Advances in Physics: X

ISSN: 2374-6149 (Online) Journal homepage: www.tandfonline.com/journals/tapx20

Bibliometric analysis, current studies, and future perspective of biochar filled polymer composite: a sustainable filler for enhancing physical properties

Borhen Louhichi , Abdullah A. Elfar , Santosh Kumar Sahu, Nadir Ayrilmis , It Ee Lee & Gwo Chin Chung

To cite this article: Borhen Louhichi , Abdullah A. Elfar , Santosh Kumar Sahu, Nadir Ayrilmis , It Ee Lee & Gwo Chin Chung (2026) Bibliometric analysis, current studies, and future perspective of biochar filled polymer composite: a sustainable filler for enhancing physical properties, Advances in Physics: X, 11:1, 2646244, DOI: 10.1080/23746149.2026.2646244

To link to this article: https://doi.org/10.1080/23746149.2026.2646244

Published online: 19 Mar 2026.

ADVANCES IN PHYSICS: X
2026, VOL. 11, NO. 1, 2646244
https://doi.org/10.1080/23746149.2026.2646244

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

OPEN ACCESS Check for updates

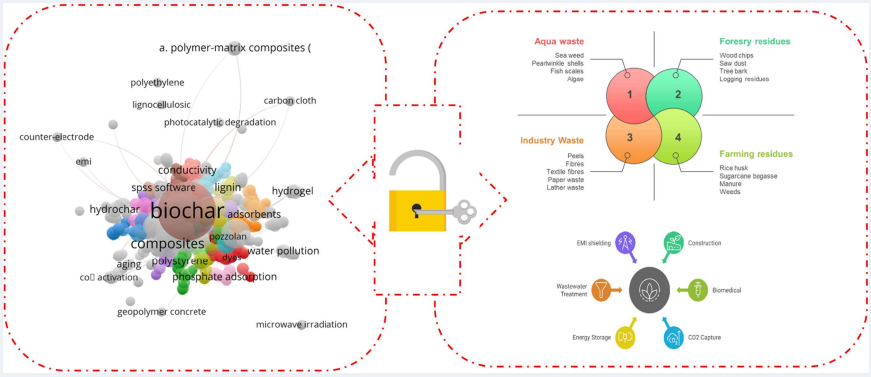
Bibliometric analysis, current studies, and future perspective of biochar filled polymer composite: a sustainable filler for enhancing physical properties

Borhen Louhichi[a], Abdullah A. Elfar[b], Santosh Kumar Sahu[c], Nadir Ayrilmis[d], It Ee Lee[e,f] and Gwo Chin Chung[e,g]

[a]Engineering Sciences Research Center (ESRC), Deanship of Scientific Research, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia; [b]Industrial Engineering Department, College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia; [c]School of Mechanical Engineering, VIT-AP University, Amaravati, India; [d]Department of Wood Mechanics and Technology, Istanbul University – Cerrahpasa, Istanbul, Turkey; [e]Faculty of Artificial Intelligence and Engineering, Multimedia University, Cyberjaya, Malaysia; [f]Centre for Smart Systems and Automation, COE for Robotics and Sensing Technologies, Multimedia University, Cyberjaya, Malaysia; [g]Centre for Wireless Technology, COE for Intelligent Network, Multimedia University, Cyberjaya, Malaysia

ABSTRACT

This study presents a comprehensive review on biochar-filled polymer composites as a sustainable material. Biochar has emerged as one of the most promising reinforcement fillers in polymer matrices owing to its high surface area, thermal stability, and renewability. In addition, it enhances the mechanical properties of polymer matrices, including tensile strength, stiffness, and impact resistance. The study examined 450 articles published over the past decade, from November 2013 to November 2025, using data from Scopus and VOSviewer software to investigate global trends in research and international collaborations. It was followed by a critical review of various synthesis methods for biochars and their subsequent effects on composite properties, including mechanical, thermal, water-absorption, and biodegradability. Several studies have reported that incorporating 5–10 wt.% biochar can substantially improve the tensile strength, Young's modulus, hardness, impact strength, thermal properties, and crystallinity of polymers. Furthermore, it enhances several other properties, while influencing water absorption behavior and biodegradability depending on composition. The challenges and prospects for biochar-filled polymer composites are also discussed in depth. The study concludes that economic and ecological benefits will render the biochar-filled polymer composite an important material for developing eco-friendly construction materials, biomaterials, wastewater treatment, energy storage, CO_2 capture, and soil remediation.



ARTICLE HISTORY

Received 12 December 2025
Accepted 11 March 2026

KEYWORDS

Biochar; polymer composite; synthesis techniques; physical properties; water absorption; bibliometric analysis

CONTACT Santosh Kumar Sahu sksahumech@gmail.com; santoshkumar.sahu@vitap.ac.in School of Mechanical Engineering, VIT-AP University, Besides A.P. Secretariat, Amaravati, 522237, Andhra Pradesh, India; It Ee Lee ielee@mmu.edu.my Faculty of Artificial Intelligence and Engineering, Multimedia University, Cyberjaya, 63100, Malaysia

1. Introduction

In recent years, research on bio-based materials has experienced exponential growth, driven by an increasing emphasis on sustainability and ecological awareness. As the environmental impact of traditional polymers has become more evident, the demand for sustainable alternatives has increased. To address this issue, the principle of 3Rs reduce, reuse, and recycle takes a leading role, thus creating materials that can contribute to a circular economy [1]. One of the key solutions lies in polymer composites made from combining polymers with bio-based fillers [2,3]. Among the possible alternatives, bio-derived reinforcements, in particular, biochar (BC) is a promising reinforcement, as it is a carbon-rich material produced from biomass under limited oxygen conditions [4]. BC offers many advantages, as shown in Figure 1, such as high surface area, high-temperature stability, renewability, cost-effectiveness, and high porosity [5]. Through its porous architecture and functional surface chemistry, biochar (BC) facilitates robust interactions between polymer chains, thereby enhancing the overall performance of the composite [6]. These interactions are further supported by the presence of graphite-like sp^2-hybridised carbon, which forms graphitic microdomains within the biochar [7]. These properties make biochar a competitive alternative to other biofillers such as chitin, starch, cellulose, and lignin. Though BC is known for its light weight and thermal stability, its incorporation into the matrix increases mechanical strength owing to its graphitic characteristics, which enhance load transfer and rigidity. BC may be derived from a variety of biomass sources such as wood residues, agricultural byproducts, and food waste [8]. Atmospheric conditions and temperature during BC processing will have a dominant effect on its performance in the polymer matrix [9]. The crystalline peak and other key material elements further enhance the composites' mechanical and thermal properties. When BC is processed at a temperature below 800 °C and in a N_2 atmosphere, the XRD patterns usually show a broad peak between 20° and 30° in 2θ, corresponding to an amorphous phase [10]. Biochar exhibits increased graphitization at temperatures above 800 °C [11]. On the surface of BC, there are C—O and C═O functional groups. The presence of these groups increases the probability of their interaction with the polymer matrix, and hence BC is a promising reinforcement for polymer composites [12].

2. Bibliometric analysis

A literature search was conducted in the Scopus database using the keywords 'biochar' and 'polymer composite'. A total of 450 articles published from January 2013 to November 2025 were screened based on titles, keywords, and abstracts. The database, including research articles, review papers, conference papers, and book chapters, were considered in order to capture the complete research landscape. Only duplicate records were removed during the data cleaning process. The analysis was performed using VOSviewer

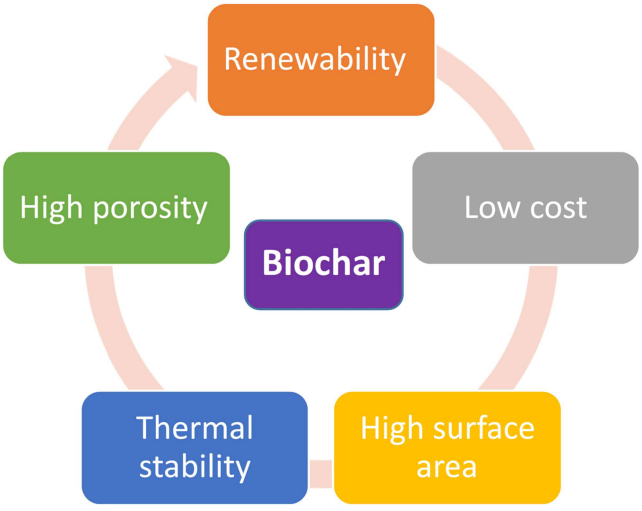


Figure 1. Advantages of biochar.

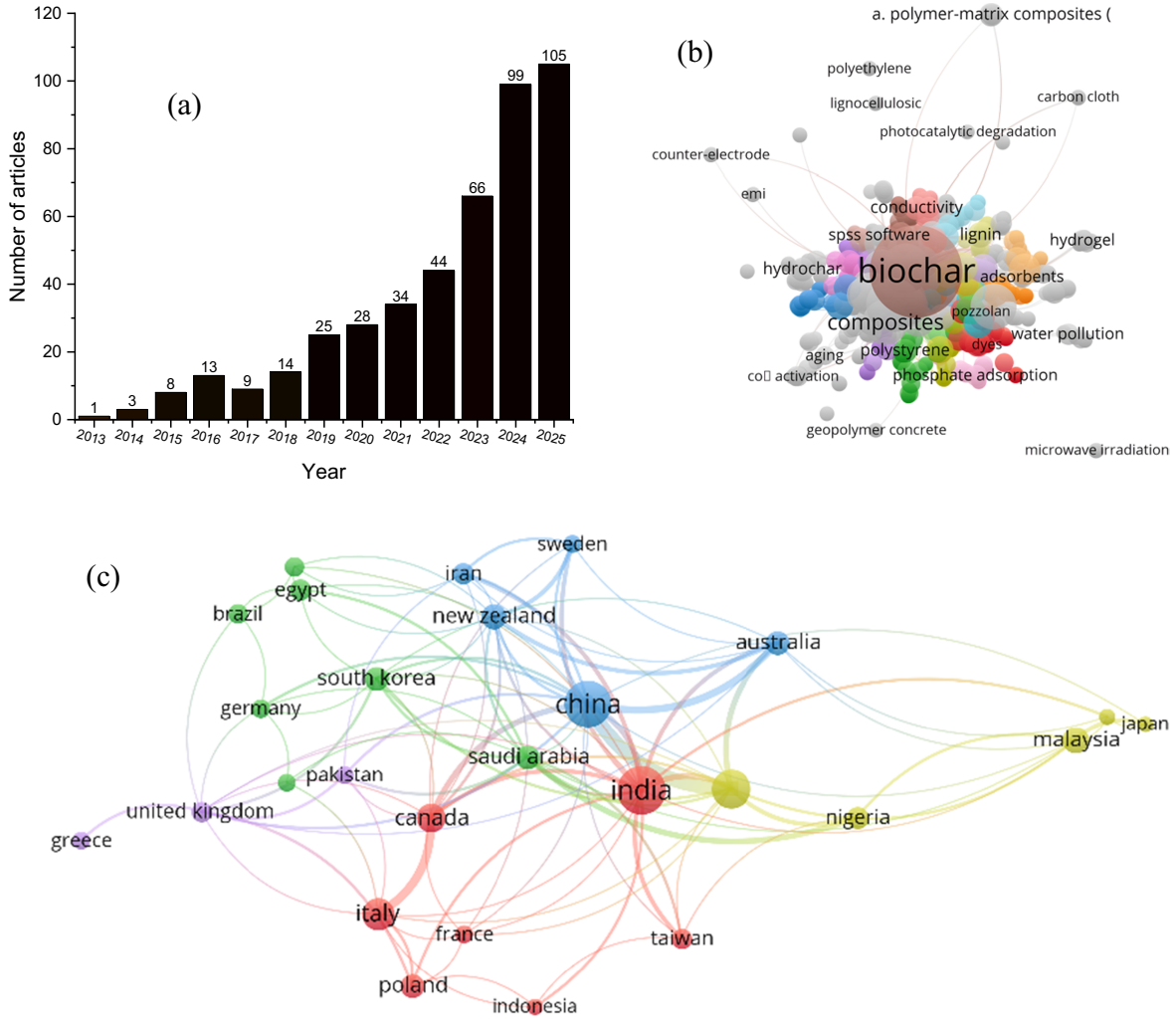


Figure 2. a) Number of articles vs. year [13]; b) word cloud visualisation; c) global distribution of research and research collaboration.

software (version 1.6.20), as shown in Figure 2a [13]. The result is displayed in Figure 2b as a word cloud, with 'biochar' at the centre, surrounded by related terms such as 'composites,' 'conductivity,' 'adsorbents,' and 'polyethylene.' The size of each word reflects its importance or frequency in biochar-related research. To map international collaboration networks, a country co-occurrence analysis was performed using VOSviewer, by setting a minimum threshold of two publications per country. Figure 2c illustrates the global distribution of research in this emerging field and shows the relationships among countries involved in biochar research. Each node represents a country, and the connections between them indicate collaboration, trade, or shared interests in biochar. Thicker lines (e.g. Canada and Italy) and larger circles indicate (e.g. India and China) stronger connections and more active research collaborations on biochar-related topics.

