Basel). 2020;13:1327.
97. Poulose AM, et al. Date palm biochar-polymer composites: An investigation of electrical, mechanical, thermal and rheological characteristics. Sci Total Environ. 2018;619–620:311–8.
98. Elnour AY, et al. Effect of Pyrolysis Temperature on Biochar Microstructural Evolution, Physicochemical Characteristics, and Its Influence on Biochar/Polypropylene Composites. Appl Sci. 2019;9:1149.
99. Alghyamah AA, et al. Biochar/polypropylene composites: A study on the effect of pyrolysis temperature on crystallization kinetics, crystalline structure, and thermal stability. J King Saud Univ - Sci. 2021;33:101409.
100. Roy D, Audus DJ, Migler KB. Rheology of crystallizing polymers: The role of spherulitic superstructures, gap height, and nucleation densities. J Rheol (N Y N Y). 2019;63:851–62.
101. Petousis M, et al. Biochar for sustainable additive manufacturing: Thermal, mechanical, electrical, and rheological responses of polypropylene-biochar composites. Biomass Bioenergy. 2024;186:107272.
102. Low RJY, et al. Investigation of Far Infrared Emission and UV Protection Properties of Polypropylene Composites Embedded with Candlenut-Derived Biochar for Health Textiles. Molecules. 2024;29:4798.
103. Venkata KNN, Shanmugam V. Comparing the effects of biochar addition to polypropylene on the machining properties of biocomposites. in 170012 (2024). https://doi.org/10.1063/5.0186438
104. Ye Y, Zhang S, Zhou C, Li X. Preparation and Characterization of Biochar/Plastic Composites from Recycled Waste Plastics and Agricultural Waste-Reed Straw. at https://doi.org/10.2139/ssrn.4791959 (2024).
105. Yang J, et al. Double-function synergistic treatment system: Mask-biochar package for methylene blue adsorption and high-quality bioproducts recovery via pyrolysis in wastewater treatment and fuel production. J Mol Liq. 2024;396:124034.
106. Cheng H, et al. Enhancement of Electromagnetic Interference Shielding Performance and Wear Resistance of the UHMWPE/PP Blend by Constructing a Segregated Hybrid Conductive Carbon Black–Polymer Network. ACS Omega. 2021;6:15078–88.
107. Li S et al. Mechanical, electrical, and thermal properties of highly filled bamboo charcoal/ultra-high molecular weight polyethylene composites. Polym Compos 39, (2018). https://doi.org/10.1002/pc.24839 https://doi.org/10.1002/pc.24839
108. Zecchi S, et al. A Comprehensive Review of Electromagnetic Interference Shielding Composite Materials. Micromachines. 2024;15:187.
109. Li S, Li X, Deng Q, Li D. Three kinds of charcoal powder reinforced ultra-high molecular weight polyethylene composites with excellent mechanical and electrical properties. Mater Des. 2015;85:54–9.
110. Zhang Q, et al. Production of high-density polyethylene biocomposites from rice husk biochar: Effects of varying pyrolysis temperature. Sci Total Environ. 2020;738:139910.
111. Arrigo R, Jagdale P, Bartoli M, Tagliaferro A, Malucelli G. Structure–Property Relationships in Polyethylene-Based Composites Filled with Biochar Derived from Waste Coffee Grounds. Polym (Basel). 2019;11:1336.

112. Ashraf A, et al. The development of plastic waste and sewage sludge co-pyrolyzed biochar composites with improved interfacial characteristics for the effective removal of ciprofloxacin. Process Saf Environ Prot. 2024;184:766–81.
113. Ogunsona EO, Misra M, Mohanty AK. Sustainable biocomposites from biobased polyamide 6,10 and biocarbon from pyrolyzed miscanthus fibers. J Appl Polym Sci 134, (2017).https://doi.org/10.1002/app.44221 https://doi.org/10.1002/app.44221
114. Watt E, Abdelwahab MA, Mohanty AK, Misra M. Biocomposites from biobased polyamide 4,10 and waste corn cob based biocarbon. Compos Part Appl Sci Manuf. 2021;145:106340.
115. Ogunsona EO, Misra M, Mohanty AK. Accelerated hydrothermal aging of biocarbon reinforced nylon biocomposites. Polym Degrad Stab. 2017;139:76–88.