3. Microstructure and elemental analysis

The microstructure and elemental composition of biochar are essential for understanding the physical properties, porosity, and chemical elements of biochar. Vidakis et al. [14] performed microstructural and elemental analyses of the olive tree pruning biomass biochar through SEM and EDS elemental analysis as shown in Figure 3. Figure 3A (2000× magnification) revealed a porous and heterogeneous structure in the SEM image, which is interconnected cavities or channels created during the thermochemical degradation

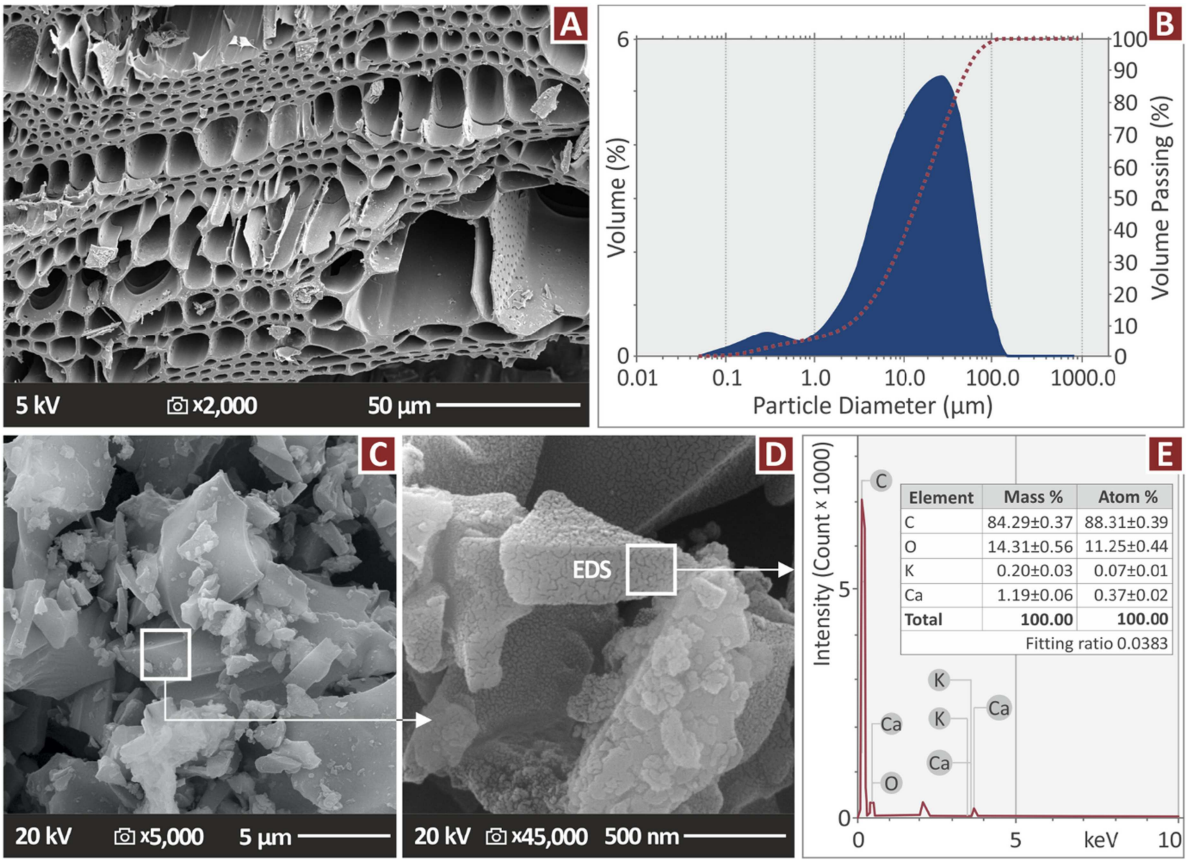


Figure 3. A) SEM image at 2000×; B) particle size distribution; C) SEM image at 45,000×; D) EDS mapping; E) critical elements of biochar [14].

of lignocellulosic biomass. The particle size distribution in Figure 3B shows that most of the particles are in the micrometre range with a wide distribution between sub-micron and tens of micrometres. A more detailed morphology of individual biochar particles was also observed in the higher-magnification SEM images (Figure 3C and D), and these particles had irregular shapes and sharp edges and rough surfaces. Figure 3E shows the EDS spectrum gives an idea of the elemental composition of the biochar. The analysis shows that carbon was the dominant element (84.29%), confirming the carbon-rich nature of the biochar. Oxygen is the second most abundant element (14.31%), which is typically associated with oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl groups present on the biochar surface. Minor amounts of potassium (0.20%) and calcium (1.19%) were also detected, which originate from the mineral content of the original biomass feedstock. These inorganic components have the potential to modify surface reactivity, catalytic activity and electrical conductivity of biochar. Similar observations have been cited in other studies. Guo et al. [15] confirmed the porous structure of wood waste biochar, with ZnCl2 serving as the activation agent during pyrolysis. The EDS images confirmed the presence of Fe, Zn, and O elements. Sharma et al. [16] demonstrated that the corn biochar from the downdraft gasifier exhibited pore openings ranging from 20 to 200 microns, with minerals such as potassium (31.7%) and phosphorus (9.6%) concentrated on the surface.

4. Classification of biochar based on different feedstock

Biochar is simply a porous, carbon-based substance, which is formed as a result of decomposing organic biomass. A variety of feedstocks and production processes can be used to produce any type of biochar. Figure 4 indicates that biochar feedstocks can be categorised into four categories according to their source: Aqua waste, forestry residues, industry waste, and farming residues [17]. Every category has its own

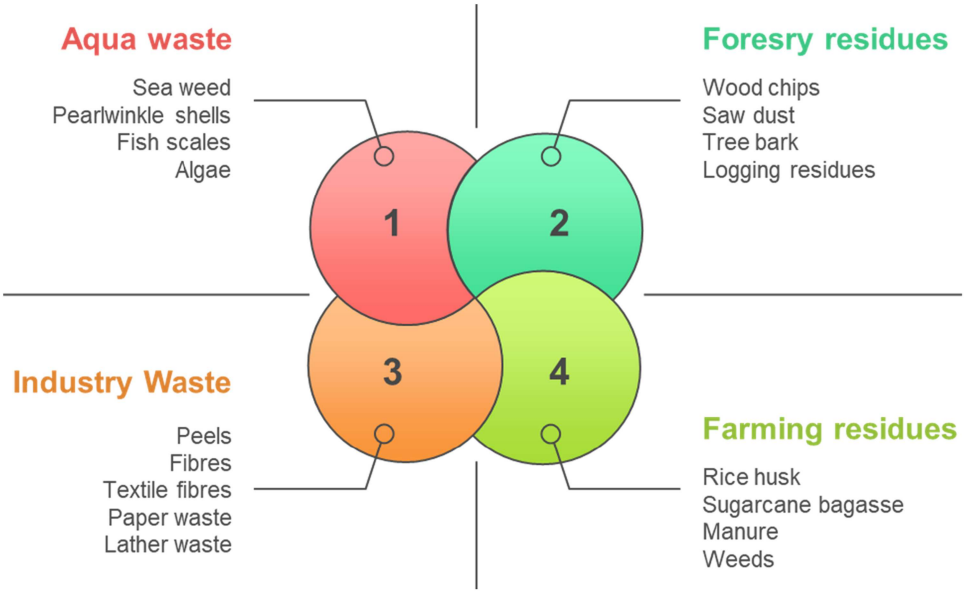


Figure 4. Classification of biochar based on different feedstock.

organic materials, which are excellent in the production of biochar. Aqua waste contains substances such as seaweed, winkle-shell pearls, fish scales and algae, all of which are rich in carbon and provide the resulting biochars with high surface areas and high adsorption capacities. Water filtration and soil improvement are some of the common uses of these biochars. Forestry residues entail wood chips, sawdust, tree bark and logging residues. The raw material is lignocellulosic in nature, loaded with cellulose, hemicellulose, and lignin, and thus these feedstocks produce porous biochars, which are perfect in carbon sequestration, improving soil health, and energy storage [18]. Industry waste includes peels, fibres, textile fibres, paper waste and leather waste, as well as manufacturing by-products that are rich in organic matter. This group of materials contains a lot of cellulose and lignin that enhance the mechanical and adsorptive characteristics of biochars, which are applicable in pollution control, wastewater treatment, and soil amendments [19]. Farming residues include rice husk, sugarcane bagasse, manure, and weeds, which are rich, renewable sources of biochar. These feedstocks are lignocellulosic biomass in nature and thus they are applicable in processes that require biochars that contain high amounts of fixed carbon to enhance soil fertility and to sequester carbon and energy.

5. Synthesis techniques of biochar

The biochar feedstock plays a key role in creating eco-friendly materials for use in various industries and environmental applications. In general, biochar classification from different feedstocks is based on their physicochemical and surface characteristics. Biochar generally synthesized using various methods, including pyrolysis, torrefaction, gasification, hydrothermal liquefaction, and solvothermal liquefaction, as shown in Figure 5, and discussed in the subsequent section [20,21].

5.1. Pyrolysis

Pyrolysis is one of the most widely adopted methods for producing biochar, as shown in Figure 6a [22]. The significant elements of biomass feedstock are cellulose, hemicellulose, and lignin. It uses heat to break down biomass in an oxygen-free atmosphere, which creates solid (biochar or pyrochar), liquid, and gas products. Pyrolysis typically occurs in a closed reactor at temperatures between 400 and 800 °C. There are four basic types of pyrolysis based on the heat source: thermal, solar, infra-red, and microwave-assisted [23]. It is also commonly divided into slow, intermediate, and fast pyrolysis based on how quickly it heats up and how long it stays in the system [24]. Liu et al. [25] demonstrated that the pyrolysis temperature

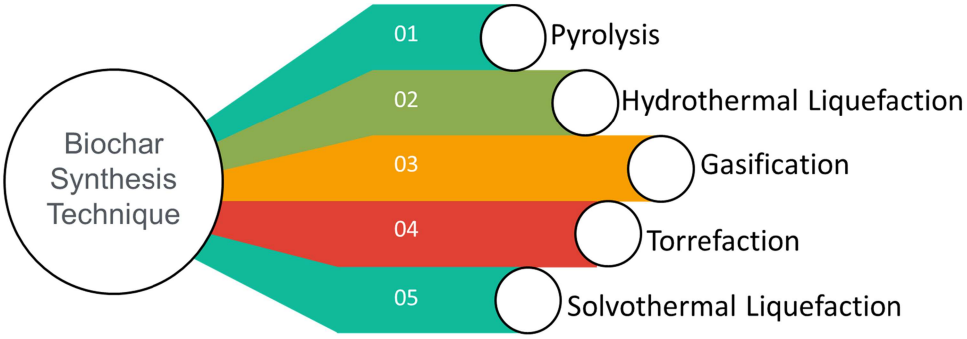


Figure 5. Synthesis techniques of biochar.

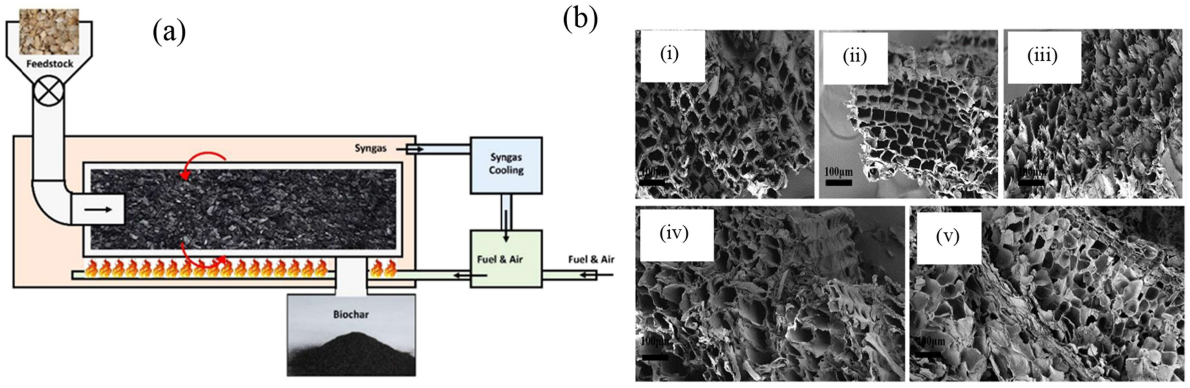


Figure 6. a) Schematic diagram of the pyrolysis method [22]; b) morphology of biochar at pyrolysis temperatures: li) PC300, ii) PC400, iii) PC500, iv) PC600, and v) PC700 [25].

influences the biochar pore formation as depicted in Figure 6b (i) to (v). It was observed that when the pyrolysis temperature increased from 300 to 600 °C, the surface area and pore volume of biochar increased, which improved filler–matrix interactions and facilitated mechanical interlocking and stress transfer within the composite. However, excessively high temperatures (e.g. ~700 °C) may lead to structural damage or pore collapse, which can reduce these reinforcing effects. The study by Singh et al. [26] confirmed that higher pyrolysis temperatures (300 to 600 °C) reduce biochar yield but increase carbon content, pH, and conductivity.

5.2. Hydrothermal liquefaction (HTL)

HTL is a modern thermochemical conversion technology that effectively converts wet or moist biomass into high-value energy products, as illustrated in Figure 7a. This technique is particularly appropriate for treating feedstocks with high moisture contents, such as sewage sludge, food residues, algae, agricultural waste, and municipal organic matter, without prior drying. A study by Aktas et al. [27] examined municipal sludge biochar produced via HTL, and its microstructure is illustrated in Figure 7b. The SEM images in Figure 7b (i, ii, iii) depict biochar, hydrochar (iv, v, vi), and GAC (vii, viii, ix) at different magnifications. Here, abundant macropores characterise biochar, hydrochar displays limited pore structures, and GAC features interconnected pores and a coarse surface, demonstrating significant adsorption potential. The HTL process is usually performed in a water medium at high pressure and temperature, generally in a subcritical regime, where water serves as a solvent, reactant, and catalyst simultaneously [28]. Under those conditions, biomass decomposes into bio-oil, gaseous products, and a carbon-rich solid, known as hydrochar [29]. Generally, four successive steps are involved in the HTL process: feedstock conditioning, pressurisation and heating, liquefaction, and final separation of product phases. Hydrochar

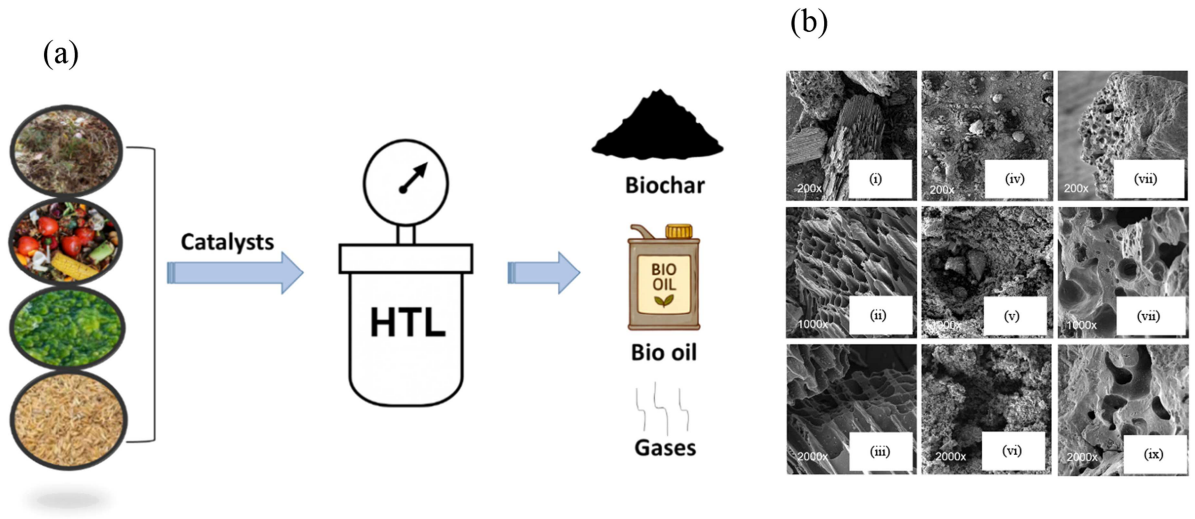


Figure 7. a) Schematic diagram of the HTL reactor; b) SEM image at different magnifications of biochar (i, ii, iii), hydrochar (iv, v, vi), and GAC (vii, viii, ix) [27].

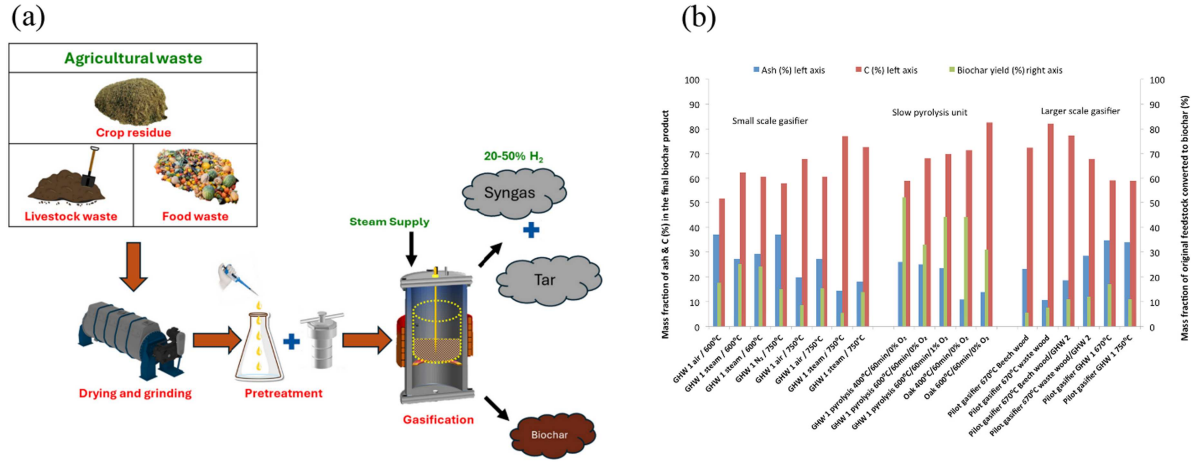


Figure 8. a) Schematic diagram of gasification technique for biochar synthesis [30]; b) effect of temperature and gasification medium on biochar yield and composition [31].

is produced via hydrothermal carbonisation, a process similar to HTL that transforms the solid fraction of biomass into a carbon-rich residue under subcritical water conditions. Both biochar and hydrochar are carbonaceous materials, yet they differ in their synthesis routes, raw materials, and eventual chemical and structural properties. Rather than in a simple linear sequence in HTL, complex reactions such as hydrolysis, decarboxylation, dehydration, polymerisation, and aromatisation occur simultaneously and interactively to determine the transformation of biopolymers such as cellulose, hemicellulose, lignin, and proteins into energy-rich intermediates and solid carbon frameworks.

5.3. Gasification

Gasification is an advanced thermochemical conversion that transforms carbon-based materials into a combustible gaseous mixture, synthesis gas, as shown in Figure 8a [30]. These are usually obtained from biomass such as wood, crop residues, forestry by-products, and agricultural wastes. Figure 8b highlights the significant role of the gasifier, where more oxidative (reactive) environments lead to a decrease in biochar yield, as more mass is converted into product gas [31]. Unlike combustion, which fully oxidises the

feedstock, gasification takes place under conditions of limited oxygen or steam, producing a mixture of carbon monoxide, hydrogen, methane, and other light hydrocarbons. It has been considered an environmentally sustainable route for renewable energy and chemical feedstocks from low-value/waste biomass [32]. Before feeding into the gasifier, the raw biomass is pretreated by drying, size reduction, and homogenisation to enhance reactivity and ensure stable feeding into the reactor. Inside the gasifier, partial oxidation reactions at elevated temperatures break down organic matter, producing syngas and a small amount of solid residue called biochar. The produced syngas can be used directly for heat and power generation or upgraded to liquid fuels and valuable chemicals. In general, the biochar residual from gasification has a high ash and mineral content due to the intense thermal treatment; thus, it is suitable for soil improvement, nutrient recovery, and carbon sequestration [33].

5.4. Torrefaction

A schematic of the typical torrefaction process is shown in Figure 9 [34]. Here, a mild thermal treatment of biomass is generally conducted at 200–350 °C under oxygen-free or inert conditions. Its primary purpose is to eliminate moisture and some volatile compounds, thereby improving the physical and chemical properties of biomass [35]. The treated material is consequently more energy dense, hydrophobic, biologically stable, and easier to grind and store than the raw material. Torrefaction thermally decomposes the significant components of lignocellulosic biomass, hemicellulose, cellulose, and lignin. Among them, hemicellulose is the most temperature sensitive and degrades into gases, including CO_2 and H_2O [36]. Such a selective decomposition reduces the hydrogen and oxygen contents and increases the carbon concentration in the product. Figure 9b and c show the effects of torrefaction on biochar yield [37]. Figure 9b demonstrates that non-oxidative torrefaction of pine wood pellets under N_2 for 60 minutes increased biochar yield from 34% to 98%, while Figure 9c shows that oxidative torrefaction with air achieved a similar biochar yield in a shorter processing time. In recent years, microwave-assisted torrefaction has emerged as an alternative to conventional heating [38]. This kind of torrefaction offers greater control, high process efficiency, and a lower. Oxygen-to-carbon ratio in the obtained material.

5.5. Solvothermal liquefaction (STL)

A schematic of the typical STL process is shown in Figure 10 [39]. It follows an advanced thermochemical conversion route that employs heat, pressure, and a solvent medium to convert raw solid biomass into liquid biofuels and biochar. Complementary to hydrothermal liquefaction, which uses water as the reaction medium, STL uses a range of organic solvents that may interact more selectively with biomass's structural components.

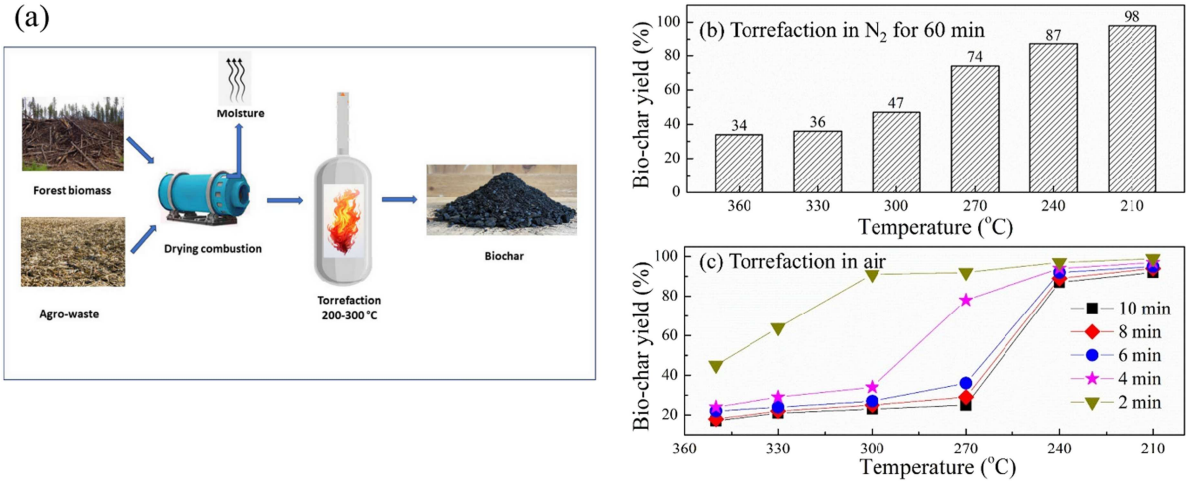


Figure 9. a) Schematic diagram of the torrefaction process for synthesis of biochar [34]; biochar yield from b) non-oxidative torrefaction of pine wood pellets under N2; c) oxidative torrefaction of pine wood pellets with air [37].

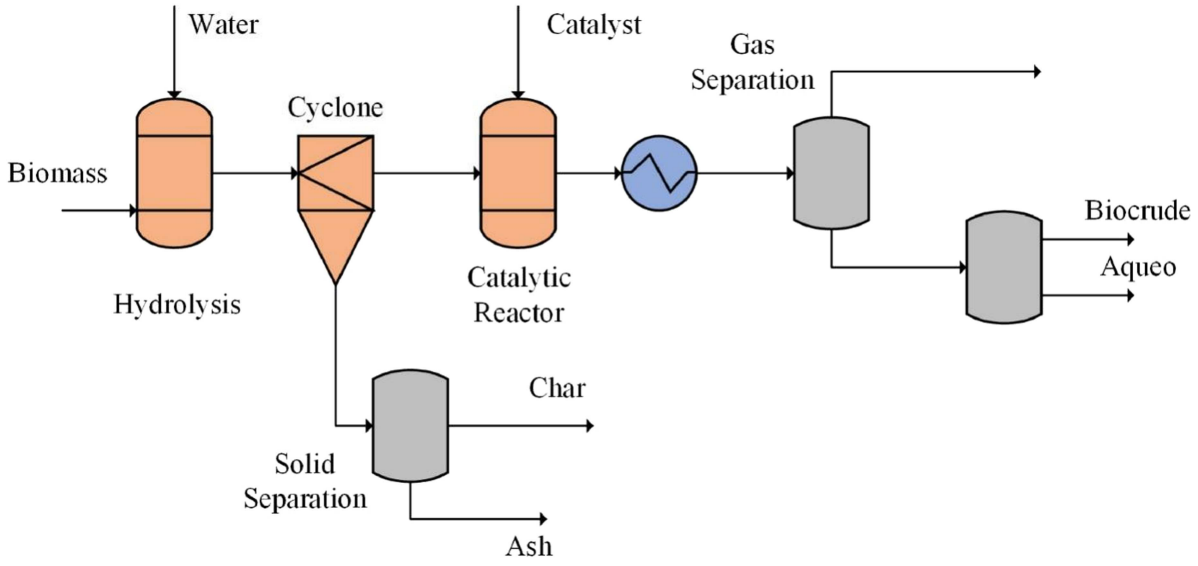


Figure 10. Schematic image of the STL process for the synthesis of biochar [39].

These organic solvents, mainly alcohols, phenols, or other polar organics, allow the dissolution and depolymerisation of biopolymers under controlled thermal conditions [40]. STL includes several key steps: preparation of feedstock, high-temperature and high-pressure reaction, and subsequent separation of the resulting phases. Due to the cooperative effects of heat, pressure, and solvent chemistry in the reactor, lignocellulosic feedstock components such as cellulose, hemicellulose, and lignin degrade into smaller organic molecules, thereby suppressing excessive char formation. STL can provide liquid and solid products, typically a high-quality bio-oil rich in oxygenated compounds and a carbonaceous residue, biochar, depending on the solvent and reaction parameters [41]. This feature opens an avenue for controlling product composition and, in recent years, has attracted growing interest as a pathway to efficient biomass valorisation.

6. Activation of biochar

Activation alters structural and surface characteristics, increases surface area, develops pore networks, and introduces functional groups that enhance reactivity and adsorption potential [42,43]. Activation involves treating either the carbonized material with reactive gases at high temperature or impregnating it with chemical agents that alter its internal structure during thermal treatment. Various physical and chemical activation strategies can significantly improve biochar performance.

6.1. Physical activation

Physical activation improves textural, structural, and surface properties, enhancing material performance in adsorption, catalysis, and electrochemistry [44]. In physical activation, an oxidising gas is used at high temperature to react with the solid in controlled gas–solid reactions, generating porosity and modifying surface functionalities. The carbonized precursor is treated with activating gases-steam, carbon dioxide, or air-usually in the temperature range from 500 to 900 °C [45]. The partial reactions of these gases with the carbon matrix during activation, $C + H_2O \rightarrow CO + H_2$ and $C + CO_2 \rightarrow 2CO$, selectively remove amorphous carbon and open sealed pores. This leads to the development of a specific surface area, enhanced pore connectivity, and the formation of oxygenated functional groups (–C–O, –C = O, and –COOH), which strengthen ion-exchange capacity and surface reactivity [46]. Carbon dioxide activation leads to a slow and uniform process of etching, developing well-defined pores and stable surface functionalities [47]. The pore geometry and surface chemistry of biochar formed during activation depend strongly on process variables, such as activation temperature, gas flow rate, and residence time. Advanced techniques such as purging gases under low-oxygen atmospheres further refine the activation process.

6.2. Chemical activation

Chemical activation is a very efficient and widely adopted approach in tailoring surface chemistry and pore structure. In this process, biomass precursors or preformed biochar were treated with particular chemical activating agents [48]. Upon thermal treatment, it promotes decomposition, pore development, and the incorporation of reactive surface groups within the carbon matrix [49]. Generally, the activation agents for biochar modification include acids, alkalis, and salts, which induce specific structural and chemical transformations of the carbon matrix. Acidic activators, including phosphoric acid (H_3PO_4) and sulphuric acid (H_2SO_4), promote dehydration reactions and introduce oxygen-containing functional groups, such as –OH, –COOH, and –C═O, thereby improving the adsorption of heavy metals, dyes, and other polar contaminants during water purification [50]. In contrast, alkaline activators, such as potassium hydroxide and sodium hydroxide, react vigorously with the carbon skeleton, forming micropores and mesopores and thus considerably increasing the specific surface area, which holds great promise for supercapacitors, battery electrodes, and catalytic supports [51]. In the same vein, salt-based activators such as zinc chloride and ferric chloride act as dehydrating and templating agents, facilitating pore development and the thermal stabilisation of the carbon network [52,53]. Precisely, the type of activating agent, impregnation ratio, and activation temperature were adjusted to tune the pore structure and surface chemistry of biochar. Moreover, it can be combined synergistically with heteroatom doping (e.g. nitrogen, sulphur, or phosphorus) or metal incorporation (e.g. Fe, Mn, or Ni) to enhance selectivity, electrical conductivity, and catalytic reactivity. A chemical activation route appears to be versatile and controllable for designing tailored biochar materials with superior structural and chemical properties for environmental remediation, catalysis, and energy storage.

7. Polymers matrix for biochar composite

Polymer matrices are broadly divided into two major groups, namely thermoplastics and thermosets. Thermosetting materials belong to the class of polymers that, upon curing, form cross-link structures that render them rigid and non-meltable. The other class, thermoplastics, retains the ability to be heated and remoulded. Therefore, in general, thermoplastics allow more flexible manufacturing processes than thermosets do [54–56]. Although the consumption of thermoplastics has increased significantly over the last few decades, thermoset composites still dominate the market and account for about two-thirds of the total composite industry. This superiority in heat resistance and mechanical properties, along with lower manufacturing costs compared to thermoplastics, makes thermosets suitable for high-performance applications across a wide range of industries, including automotive, aerospace, and construction [57]. Furthermore, the wide range of matrix systems and producers within the thermoset category has contributed to its sustained dominance. On the other hand, thermoplastics offer significant advantages, including faster processing, durability, and recyclability. Thus, their great importance has now been recognised in today's market for sustainable development. These properties make thermoplastic composites quite attractive to industries seeking efficient, ecologically friendly production methods. The potential for reuse and recycling of thermoplastic composites enhances their prospects for high-volume applications. Thus, thermoplastic composites are now finding their way into such sectors as consumer goods and the automotive industry. Table 1 summarises some key mechanical properties of thermoplastic and thermoset composites.