116. JubinvilleD, Abdelwahab M, Mohanty AK, Misra M. Comparison in composite performance after thermooxidative aging of injection molded polyamide 6 with glass fiber, talc, and a sustainable biocarbon filler. J Appl Polym Sci 137, (2020). https://doi.org/10.1002/app.48618
117. Chang BP, Mohanty AK, Misra M. Sustainable biocarbon as an alternative of traditional fillers for poly(butylene terephthalate)-based composites: Thermo-oxidative aging and durability. J Appl Polym Sci 136, (2019).https://doi.org/10.1002/app.47722 https://doi.org/10.1002/app.47722
118. Asyraf MRM, et al. Mechanical properties of oil palm fibre-reinforced polymer composites: a review. J Mater Res Technol. 2022;17:33–65.
119. Benkraled L, et al. Effect of Plasticization/Annealing on Thermal, Dynamic Mechanical, and Rheological Properties of Poly(Lactic Acid). Polym (Basel). 2024;16:974.
120. Chanda A, Adhikari J, Ghosh M, Saha P. PTT-Based Green Composites. in 167–185 (2023). https://doi.org/10.1007/978-981-19-7303-1_9
121. Jurczyk S, et al. Mechanical and Rheological Evaluation of Polyester-Based Composites Containing Biochar. Polym (Basel). 2024;16:1231.
122. Sundarakannan R, Arumugaprabu V, Sathish T, Rangappa SM, Siengchin S. Mechanical and erosion performance of sugarcane biochar-reinforced polymer composites. Biomass Convers Biorefinery. 2024;14:15453–68.
123. Andrzejewski J, Mohanty AK, Misra M. Development of hybrid composites reinforced with biocarbon/carbon fiber system. The comparative study for PC, ABS and PC/ABS based materials. Compos Part B Eng. 2020;200:108319.
124. Nan N, DeVallance DB, Xie X, Wang J. The effect of bio-carbon addition on the electrical, mechanical, and thermal properties of polyvinyl alcohol/biochar composites. J Compos Mater. 2016;50:1161–8.
125. Diaz CA, Shah RK, Evans T, Trabold TA, Draper K. Thermoformed Containers Based on Starch and Starch/Coffee Waste Biochar Composites. Energies. 2020;13:6034.
126. Li Z, Reimer C, Wang T, Mohanty AK, Misra M. Thermal and Mechanical Properties of the Biocomposites of Miscanthus Biocarbon and Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate) (PHBV). *Polymers (Basel).* 12, 1300 (2020).
127. Babalar M, Siddiqua S, Sakr MA. A novel polymer coated magnetic activated biochar-zeolite composite for adsorption of polystyrene microplastics: Synthesis, characterization, adsorption and regeneration performance. Sep Purif Technol. 2024;331:125582.
128. Yang B, et al. Fe3O4/biochar modified with molecularly imprinted polymer as efficient persulfate activator for salicylic acid removal from wastewater: Performance and specific recognition mechanism. Chemosphere. 2024;355:141680.
129. Ramesh K, Raghavan V. Agricultural Waste-Derived Biochar-Based Nitrogenous Fertilizer for Slow-Release Applications. ACS Omega. 2024;9:4377–85.
130. Yulia E, Purwasasmita BS, Nugraha N, Ekawati E, Nugraha AB. Fabrication of Adsorbent Using Nano-Sized Lignocellulosic Biochar Coated on Luffa Aegyptiaca Sponge to Remove Heavy Metal Chromium VI. Sains Malaysiana. 2024;53:189–200.
131. Yi P, et al. Biomimetic self-lubricating silicone composite based on biochar for antifouling with improved long-term release. Prog Org Coat. 2024;189:108306.
132. Mosaffa E, Patel RI, Banerjee A, Basak BB, Oroujzadeh M. Comprehensive analysis of cationic dye removal from synthetic and industrial wastewater using a semi-natural curcumin grafted biochar/poly acrylic acid composite hydrogel. RSC Adv. 2024;14:7745–62.
133. Zhang H, et al. Multifunctional carboxymethyl cellulose sodium encapsulated phosphorus-enriched biochar composites: Multistage adsorption of heavy metals and controllable release of soil fertilization. Chem Eng J. 2023;453:139809.
134. Paul NEE, Sudeshkumar MP, Duraimurugan P, Jayaseelan V. Synthesis and characterization of cardanol oil and cassava tuber peel biochar toughened epoxy composite coating for structural application. Biomass Convers Biorefinery. 2023;13:7301–10.
135. Kassem I, et al. Cellulose Nanofibers/Engineered Biochar Hybrid Materials as Biodegradable Coating for Slow-Release Phosphate Fertilizers. ACS Sustain Chem Eng. 2022;10:15250–62.