Table 1. Mechanical properties of some adopted thermoplastic and thermoset matrices.

Type of polymer matrix	Matrix name	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Reference
Thermoplastic	Polylactic acid	1.24	25.80	0.867	[58]
	Polypropylene	0.98	68.4	2.3	[59]
	Polyethylene	0.95	–	1	[60]
	Polystyrene	1.04–1.05	35.9–56.5	1.2–2.6	[61]
	Polyurethane	0.83	6	0.162	[62]
Thermoset	Epoxy	0.917	60–275	2–12	[63]
	Vinyl ester	1.29	4.85	–	[64]
	Polyester	1.20	276.60	5.90	[65]
	Phenolic	1.2–1.4	35–60	2.7–4.1	[66]

7.1. Fabrication methods for biochar-filled polymer composite

7.1.1. Solution casting

A schematic diagram of the solution casting method is shown in Figure 11a. In the solution-casting process, a mandrel or mould, typically made of metal, glass, or Teflon, is immersed in or coated with a polymer solution or molten resin, allowing a thin, uniform film to form on its surface. After controlled withdrawal, the coated mould is dried, cured, or solvent evaporated to solidify the polymer layer. For example, polylactic acid (PLA) dissolved in suitable solvents can be cast into films that incorporate biochar and exhibit improved barrier and mechanical properties [67]. The simplicity and versatility of casting make it ideal for producing thin films, coatings, or membranes, especially in laboratory-scale studies. However, polymers with high melt viscosity or poor thermal stability, such as polyoxymethylene (POM), polycarbonate (PC), and polypropylene (PP), are generally unsuitable for casting due to difficulties in achieving homogeneous flow and defect-free solidification.

7.1.2. In-situ polymerisation

The *in situ* polymerisation method is a technique that allows the generation of polymer chains within a host material, as depicted in Figure 11b [68], resulting in a uniform dispersion and strong interfacial bonding. During this process, the monomer to be used, together with an initiator or catalyst, is introduced into the matrix, typically biochar, which facilitates impregnation and proper anchorage of the monomer. Upon dispersion, heat, radiation, or chemical activation will initiate controlled polymerisation. Such polymerisation initiates the growth of polymer chains around and onto the embedded phase [70]. This localised polymerisation reduces phase separation, enhances mechanical integrity, and improves load transfer efficiency between the polymer and biochar. Since polymer formation occurs only where needed, composites prepared by this approach typically exhibit enhanced stability, characterised by fewer voids and greater dispersion of functional additives. Thus, the extensive use of in situ polymerisation can also be found in many advanced composites, coatings, and filler-reinforced systems.

7.1.3. Melt blending

A schematic diagram of the melt-blending process is presented in Figure 11c. Melt blending is one of the most efficient and widely used techniques for fabricating biochar-reinforced polymer composites, owing to its simplicity, environmental compatibility, and industrial scalability. In this process, biochar particles are physically mixed into a molten thermoplastic polymer (PP, PE, PLA, or PCL) under controlled temperature and shear conditions to achieve homogeneous dispersion [71,72]. No solvent or chemical surface modification of biochar is used in this approach, making it environmentally friendly, cost-effective, and suitable for scaled-up production. During melt blending, the polymer pellets are initially melted in an extruder, internal mixer, or two-roll mill. The biochar feed is then introduced into the melted matrix. High viscosity in the polymer melt prevents the reagglomeration of biochar particles, resulting in better dispersion and uniform distribution.

7.1.4. Fused deposition modelling

Fused deposition modelling (FDM) is the most popular, cost-effective AM technique for fabricating biochar-polymer composites, as shown in Figure 11d [69]. A thermoplastic filament filled with biochar is heated to a semi-molten state and extruded via the nozzle to form a 3D object layer by layer, following a computer-aided design (CAD) model. This technique enables the development of customised, sustainable composite parts via a simple, clean, and scalable process. PLA, PP, and PETG are thermoplastics commonly used as matrix polymers for biochar-filled filaments owing to their low melting temperatures, good flow behaviour, and printability [73].

8. Evaluation of physical properties

8.1. Mechanical properties

Mechanical characterisation is crucial for understanding how biochar reinforcement affects the tensile strength, stiffness, impact resistance, hardness, and flexibility of these composites. These tests provide

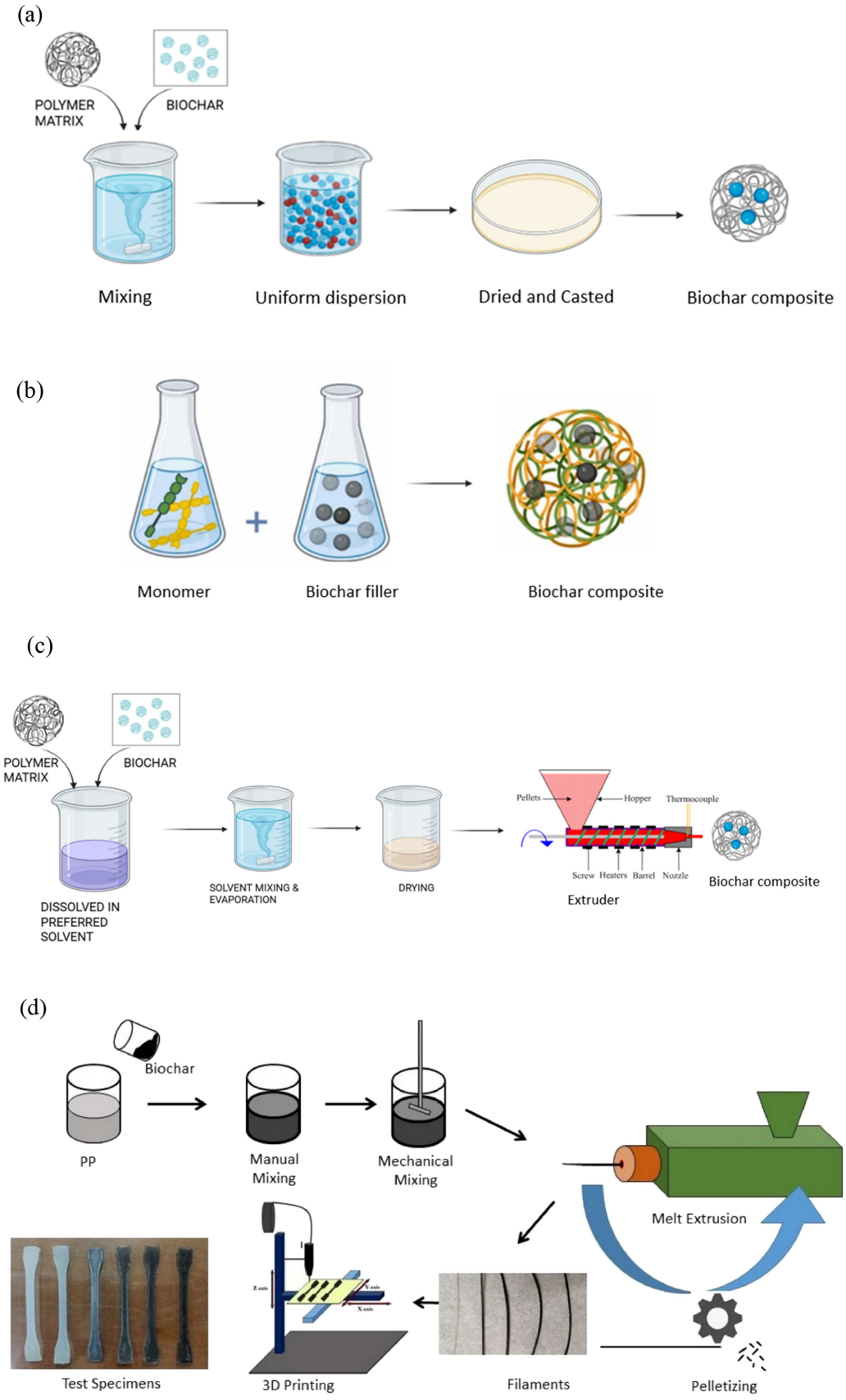


Figure 11. Fabrication process schematic diagram using a) solution casting; b) *In situ* polymerisation [68]; c) melt blending; d) fused deposition modelling [69].

valuable insights into the load transfer efficiency, interfacial adhesion, and structural integrity, guiding their optimisation for engineering and sustainable applications. Various studies examine the mechanical performance of biochar-reinforced polymers under different processing and loading conditions. Baniasadi et al. [74] reported an evaluation of the mechanical properties of PA1010 and wood-chip biochar. Figure 12a depicts the tensile stress–strain response, Figure 12b the bending curve, and Figure 12c a comparative view of the PA1010/biochar (0–50 wt.%) biocomposites. Results demonstrate improvements of 44% in tensile strength, 112% in tensile modulus, and 82% in flexural strength due to biochar reinforcement. The SEM fractography images in Figure 13 show structural changes in PA 11 upon incorporation of biochar and APP. Figure 13a shows the typical ductile fracture of neat PA 11, with fibril tears. In Figure 13b (BC_APP_PA 11_COMP), the addition of APP-doped biochar results in crystalline chunks with clean edges, indicating the nucleation effect. Figure 13c (BC_APP_WG_COMP) shows successful doping of APP inside the biochar pores, with the formation of phosphoric acid crystals, as the doping mechanism differs for APP. Figure 13d (BC_APP_WG_INJ) reveals injection-moulding issues, with large gaps in the polymer matrix and exposed phosphoric acid crystals, which likely hindered cohesive fusion [75]. The impact strength and interlaminar shear strength (ILSS) results of biochar

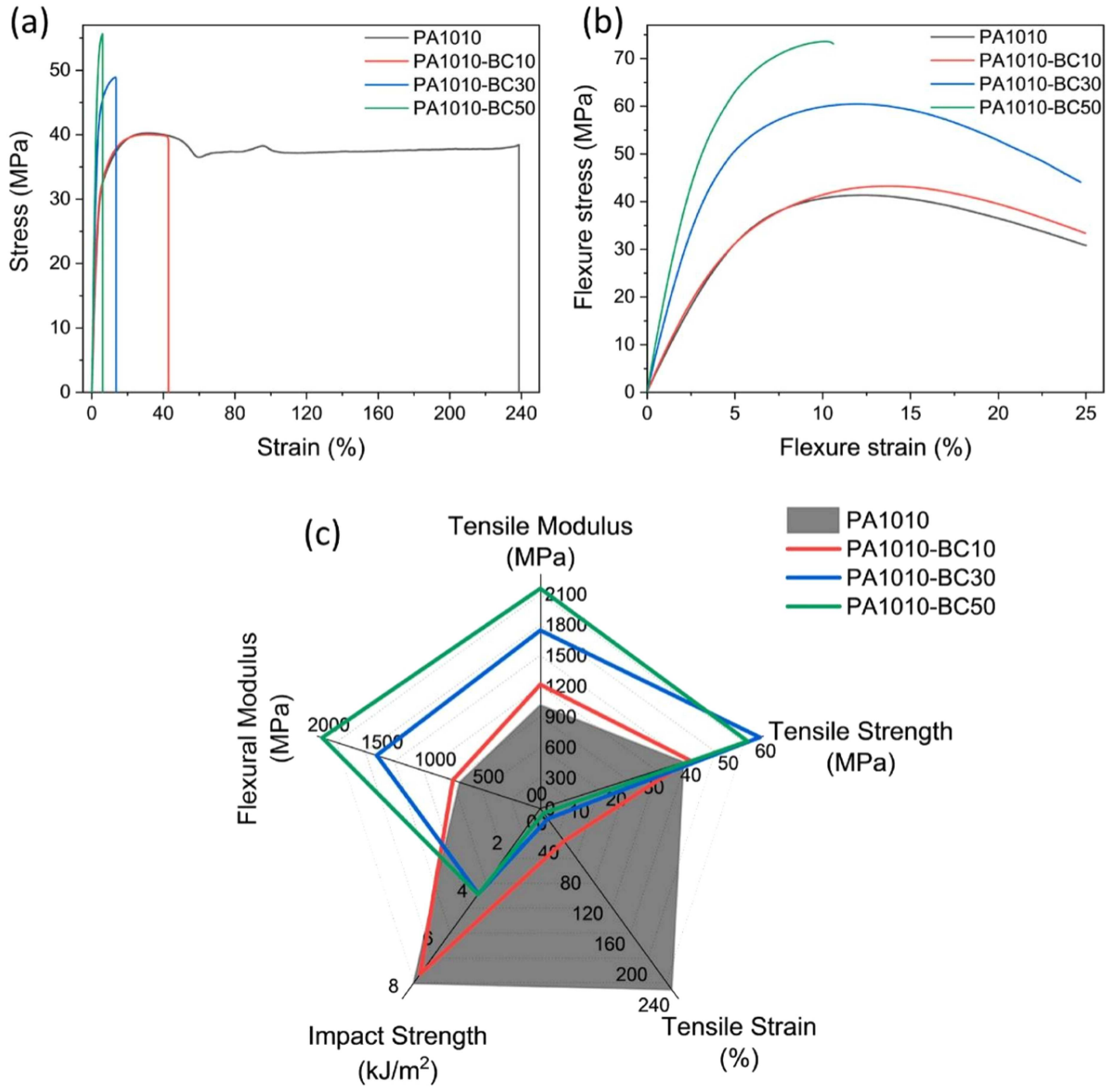


Figure 12. a) Stress vs. strain; b) flexural stress vs. strain; c) comparative view of mechanical properties [74].

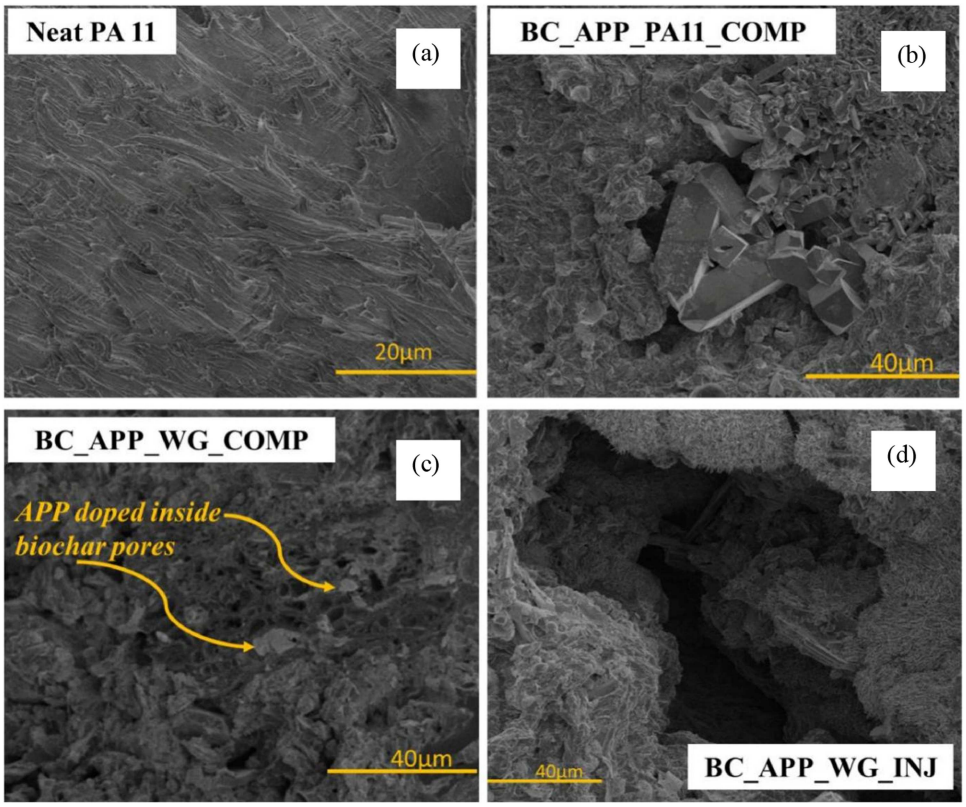


Figure 13. SEM fractography of a). Neat PA 11; b) BC_APP_PA 11_COMP); c) (BC_APP_WG_COMP); d) BC_APP_WG_INJ sample [75].

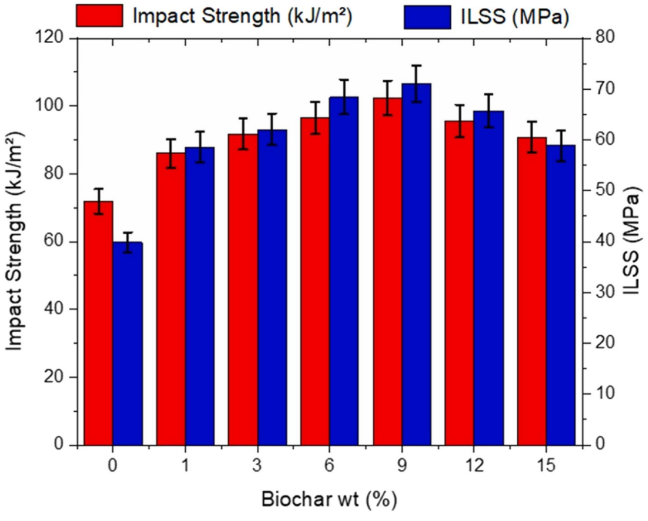


Figure 14. Impact strength and interlaminar shear strength (ILSS) vs. samples [76].

fibre composites are shown in Figure 14 [76]. The results showed that the impact strength and ILSS of composites increased up to 9 wt.% biochar, with peak improvements of 42.3% and 78.3%, respectively. Beyond 9 wt.%, both properties decreased due to particle agglomeration and weakened bonding. The increase in pyrolysis temperature (>300 °C) was reported to result in increased Young's modulus values in the range of 5.64–5.95 GPa for the softwood and hemp-derived biochars [77]. The PLA/PEMA matrices reinforced with optimised Jatropha seed biochar through Doptimal mixture design and microwave

pyrolysis showed improved mechanical properties with a tensile strength of nine wood/polypropylene (PP) biocomposites reinforced with waste-derived activated biochar (1–3 wt.%) exhibited enhanced tensile, flexural, impact, and microhardness properties due to the high surface area of the filler (335 m^2/g), which provided strong interfacial interlocking. The optimised 1 wt.% compatibilizer content maintained mechanical and flammability performance while reducing production costs by ~18% [78]. Polypropylene (PP) biocomposites reinforced with cashew and bael shell biochar (2.5–7.5 wt.%) showed notable mechanical improvement, with five wt.% bael biochar achieving a 54.66% increase in tensile strength, while higher filler loadings reduced interfacial bonding and overall strength [79]. PLA/hydrochar composites containing 5–20 wt.% rice straw hydrochar showed a substantial rise in tensile modulus from 2.63 GPa (neat PLA) to 6.18 GPa—an increase of about 135%. The enhanced stiffness and storage modulus confirm strong interfacial interactions between PLA and hydrochar [80]. Rice husk biochar particles (45–510 nm) were incorporated into an unsaturated polyester matrix at 0.5–2.5 wt.% loading. The composite with 2.5 wt.% of 45 nm biochar showed a 56.36% reduction in specific wear rate and a 6.42% decrease in friction coefficient compared to pure resin, demonstrating that finer biochar particles significantly enhance tribological performance [81]. Sugarcane bagasse biochar (5–12 wt.%) reinforced PVA biocomposite films exhibited a decline in tensile strength with increasing filler content, reaching a minimum of 3.12 MPa at 12 wt.% biochar produced at 1000 °C. The reduction in strength at higher pyrolysis temperatures was attributed to thermal degradation of fibrous residues and functional groups, weakening the interfacial bonding between the biochar and the PVA matrix [82]. The impact strength of the polyester composite samples increased with the addition of sugarcane biochar, reaching its peak at 10 wt.% reinforcement, where a 27% increase in impact strength was observed compared to neat polyester. Mechanical analysis showed that biochar feedstock significantly influenced composite performance. PLA and PCL filled with wood chip biochar exhibited up to 1.5× higher tensile strength and 2× greater elongation at break than those with dairy manure biochar, due to lower moisture content and better interfacial compatibility [83]. Rice husk biochar-reinforced HDPE composites showed significantly improved tensile (20 MPa) and bending (53.7 MPa) strengths compared to conventional wood plastic composites, due to strong interfacial bonding, though a higher filler content slightly reduced impact strength and crystallisation rate [84]. Table 2 refers to the important literature articles on mechanical properties of biochar-polymer composites.

8.2. Thermal properties

The thermal characterisation of biochar-polymer composites is essential for understanding how biochar incorporation affects their thermal stability, crystallinity, conductivity, and degradation behaviour. Such assessments highlight the composites' resistance to heat flow, their ability to dissipate thermal energy, and the variation in crystallisation and glass transition temperatures, all of which are crucial for performance improvement under elevated temperatures. Several works have focused on the thermal analysis of the biochar-reinforced polymer composite. Figure 15a shows the TG results, and Figure 15b depicts the DTG curves of neat and PBSA filled with 0, 5, 10, 15, and 20 wt.% biochar loadings [94]. The results indicated that the introduction of 10 wt.% biochar into PBSA enhanced the thermal stability of this system, shifting the onset degradation temperature by 12–15% compared to neat PBSA. Flax–fibre–reinforced polymer composites filled with 0–15 wt.% biochar were fabricated through hand layup, and the thermal behaviour of the composites was investigated [95]. TGA analysis demonstrated the tendency of biochar addition to improve the thermal stability of the composites, and that the 10 wt.% biochar composite exhibited the highest onset and maximum degradation temperature due to the presence of carbon-rich and thermally stable biochar, which delayed polymer decomposition and improved the formation of char residue. Sahu et al. [96] reported the thermal property evaluation by incorporating coconut shell BC (at 1, 2, 5, and 10 wt.%) into the PLA matrix. Figure 16a represents the DSC thermograms, and Figure 16b denotes the % crystallinity results obtained from the test. An increase in crystallinity from 24% to 47% was reported upon adding 10 wt.% biochar.

Pradeep et al. [97] performed thermal analysis of vinyl ester composites with Cocos nucifera shell biochar at 5, 10, and 15 wt.%. DSC studies showed increases in the glass transition temperature from 156 to 164.8 °C and the degradation temperature from 255.54 to 263.76 °C for alkali-treated biochar composites. Natrayan et al. [98] investigated that the incorporation of 3 wt.% of palm flower biochar into 40 wt.% of

Table 2. Important literature articles on the mechanical properties of biochar polymer composite.

Polymer matrix	Biochar	Mechanical properties	Observation	Reference
Epoxy	Almond shell biochar (ABC) (0 to 20 wt.%)	Tensile and flexural strength	The optimum tensile strength and flexural strength were observed at 10 wt. % of ABC.	[85]
Waste polypropylene bottle flakes (wPP)	Pine needle waste	Tensile, compressive, and flexural strength	The optimal mechanical performance of the wPP/biochar composite was achieved at 40 wt. % biochar, with a 97.30% increase in tensile modulus, 141.92% in flexural modulus, 54.60% in flexural strength, and 28.85% in compressive strength.	[86]
Epoxy	Poultry litter waste (PLW) (2.5 to 10 wt.%)	Tensile, Impact	The addition of biochar (BC) to epoxy resin composites decreases impact strength (from 9.9 to 3.5 kJ/m^2), tensile strength, and strain at break, particularly at higher BC concentrations (10 wt.%), due to poor dispersion and agglomeration of BC particles.	[87]
HDPE	Olive tree prunings (2 to 10 wt.%)	Tensile, flexural Impact, Vickers hardness,	Tensile strength, flexural strength, Impact strength, and hardness are improved at an optimal biochar loading of 6 wt.%.	[88]
Polyester Resin with woven S-glass fabric	Sugar cane husks (0 to 15 wt.%)	Tensile, Flexural, Impact, Hardness	Composites with 10 wt.% biochar achieved the highest tensile strength (119 MPa), flexural strength (154 MPa), and impact strength (45 MPa).	[89]
PLA/starch	Waste coffee grounds (0–20 wt.%) with different particle size.	Tensile	Smaller biochar (BC) particle sizes and higher BC loadings significantly influence the tensile strength of PLA/starch composites.	[90]
HDPE	Rice husk (with four different mass ratios and four activated agent)	Tensile, flexural, DMA	ABHC-0.5 showed the highest values: flexural strength (38.66 MPa), flexural modulus (2.46 GPa), tensile strength (32.17 MPa), and tensile modulus (1.95 GPa).	[91]
PP with compatibilizer	Miscanthus grass biocarbon (Particle size: <20 µm, 106–125 µm)	Tensile, Impact strength	The most influential factor for both Tensile and impact toughness was the type of compatibilizer used.	[92]
PP	Pine wood (0 to 35 wt.%)	Tensile and flexural	Increasing biochar content improved the tensile modulus, flexural strength.	[93]

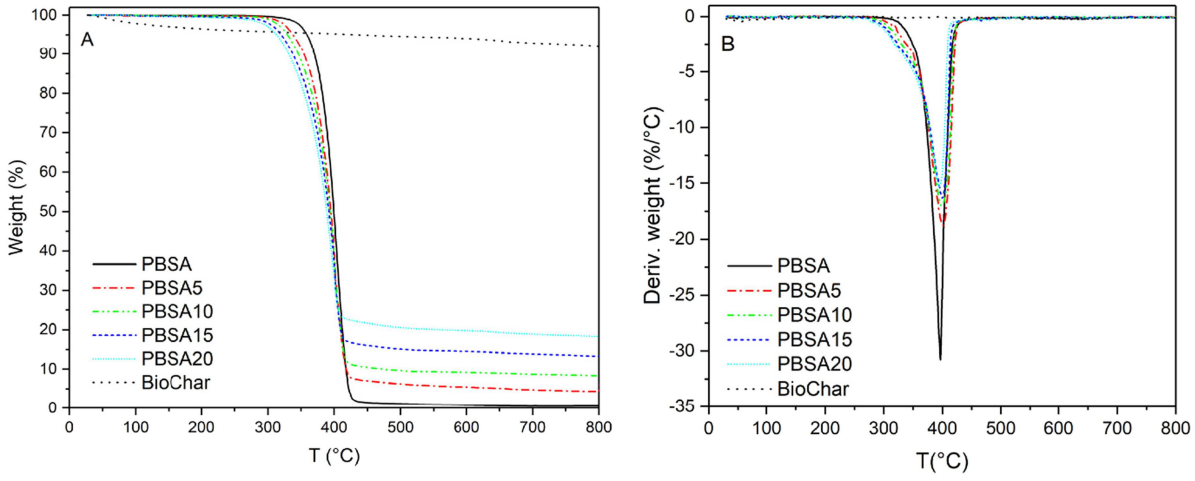


Figure 15. A) TGA; B) DTG results for all samples [94].

Opuntia cladode fibre and 57 wt.% of resin significantly improved the thermal conductivity of the biocomposites from 0.36 to 0.49 W/mK. Increasing biochar content improved thermal conductivity, demonstrating that biochar addition effectively enhances heat conduction. Uram et al. [99] used the DMTA method to assess the properties of polyurethane foams with various biochar (BioC) filler contents (0, 5, 10, 15, and 20 wt.%). The storage modulus presented in Figure 17A shows that the addition of BioC reduces the foam's rigidity. With higher BioC content, a greater decrease was observed. Figure 17B presents the loss modulus, and Figure 17C shows the tan δ. A small change in the damping properties was observed even with 20 wt.% filler. Another study explored the use of wood biochar, rice husk biochar,

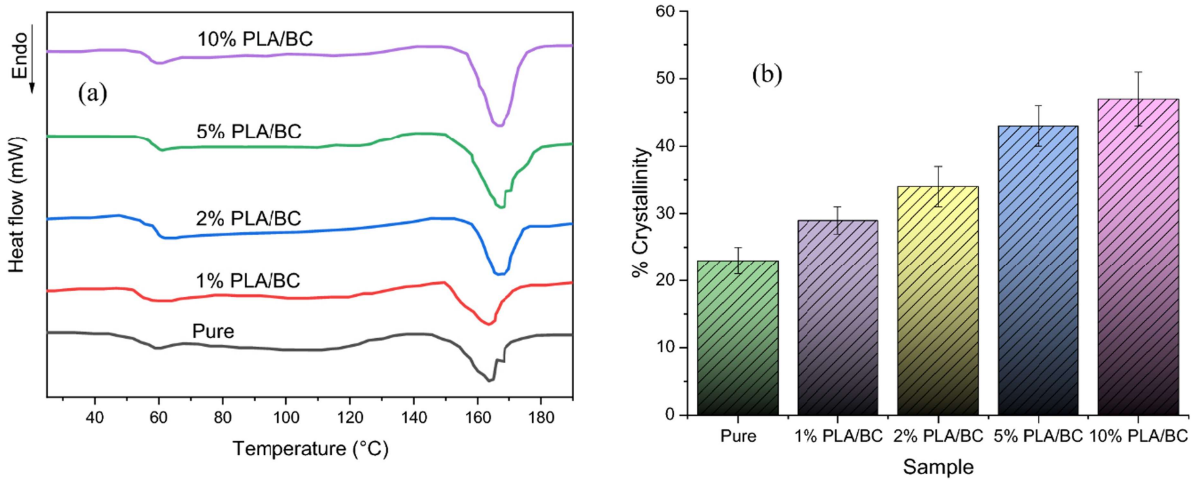


Figure 16. a) DSC thermograms; b) % crystallinity for all samples [96].