136. Yao Q, et al. Cow dung-derived biochars engineered as antibacterial agents for bacterial decontamination. J Environ Sci. 2021;105:33–43.
137. González ME, et al. Evaluation of biodegradable polymers as encapsulating agents for the development of a urea controlled-release fertilizer using biochar as support material. Sci Total Environ. 2015;505:446–53.
138. Chen S, et al. Preparation and characterization of slow-release fertilizer encapsulated by biochar-based waterborne copolymers. Sci Total Environ. 2018;615:431–7.
139. Mousavi SR, et al. A review of electrical and thermal conductivities of epoxy resin systems reinforced with carbon nanotubes and graphene-based nanoparticles. Polym Test. 2022;112:107645.
140. Khan A, et al. Low-Cost Carbon Fillers to Improve Mechanical Properties and Conductivity of Epoxy Composites. Polym (Basel). 2017;9:642.
141. Giorcelli M, Bartoli M. Development of Coffee Biochar Filler for the Production of Electrical Conductive Reinforced Plastic. Polym (Basel). 2019;11:1916.
142. Ikram S, Das O, Bhattacharyya D. A parametric study of mechanical and flammability properties of biochar reinforced polypropylene composites. Compos Part Appl Sci Manuf. 2016;91:177–88.
143. Chatterjee R et al. Effect of Pyrolysis Temperature on PhysicoChemical Properties and Acoustic-Based Amination of Biochar for Efficient CO2 Adsorption. Front Energy Res 8, (2020).https://doi.org/10.3389/fenrg.2020.00085 https://doi.org/10.3389/fenrg.2020.00085

144. Matykiewicz D. Hybrid Epoxy Composites with Both Powder and Fiber Filler: A Review of Mechanical and Thermomechanical Properties. Mater (Basel). 2020;13:1802.
145. Zuccarello B, et al. New Concept in Bioderived Composites: Biochar as Toughening Agent for Improving Performances and Durability of Agave-Based Epoxy Biocomposites. Polym (Basel). 2021;13:198.
146. Al-Mufti SMS, Almontasser A, Rizvi SJA. Unsaturated Polyester Resin Filled with Cementitious Materials: A Comprehensive Study of Filler Loading Impact on Mechanical Properties, Microstructure, and Water Absorption. ACS Omega. 2023;8:20389–403.
147. Akaluzia RO, et al. Evaluation of the effect of reinforcement particle sizes on the impact and hardness properties of hardwood charcoal particulate-polyester resin composites. Mater Today Proc. 2021;38:570–7.
148. Sundarakannan R, Shanmugam V, Arumugaprabu V, Manikandan V, Sivaranjana P. Development and Sustainability of Biochar Derived from Cashew Nutshell-Reinforced Polymer Matrix Composite. Mech Dynamic Prop Biocomposites. 2021;Wiley255–64. https://doi.org/10.1002/9783527822331.ch13.
149. Richard S, Selwin Rajadurai J, Manikandan V. Effects of Particle Loading and Particle Size on Tribological Properties of Biochar Particulate Reinforced Polymer Composites. J Tribol 139, (2017).https://doi.org/10.1115/1.4033131 https://doi.org/10.1115/1.4033131
150. Richard S, et al. Study of Tribological Properties of Nano-Sized Red Mud Particle-Reinforced Polyester Composites. Trans Indian Inst Met. 2019;72:2417–31.
151. Peterson SC, Kim S. Reducing Biochar Particle Size with Nanosilica and Its Effect on Rubber Composite Reinforcement. J Polym Environ. 2020;28:317–22.
152. Giorcelli M, et al. High-Temperature Annealed Biochar as a Conductive Filler for the Production of Piezoresistive Materials for Energy Conversion Application. ACS Appl Electron Mater. 2021;3:838–44.
153. Das O, Bhattacharyya D, Hui D, Lau K-T. Mechanical and flammability characterisations of biochar/polypropylene biocomposites. Compos Part B Eng. 2016;106:120–8.
154. Zhao W, Kumar Kundu C, Li Z, Li X, Zhang Z. Flame retardant treatments for polypropylene: Strategies and recent advances. Compos Part Appl Sci Manuf. 2021;145:106382.
155. Li S, Huang A, Chen Y-J, Li D, Turng L-S. Highly filled biochar/ultra-high molecular weight polyethylene/linear low density polyethylene composites for high-performance electromagnetic interference shielding. Compos Part B Eng. 2018;153:277–84.
156. Li S, et al. Effect of carbonization temperature on mechanical properties and biocompatibility of biochar/ultra-high molecular weight polyethylene composites. Compos Part B Eng. 2020;196:108120.