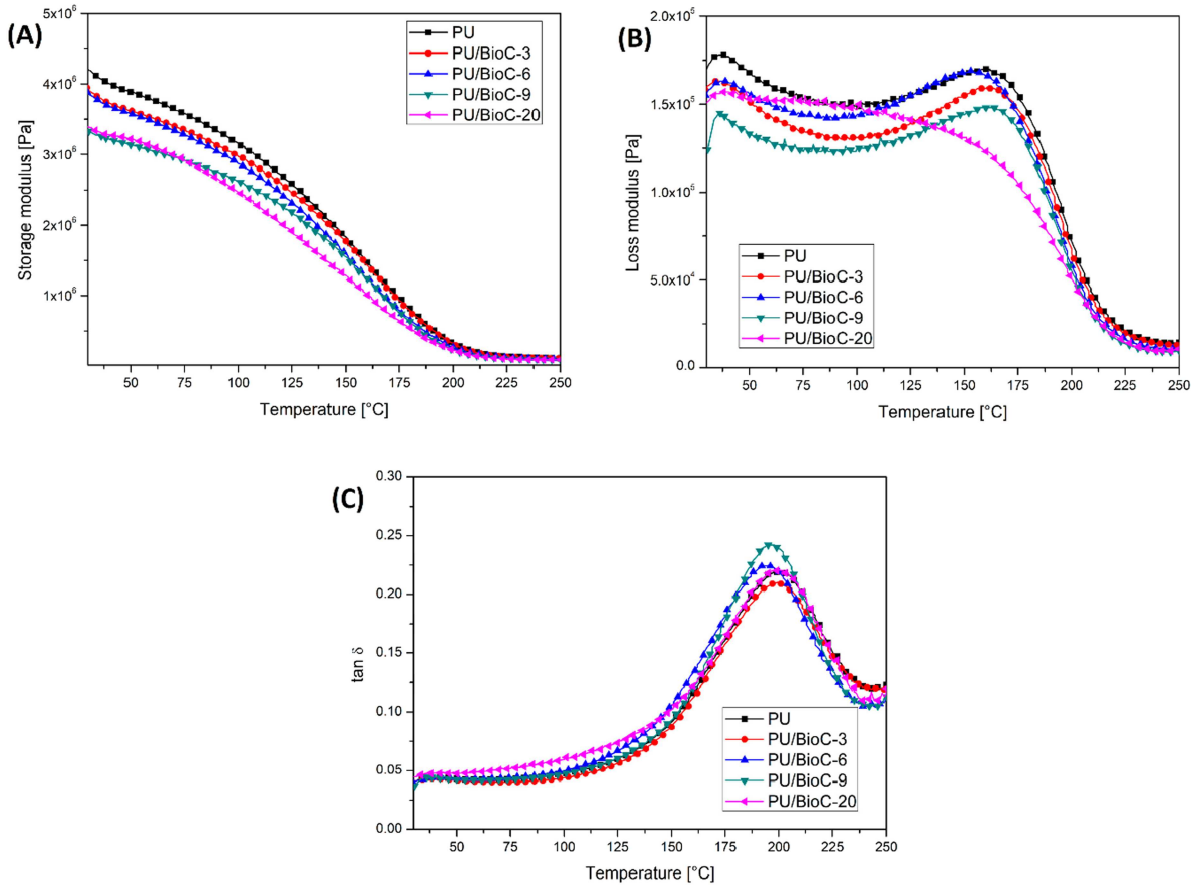


Figure 17. A) Storage modulus; B) loss modulus; C) tan δ for all samples [99].

and bamboo biochar as fillers in wood polymer biochar composites with wood flour, polypropylene (PP), and maleic anhydride polypropylene (MAPP) [100]. The results showed that biochar enhanced the thermal stability and flame retardancy. Table 3 lists important literature articles on the thermal properties of biochar-polymer composites.

Table 3. Important literature articles on thermal properties of biochar polymer composite.

Polymer matrix	Biochar (BC)	Properties evaluated	Observation	Reference
Epoxy resin LY556	Submicron pore-sized Coffee emesis (SCB)(0 to 3 wt.%)	Thermal conductivity	Thermal conductivity increased linearly with increasing biochar content, with EGC3 (3 wt.% coffee emesis biochar, 67 wt.% resin, and 30 wt.% glass fibre) exhibiting a thermal conductivity of 0.462 W/m K.	[101]
PLA	Softwood pellets (1 to 5 wt.%)	DSC	The addition of biochar (BC) to PLA increased the glass transition temperature (Tg).	[102]
HDPE	Wood residues from Eucalyptus sp. (0 to 15 wt.%)	TGA, Crystallinity	Incorporating biochar into HDPE composites did not significantly affect the thermal properties or crystallinity, as indicated by TGA, which showed mass loss between 400 and 500 °C and a maximum decomposition temperature of 487 °C.	[103]
Epoxy resin	Olive pomace (0 to 10 wt.%)	TGA	Thermal analysis showed that incorporating nano-biochar from olive pulp into epoxy composites increased thermal stability.	[104]
PLA	Hardwood (0, 10 wt.%)	DSC	The addition of 10 wt% biochar (10BC) to PLA reduced the glass transition temperature (T_g) from 61.4 to 53.1 °C	[105]
PLA/PBAT	Pine wood (0 to 10 wt.%)	TGA, DSC	The addition of 10 wt.% BC increased PLA crystallisation from 22.53% to 34.14%, while TGA showed a lower degradation onset temperature and increased char residue at 550 °C with higher biochar content.	[106]
PP	Date palm tree wastes (5 to 20 wt.%)	TGA	TGA showed that BC particles enhanced the thermal stability of the BC/PP composites.	[107]

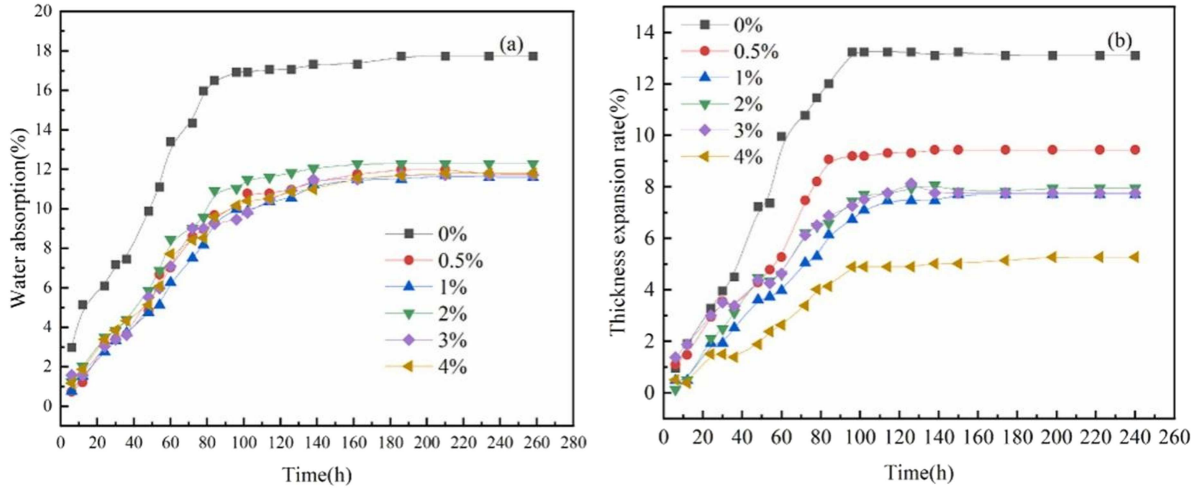


Figure 18. a) Water absorption vs. time; b) thickness expansion vs. time [110].

8.3. Water absorption

Water absorption is a key concern for biochar-polymer composites, as it influences moisture uptake and long-term durability. The addition of biochar to the polymer can make the composite material more hydrophobic or hydrophilic, potentially altering its water absorption and swelling characteristics. The water absorption rate depends on many factors, including biochar size, type, and concentration, as well as interactions between biochar particles and the polymer [108,109]. The study by Zhang et al. [110] demonstrated that water absorption increased in landscaping waste and polylactic acid (LW/PLA) composites with immersion time, as shown in Figure 18a. The incorporation of biochar (BC) reduced water absorption, with a 6.14% decrease observed in the 1 wt.% BC composite, as BC filled the pores in the interfacial bond. Additionally, as shown in Figure 18b, higher BC content led to reduced thickness expansion, with the lowest expansion at 4% BC, indicating enhanced dimensional stability due to improved interfacial bonding and reduced water penetration. Muthukumarasamy and Karthik [111] reported on the effects of almond biochar (ABC) and caryota fibre (CF) as micro fillers in epoxy composites, varying their content from 10 to 30 wt.% (CF) and 4–12 wt.% (ABC). Water absorption

increased with higher ABC content and longer exposure time. A study by Srivastava [112] focused on epoxy composites with varying filler combinations; sample A (90% epoxy, 10% chitosan) exhibited the lowest water absorption at 2.326%. while sample E (90% epoxy, 10% biochar) had the highest water absorption at 9.039%. Zhu et al. [113] investigated the water absorption properties of PA6/BC composites with varying biochar (BC) content (up to 30 wt.%). The results showed that as BC content increased, the composites' water absorption decreased. A study by Srivastava [114] examined water absorption in four composite samples with varying filler compositions: sample A (90 wt.% epoxy, 10 wt.% biochar), sample B (80 wt.% epoxy, 20 wt.% biochar), sample C (80 wt.% epoxy, 10 wt.% biochar, 10% rice bran), and sample D (80% epoxy, 10% biochar, 5% coconut coir). The water absorption results revealed that as the biochar content increased, water uptake decreased, with sample B showing the lowest water absorption, followed by Sample A, Sample D, and Sample C. Gurusamy et al. [115] reported on the water absorption properties of pistachio nut shell (PNS) biochar and short Turkish hemp (STH) fibres in a polyester resin matrix with varying biochar content (5–25 wt.%). It was noted that higher biochar concentrations (>15 wt.%) led to increased void formation and higher water absorption, negatively affecting the composite's properties. A study by Natrayan [98] investigated the water absorption properties of biocomposites made with Opuntia cladode fibre and palm flower biochar with varying biochar contents (3–5 wt.%). The results showed that water absorption was reduced with the silane surface treatment, with the composite containing 3 wt.% biochar (composite C3) demonstrating the lowest water absorption. A study by Vengadesan [116] demonstrated the contact angle and water absorption properties of PLA-rice husk (RHBC) composites reinforced with bamboo biochar, varying the biochar content from 5% to 25% as shown in Figure 19. The contact angle for pure PLA was 65°, which increased to 68° for the RHC composites. As the biochar content increased further, the contact angles increased to 73°, 75°, 77°, 80°, and 85° for RHBC1, RHBC2, RHBC3, RHBC4, and RHBC5, respectively. The results showed an increase in contact angle (hydrophobicity) with increasing biochar content.

8.4. Biodegradability

Biodegradability refers to a substance's ability to decompose naturally through the action of microorganisms, such as bacteria and fungi, into simpler, non-toxic compounds that do not harm the environment [117]. Biodegradation of biochar-polymer composites varies with the composition and type of the polymer matrix and biochar. Biodegradability also depends on various environmental factors, such as moisture, temperature, and microbial activity. Additionally, it influences the rate and extent of biodegradation during organic recycling processes like industrial composting, home composting, and anaerobic digestion [118]. This process is vital for ensuring that materials break down efficiently and do not accumulate in ecosystems, causing pollution and harm. The rate and extent of biodegradation are influenced by factors such as the material's chemical composition, environmental conditions (e.g. temperature and moisture), and the presence of microorganisms capable of decomposing it. While biochar itself is resistant to rapid biodegradation due to its stable, carbon-rich structure, it can promote the biodegradation of other organic materials in the environment [119]. The biodegradation study by She et al. [120] of biochar/gutta-percha composite films was assessed by measuring weight loss during soil burial over 60 days. Figure 20A shows that the 2% and 4% biochar films exhibited slower degradation (9.56% and 11.20% weight loss, respectively) due to biochar's hydrophobic nature. In contrast, the 6% and 8% biochar films exhibited higher degradation (15.04% and 17.40%) due to stronger interactions between biochar and the gutta-percha matrix. Figure 20B shows the weight loss vs. time plot during enzymatic hydrolysis of neat PBSu and PBSu/BC biocomposites [121]. The biodegradability of PBSu biocomposites was significantly enhanced with the addition of biochar (BC) at different weight percentages (1%, 2.5%, and 5%). Pristine PBSu exhibited only a 0.25% weight loss after 30 days of enzymatic hydrolysis. In contrast, the biocomposites showed much higher weight losses, with the 1%, 2.5%, and 5% BC composites losing approximately 1.66%, 1.70%, and 1.88% of their initial weight, respectively. The biodegradability of different composite sandwich structures was evaluated through a 100-day soil burial test. Wang et al. [122] reported the biodegradability of WPCs made from corrugated cardboard (CCB) and biochar fibres pyrolyzed at 350, 400, and 450 °C, compounded with HDPE and MAPE. The CCB450 biochar composite showed the least weight loss (0.07% for white rot, 0.06% for brown rot), demonstrating improved decay resistance compared to the CCB

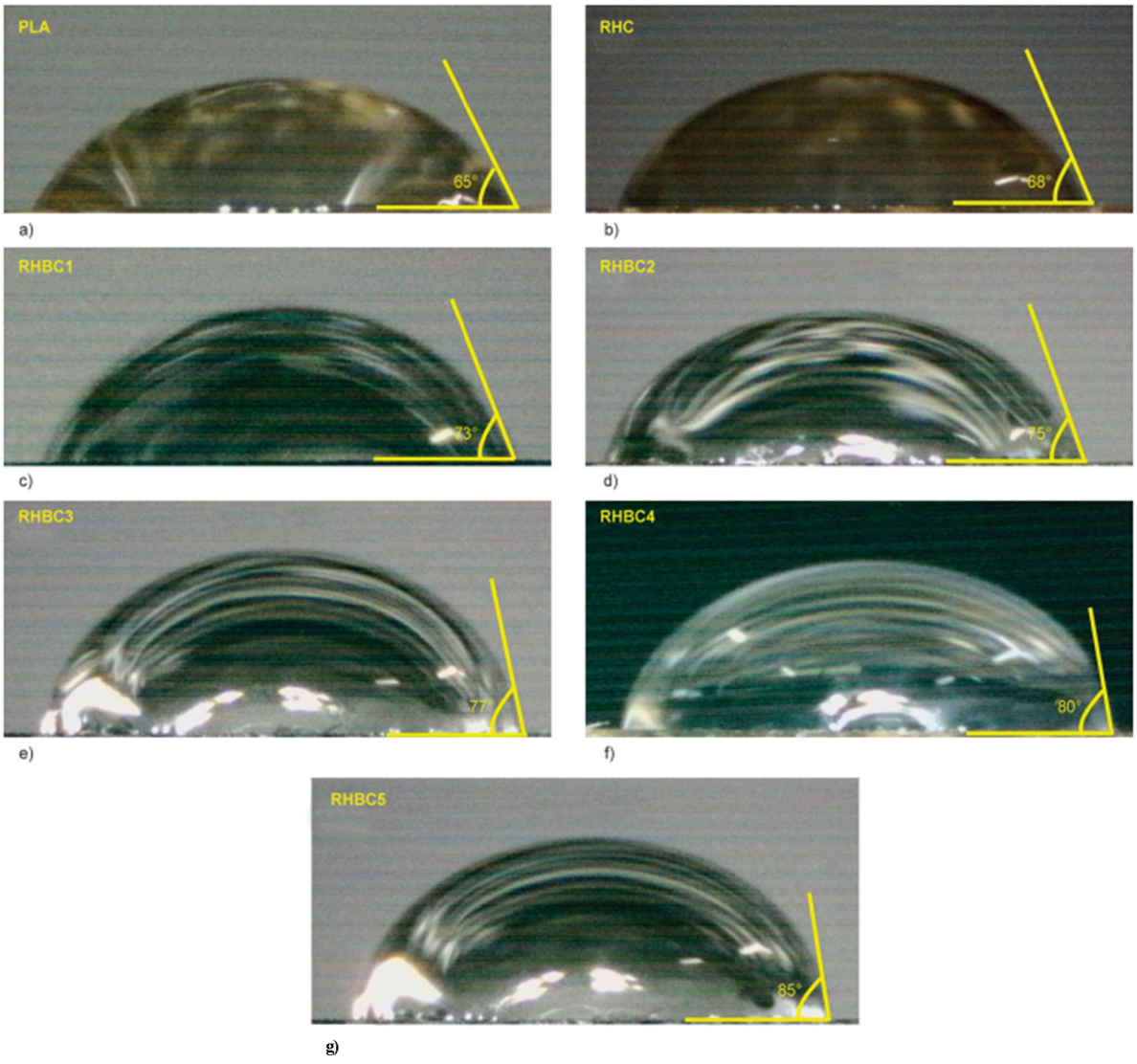


Figure 19. Contact angle results for all samples: a) PLA; b) BHC; c) RHBC1; d) RHBC2; e) RHBC3; f) RHBC4; g) RHBC5 [116].

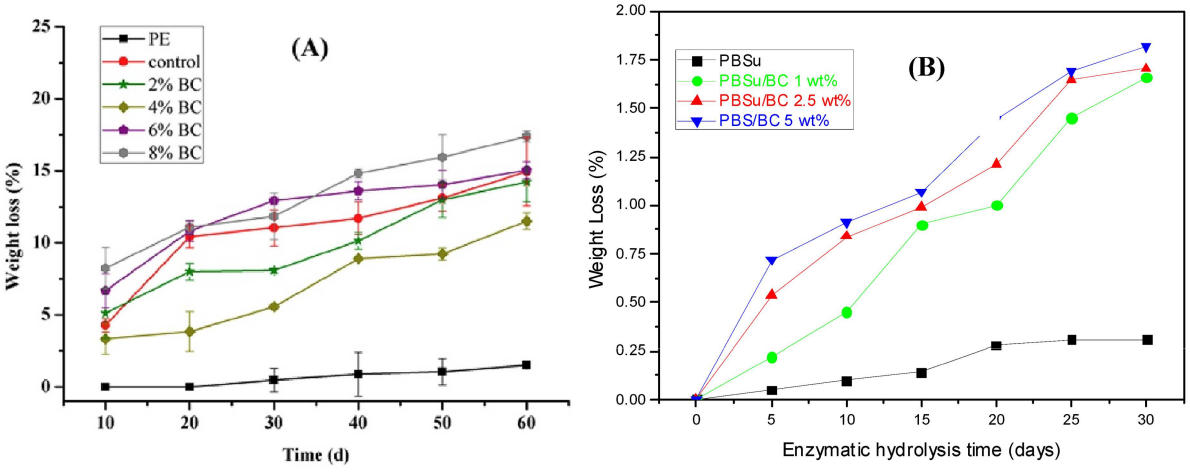


Figure 20. A) Weight loss vs. time [120]; B) Weight loss vs. enzymatic hydrolysis time [121].

composite (0.31% and 1.53%, respectively). The results indicated that higher pyrolysis temperatures reduced fungal decay by decreasing polysaccharide content. The study by Musiol et al. [123] investigated the abiotic degradation of biochar in demineralised water at 70 °C and observed that the presence of biochar did not significantly affect the overall degradation process but did improve surface erosion and slightly enhance thermal stability compared to the neat matrix.

9. Application areas

Interest in biochar-polymer composites is growing, as they offer unique properties that make them a long-lasting solution across many fields. Biochar, made from organic waste, usually has a high surface area, high porosity, and water adsorption capacity. These composites become versatile materials for adoption in many fields, as shown in Figure 21, and a detailed description is provided below.

9.1. Construction material

The biochar-polymer composite is suitable for the construction of eco-friendly insulation and building panels, as well as fire-resistant coatings [124]. The biochar will enhance the composite's heat absorption, and the polymer matrix will provide structural stability. This helps the construction industry leave a smaller carbon footprint by using waste biomass as a resource.

9.2. Biomedical applications

The biochar-polymer composites may be adopted in biomedical fields such as drug delivery systems, wound healing, and tissue engineering [125,126]. The large surface area may be able to hold drugs or bioactive molecules. Biochar-polymer composites can be used in drug-delivery patches or implants, allowing drugs to be released slowly over a longer period. These composites are biocompatible, which means they can be used in medical devices or as scaffolds for tissue regeneration. It can be used in wound dressings that accelerate healing by killing germs via biochar-mediated adsorption of pathogens.

9.3. CO_2 capture

Biochar has significant potential to store and capture CO_2, one of the critical greenhouse gases driving global warming. CO_2 can stick to biochar because it is porous. The polymer matrix makes the composite

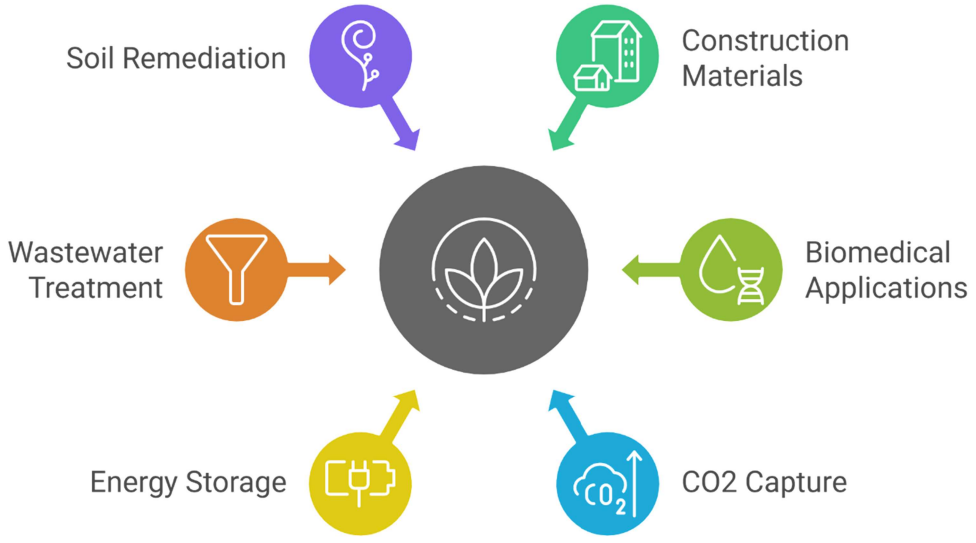


Figure 21. Application of biochar polymer composite.

more stable and flexible, thereby making it easier to capture CO_2 from the air or factories. These kinds of composites can be used in systems that filter air, scrub carbon, or even capture dirty air directly [127].

9.4. Energy storage

The biochar polymer composites have potential for applications in batteries and supercapacitors, which are the major systems for energy storage [128]. Energy storage uses biochar as the high-surface-area electrode material, while the polymer matrix contributes to its structural stability and conductivity. Their applications in supercapacitors and lithium-ion batteries aim to improve performance by increasing energy density, cycle life, and overall efficiency.

9.5. Wastewater treatment

When biochar and polymers are combined, they form a composite material for cleaning wastewater [129]. This composite can be used in filtration systems or as an adsorbent to remove heavy metals, organic pollutants, and other impurities from water. The biochar's porosity and functional groups allow it to adsorb a wide range of pollutants. The polymer matrix can be made to make the composite reusable. So a composite biochar-polymer could be useful in industrial effluent treatment plants, municipal water filtration systems, and even portable water purifiers.

9.6. Soil remediation

In agriculture, biochar-polymer composites may be adopted to improve soil by enhancing its ability to retain nutrients, water, and structure. The biochar component helps increase the soil's nutrient- and water-retention capacity, while the polymer matrix can aid controlled release of fertilisers or other amendments [130]. Application of contaminated soils may provide a means to remove impurities, improve fertility, and enhance plant growth. It also plays an important role in preventing soil erosion, thereby supporting sustainable agriculture.

10. Conclusion

Biochar-filled polymer composites are emerging as sustainable, high-performance materials, offering a range of mechanical, thermal, and environmental benefits. The continued research and development in this field are poised to make significant contributions across various industries, addressing both material performance and ecological sustainability. The key findings from the study are as follows:

- Biochar serves as a low-cost filler, offering significant savings compared to traditional bio fillers.
- Adding biochar as filler into polymer matrix improves mechanical properties such as tensile strength, stiffness, and impact resistance of polymer composites. These composites offer environmental benefits by utilising waste biomass, promoting carbon sequestration, and improving biodegradability.
- Incorporating up to 5–10 wt.% of biochar significantly improves the properties of the polymer composite, including thermal stability and crystallinity.
- Biochar-polymer composites hold promise for eco-friendly construction materials, low-carbon footprint and energy-efficient products, and solutions for climate change mitigation.

The review studies reported in the literature were conducted under different conditions, including variations in biochar feedstock, synthesis and processing methods, particle size, filler dispersion, elemental composition, and testing procedures. These differences influence the reported properties of biochar-polymer composites and make direct quantitative comparison between studies difficult. Therefore, the findings discussed in this review are considered as general trends rather than precise quantitative relationships.

11. Challenges and future perspectives

Biochar's porosity and amorphous nature are advantageous in many ways; they also pose challenges due to their tendency to absorb moisture and heat. As a result, biochar-filled polymer composites can exhibit reduced performance beyond a certain weight percentage, thereby affecting overall properties. Advanced data-driven techniques, such as machine learning, finite element analysis, and micromechanical modelling, are expected to play a pivotal role in optimising and predicting biochar content and polymer matrix interactions during composite refinement [131–133]. In addition to improving the physical properties of these composites, integrating biochar with biodegradable, eco-friendly polymers offers an exciting opportunity to advance sustainable technologies. Compared to microbiochar, nanobiochar has significantly greater potential due to its enhanced surface area, reactivity, and molecular-level interactions with polymer materials. However, synthesising nanobiochar poses greater challenges, as it requires precise control over particle size, surface functionalization, and uniform distribution. The challenges involved in fully degrading biochar-polymer composites are both complex and considerable. Unlike traditional plastics, the complete breakdown of these composites is slowed by several environmental, material, and handling factors. However, incorporating biochar into biodegradable polymers not only enhances their biodegradability but also improves other properties, such as strength, stability, and thermal performance.

Author contributions

CRediT: **Borhen Louhichi:** Conceptualization, Formal analysis, Methodology, Writing – original draft; **Abdullah A. Elfar:** Conceptualization, Formal analysis, Investigation, Writing – review & editing; **Santosh Kumar Sahu:** Conceptualization, Formal analysis, Visualization, Writing – review & editing; **Nadir Ayrilmis:** Formal analysis, Visualization, Writing – review & editing; **It Ee Lee:** Conceptualization, Formal analysis, Visualization, Writing – review & editing; **Gwo Chin Chung:** Formal analysis, Visualization, Writing – review & editing.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (Grant number IMSIU-DDRSP2603).

ORCID

Santosh Kumar Sahu 0000-0002-6729-0415

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

References

[1] Paneru B, Paneru B, Alexander V, et al. Study of solid waste generation and techno-economic analysis of pyrolysis of HDPE waste plastics in an academic institution in Nepal. Int J Sustainable Eng. 2024;17(1):945–964. doi: 10.1080/19397038.2024.2416218

[2] Pęśko M, Masek A. Plant-based biofillers for polymer composites: characterization, surface modification, and application potential. Polymers. 2025;17(17):2286. doi: 10.3390/polym17172286

[3] Latos-Brozio M, Rułka K, Masek A. Review of bio-fillers dedicated to polymer compositions. Chem Biodivers. 2025;22:e202500406. doi: 10.1002/cbdv.202500406

[4] Mirzaei N, Hajinezhad A, Yousefi H, et al. Biochar at the core of nature-based carbon management: a comparative review bridging environmental sustainability and economic feasibility. Energy Sci Eng. 2025;14(1):611–624.