157. Baniasadi H, et al. Structure-property correlations study in biochar-enhanced polyamide composites for sustainable materials development. Compos Part B Eng. 2024;286:111809.
158. Ogunsona EO, Codou A, Misra M, Mohanty AK. A critical review on the fabrication processes and performance of polyamide biocomposites from a biofiller perspective. Mater Today Sustain. 2019;5:100014.
159. Ho M, Lau K, Wang H, Hui D. Improvement on the properties of polylactic acid (PLA) using bamboo charcoal particles. Compos Part B Eng. 2015;81:14–25.
160. Trivedi AK, Gupta MK, Singh H. PLA based biocomposites for sustainable products: A review. Adv Ind Eng Polym Res. 2023;6:382–95.
161. Nishida M, et al. Effect of chain extender on morphology and tensile properties of poly(l-lactic acid)/poly(butylene succinate-co-l-lactate) blends. Mater Today Commun. 2021;26:101852.
162. de Beukelaer H, Hilhorst M, Workala Y, Maaskant E, Post W. Overview of the mechanical, thermal and barrier properties of biobased and/or biodegradable thermoplastic materials. Polym Test. 2022;116:107803.
163. Karl CW, et al. Upgrading and Enhancement of Recycled Polyethylene Terephthalate with Chain Extenders: In-Depth Material Characterization. Ind Eng Chem Res. 2024;63:12277–87.
164. Singh AK, Bedi R, Kaith BS. Composite materials based on recycled polyethylene terephthalate and their properties – A comprehensive review. Compos Part B Eng. 2021;219:108928.
165. Velásquez EJ, Garrido L, Guarda A, Galotto MJ. López de Dicastillo, C. Increasing the incorporation of recycled PET on polymeric blends through the reinforcement with commercial nanoclays. Appl Clay Sci. 2019;180:105185.
166. Qin R, et al. Preparation of high-performance MXene/PVA-based flexible pressure sensors with adjustable sensitivity and sensing range. Sens Actuators Phys. 2022;338:113458.
167. Herrera N, Olsén P, Berglund LA. Strongly Improved Mechanical Properties of Thermoplastic Biocomposites by PCL Grafting inside Holocellulose Wood Fibers. ACS Sustain Chem Eng. 2020;8:11977–85.
168. Kayan GÖ, Kayan A. Polycaprolactone Composites/Blends and Their Applications Especially in Water Treatment. ChemEngineering. 2023;7:104.
169. Naser AZ, Deiab I, Defersha F, Yang S. Expanding Poly(lactic acid) (PLA) and Polyhydroxyalkanoates (PHAs) Applications: A Review on Modifications and Effects. Polym (Basel). 2021;13:4271.
170. Péter T, Litauszki K, Kmetty Á. Improving the heat deflection temperature of poly(lactic acid) foams by annealing. Polym Degrad Stab. 2021;190:109646.
171. Wazalwar R, Tripathi N, Raichur AM. Mechanical and curing behavior of epoxy composites reinforced with polystyrene-graphene oxide (PS-GO) core-shell particles. Compos Part C Open Access. 2021;5:100128.
172. Capretti M, Giammaria V, Santulli C, Boria S, Del Bianco G. Use of Bio-Epoxies and Their Effect on the Performance of Polymer Composites: A Critical Review. Polym (Basel). 2023;15:4733.
173. Wang J, et al. Toughening epoxy by nano-structured block copolymer to mitigate matrix microcracking of carbon fibre composites at cryogenic temperatures. Compos Sci Technol. 2024;251:110548.
174. Salah A, Embirsh H, et al. Unsaturated polyester resin based composites: A case study of lignin valorisation. Chemosphere. 2024;362:142144.
175. Deleanu L, Botan M, Georgescu C. Tribological Behavior of Polymers and Polymer Composites. in *Tribology in Materials and Manufacturing - Wear, Friction and Lubrication*IntechOpen, (2021). https://doi.org/10.5772/intechopen.94264
176. Zabihi A, Fasihi M, Rasouli S, Wati Sharudin R. Improving the mechanical properties and curing characteristics of styrene-butadiene rubber/butadiene rubber composites by incorporating silicon carbide. Polym Compos. 2024;45:1676–87.

177. Liu J, Yao Y, Chen S, Li X, Zhang Z. A new nanoparticle-reinforced silicone rubber composite integrating high strength and strong adhesion. Compos Part Appl Sci Manuf. 2021;151:106645.

Publisher's note