[5] Visser ED, Seroka NS, Khotseng L. Recent advances in biochar: synthesis techniques, properties, applications, and hydrogen production. Processes. 2024;12(6):1111. doi: 10.3390/pr12061111

[6] Liu X, Lin J, Zhao Z, et al. Advances in functional applications of biomass-derived carbon composites for phase change materials. Microstructures. 2025;5(2):2025039. doi: 10.20517/microstructures.2024.109
[7] Gorrazzi SA, Massazza D, Pedetta A, et al. Biochar as a substitute for graphite in microbial electrochemical technologies. RSC Sustain. 2023;1(5):1200–1210. doi: 10.1039/D3SU00041A
[8] Kwapinski W, Byrne CMP, Kryachko E, et al. Biochar from biomass and waste. Waste Biomass Valorization. 2010;1(2):177–189. doi: 10.1007/s12649-010-9024-8
[9] Bartoli M, Arrigo R, Malucelli G, et al. Recent advances in biochar polymer composites. Polymers. 2022;14(12):2506. doi: 10.3390/polym14122506
[10] Singh B, Raven MD. X-ray diffraction analysis of biochar In: Biochar: A Guide to Analytical Methods. 1st ed. Collingwood, Victoria, Australia: CSIRO Press; 2017. p. 245.
[11] Chia CH, Downie A, Munroe P. Characteristics of biochar: physical and structural properties In: Biochar for environmental management. London, England, United Kingdom: Routledge; 2015. pp. 89–109.
[12] Karunanayake L, Etampawala T, de Silva DJ, et al. Role and potential of biochar as a sustainable alternative reinforcing filler to carbon black in rubber composites. Biochar. 2025;7(1):1–27. doi: 10.1007/s42773-025-00429-3
[13] Elsevier. Scopus. Elsevie. 2025. Retrieved from: https://www.scopus.com/pages/home?display=basic&zone=header&origin=sbrowse#basic
[14] Vidakis N, Kalderis D, Petousis M, et al. Biochar filler in MEX and VPP additive manufacturing: characterization and reinforcement effects in polylactic acid and standard grade resin matrices. Biochar. 2023;5(1):39. doi: 10.1007/s42773-023-00238-6
[15] Guo H, Qin X, Cheng S, et al. Production of high-quality pyrolysis product by microwave–assisted catalytic pyrolysis of wood waste and application of biochar. Arabian J Chem. 2023;16(8):104961. doi: 10.1016/j.arabjc.2023.104961
[16] Sharma T, Ratner A. Analysis and characterization of metallic nodules on biochar from single-stage downdraft gasification. Processes. 2021;9(3):533. doi: 10.3390/pr9030533
[17] Varkolu M, Gundekari S, Omvesh, et al. Recent advances in biochar production, characterization, and environmental applications. Catalysts. 2025;15(3):243. doi: 10.3390/catal15030243
[18] Nanda S, Dalai AK, Berruti F, et al. Biochar as an exceptional bioresource for energy, agronomy, carbon sequestration, activated carbon and specialty materials. Waste Biomass Valorization. 2016;7(2):201–235. doi: 10.1007/s12649-015-9459-z
[19] Dayoub EB, Tóth Z, Soós G, et al. Chemical and physical properties of selected biochar types and a few application methods in agriculture. Agronomy. 2024;14(11):2540. doi: 10.3390/agronomy14112540
[20] Ismail IS, Othman MFH, Rashidi NA, et al. Recent progress on production technologies of food waste–based biochar and its fabrication method as electrode materials in energy storage application. Biomass Convers Biorefin. 2023;13(16):14341–14357. doi: 10.1007/s13399-023-03763-3
[21] Khan S, Irshad S, Mehmood K, et al. Biochar production and characteristics, its impacts on soil health, crop production, and yield enhancement: a review. Plants. 2024;13(2):166. doi: 10.3390/plants13020166
[22] Li S, Chan CY, Sharbatmaleki M, et al. Engineered biochar production and its potential benefits in a closed-loop water-reuse agriculture system. Water. 2020;12(10):2847. doi: 10.3390/w12102847
[23] Talwar P, Agudelo MA, Nanda S. Pyrolysis process, reactors, products, and applications: a review. Energies. 2025;18(11):2979. doi: 10.3390/en18112979
[24] Pritam K, Palla S, Puppala H, et al. Bibliometric analysis of research progress in microwave-assisted pyrolysis of biomass during 1979–2023. J Anal Appl Pyrolysis. 2024;177:106331. doi: 10.1016/j.jaap.2023.106331
[25] Liu L, Deng G, Shi X. Adsorption characteristics and mechanism of p-nitrophenol by pine sawdust biochar samples produced at different pyrolysis temperatures. Sci Rep. 2020;10(1):5149. doi: 10.1038/s41598-020-62059-y
[26] Singh SV, Chaturvedi S, Dhyani VC, et al. Pyrolysis temperature influences the characteristics of rice straw and husk biochar and sorption/desorption behaviour of their biourea composite. Bioresour Technol. 2020;314:123674. doi: 10.1016/j.biortech.2020.123674
[27] Aktas K, Liu H, Eskicioglu C. Treatment of aqueous phase from hydrothermal liquefaction of municipal sludge by adsorption: comparison of biochar, hydrochar, and granular activated carbon. J Environ Manage. 2024;356:120619. doi: 10.1016/j.jenvman.2024.120619
[28] Toor SS, Rosendahl L, Rudolf A. Hydrothermal liquefaction of biomass: a review of subcritical water technologies. Energy. 2011;36(5):2328–2342. doi: 10.1016/j.energy.2011.03.013
[29] Sivaranjanee R, Kumar PS, Rangasamy G. Advancements and environmental impact of hydrothermal processing of algal biomass. Biomass Convers Biorefin. 2025;15(9):13271–13301. doi: 10.1007/s13399-024-06074-3
[30] Shahzad HMA, Asim Z, Khan SJ, et al. Thermochemical and biochemical conversion of agricultural waste for bioenergy production: an updated review. Discover Environ. 2024;2(1):134. doi: 10.1007/s44274-024-00171-w
[31] Fryda L, Visser R. Biochar for soil improvement: evaluation of biochar from gasification and slow pyrolysis. Agriculture. 2015;5(4):1076–1115. doi: 10.3390/agriculture5041076
[32] Rasaq WA, Okpala COR, Igwegbe CA, et al. Navigating pyrolysis implementation—a tutorial review on consideration factors and thermochemical operating methods for biomass conversion. Materials. 2024;17(3):725. doi: 10.3390/ma17030725
[33] Chettri D, Boro D, Chirania M, et al. Integrating biochar production in biorefineries: towards a sustainable future and circular economy. Biofuels Bioprod Biorefin. 2024;18(6):2156–2176. doi: 10.1002/bbb.2679

[34] Rajput V, Saini I, Parmar S, et al. Biochar production methods and their transformative potential for environmental remediation. Discover Appl Sci. 2024;6(8):408. doi: 10.1007/s42452-024-06125-4
[35] Panwar NL, Divyangkumar N. An overview of recent advancements in biomass torrefaction. Environ Dev Sustain. 2024;1–48. doi: 10.1007/s10668-024-05623-0
[36] Zhu J, Guo Y, Chen N, et al. A review of the efficient and thermal utilization of biomass waste. Sustainability (Basel). 2024;16(21):9506. doi: 10.3390/su16219506
[37] Zhang M, Yang K, Wang C, et al. Oxidative torrefaction of biomass in a fluidized bed for preparation of the biochar with high grindability. Fuel. 2026;407:137403. doi: 10.1016/j.fuel.2025.137403
[38] Romyen P, Pianroj Y, Punvichai T, et al. Utilization of used bleaching clay in pellet fuel production with torrefied oil palm fronds. BioResources. 2023;18(4):6986–7002. doi: 10.15376/biores.18.4.6986-7002
[39] Shahbaz M, AlNouss A, Ghiat I, et al. A comprehensive review of biomass based thermochemical conversion technologies integrated with CO2 capture and utilisation within BECCS networks. Resour Conserv Recycl. 2021;173:105734. doi: 10.1016/j.resconrec.2021.105734
[40] Ghosh A, Haverly MR. Solvent liquefaction In: Thermochemical processing of biomass: conversion into fuels, chemicals and power. New Jersey, USA: John Wiley & Sons; 2019. pp. 257–306. doi: 10.1002/9781119417637.ch8
[41] Azwar E, Mahari WAW, Liew RK, et al. Remediation and recovery of kariba weed as emerging contaminant in freshwater and shellfish aquaculture system via solvothermal liquefaction. Sci Total Environ. 2023;876:162673. doi: 10.1016/j.scitotenv.2023.162673
[42] Sajjadi B, Chen WY, Egiebor NO. A comprehensive review on physical activation of biochar for energy and environmental applications. Rev Chem Eng. 2019;35(6):735–776. doi: 10.1515/revce-2017-0113
[43] Panwar NL, Pawar A. Influence of activation conditions on the physicochemical properties of activated biochar: a review. Biomass Convers Biorefin. 2022;12(3):925–947. doi: 10.1007/s13399-020-00870-3
[44] Sakhiya AK, Anand A, Kaushal P. Production, activation, and applications of biochar in recent times. Biochar. 2020;2(3):253–285. doi: 10.1007/s42773-020-00047-1
[45] Huo M, Huang C, Guo A, et al. From waste to functional materials: advances in porous material synthesis and applications derived from coal gasification slag. RSC Adv. 2025;15(24):18893–18909. doi: 10.1039/D5RA02243F
[46] Yi B, Guo F, Wei Q, et al. Functionalized biochar: mechanisms of oxygen-containing functional groups in water pollutant remediation. ACS ES&T Water. 2025;5(10):5764–5784. doi: 10.1021/acsestwater.5c00416
[47] Chakraborty R, Vilya K, Pradhan M, et al. Recent advancement of biomass-derived porous carbon based materials for energy and environmental remediation applications. J Mater Chem A. 2022;10(13):6965–7005. doi: 10.1039/D1TA10269A
[48] Sahu SK, Boggarapu V, Sreekanth PR. Improvements in the mechanical and thermal characteristics of polymer matrix composites reinforced with various nanofillers: a brief review. Mater Today Proc. 2024;113:1–8. doi: 10.1016/j.matpr.2023.07.032
[49] Akhil D, Lakshmi D, Kartik A, et al. Production, characterization, activation and environmental applications of engineered biochar: a review. Environ Chem Lett. 2021;19(3):2261–2297. doi: 10.1007/s10311-020-01167-7
[50] Alqudaihi K, Alrwaily B, Alzawad B, et al. Advances in biomass-derived carbon materials: production, functionalization, and applications for contaminant removal. Chem Asian J. 2025;20(17):e00445. doi: 10.1002/asia.202500445
[51] Guan ZL, Wang YD, Wang Z, et al. The synthesis, characteristics, and application of hierarchical porous materials in carbon dioxide reduction reactions. Catalysts. 2024;14(12):936. doi: 10.3390/catal14120936
[52] Sun K, Huang Q, Chi Y, et al. Effect of ZnCl2-activated biochar on catalytic pyrolysis of mixed waste plastics for producing aromatic-enriched oil. Waste Manage (Oxford). 2018;81:128–137. doi: 10.1016/j.wasman.2018.09.054
[53] Zeng S, Kan E. FeCl3-activated biochar catalyst for heterogeneous fenton oxidation of antibiotic sulfamethoxazole in water. Chemosphere. 2022;306:135554. doi: 10.1016/j.chemosphere.2022.135554
[54] Wu G, Xie P, Yang H, et al. A review of thermoplastic polymer foams for functional applications. J Mater Sci. 2021;56(20):11579–11604. doi: 10.1007/s10853-021-06034-6
[55] Badgayan ND, Sahu SK, Samanta S, et al. Assessment of bulk mechanical properties of HDPE hybrid composite filled with 1D/2D nanofiller system. Mater Sci Forum. 2018;917:12–16. doi: 10.4028/www.scientific.net/MSF.917.12
[56] Sanaka R, Sahu SK. Experimental investigation into mechanical, thermal, and shape memory behavior of thermoresponsive PU/MXene shape memory polymer nanocomposite. Heliyon. 2024;10(2):e24014. doi: 10.1016/j.heliyon.2024.e24014
[57] Islam S, Hasan MB, Karim FE, et al. Thermoset and thermoplastic polymer composites reinforced with flax fiber: properties and application—Aa review. SPE Polymers. 2025;6(1):e10172. doi: 10.1002/pls2.10173
[58] Sundarasetty H, Louhichi B, Alrasheedi NH, et al. Machine learning guided process optimization and sustainable valorization of coconut biochar filled PLA biocomposites. Sci Rep. 2025;15(1):34647. doi: 10.1038/s41598-025-19791-0
[59] Guan R, Chen H, Zhao J, et al. Microcellular foaming of plasticized thin PC sheet: II. Mechanical properties. Polym-Plast Technol Eng. 2012;51(5):526–532. doi: 10.1080/03602559.2012.654576
[60] Sahu SK, Sreekanth PR. Evaluation of tensile properties of spherical shaped SiC inclusions inside recycled HDPE matrix using FEM based representative volume element approach. Heliyon. 2023;9(3):e14034. doi: 10.1016/j.heliyon.2023.e14034

[61] Ashby MF. Materials and the environment: eco-informed material choice. Oxford, England, United Kingdom: Elsevier; 2012.
[62] Prasad MB, Louhichi B, Sahu SK. Hybrid taguchi and machine learning framework for optimizing and predicting mechanical properties of Polyurethane/Nanodiamond nanocomposites. Comput Model Eng Sci. 2025;145(1):483–519. doi: 10.32604/cmes.2025.069395
[63] Saba N, Alothman OY, Almutairi Z, et al. Date palm reinforced epoxy composites: tensile, impact and morphological properties. J Mater Res Technol. 2019;8(5):3959–3969. doi: 10.1016/j.jmrt.2019.07.004
[64] Farahani HZ, Farahani A, Fakharian P, et al. Experimental study on mechanical properties and durability of polymer silica fume concrete with vinyl ester resin. Materials. 2023;16(2):757. doi: 10.3390/ma16020757
[65] Shahroze RM, Ishak MR, Salit MS, et al. Effect of organo-modified nanoclay on the mechanical properties of sugar palm fiber-reinforced polyester composites. BioResources. 2018;13(4):7430-7444. doi: 10.15376/biores.13.4.7430-7444
[66] Dixit D, Pal R, Kapoor G, et al. Lightweight composite materials processing In: Lightweight ballistic composites. Cambridge, England, United Kingdom: Woodhead Publishing; 2016. pp. 157–216. doi: 10.1016/B978-0-08-100406-7.00006-4
[67] Kumar R, Kumari S, Rai B, et al. Effect of nano-cellulosic fiber on mechanical and barrier properties of polylactic acid (PLA) Green nanocomposite film. Mater Res Express. 2019;6(12):125108. doi: 10.1088/2053-1591/ab5755
[68] Biglari N, Zare EN. Conjugated polymer-based composite scaffolds for tissue engineering and regenerative Medicine. Alexandria Eng J. 2024;87:277–299. doi: 10.1016/j.aej.2023.12.041
[69] 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. doi: 10.1016/j.jcomc.2021.100221
[70] Thines KR, Abdullah EC, Mubarak NM, et al. In-situ polymerization of magnetic biochar–polypyrrole composite: a novel application in supercapacitor. Biomass Bioenergy. 2017;98:95–111. doi: 10.1016/j.biombioe.2017.01.019
[71] Haneef INHM, Buys YF, Shaffiar NM, et al. Miscibility, mechanical, and thermal properties of polylactic acid/polypropylene carbonate (PLA/PPC) blends prepared by melt-mixing method. Mater Today Proc. 2019;17:534–542. doi: 10.1016/j.matpr.2019.06.332
[72] Urquijo J, Guerrica-Echevarría G, Eguiazábal JI. Melt processed PLA/PCL blends: effect of processing method on phase structure, morphology, and mechanical properties. J Appl Polym Sci. 2015;132(41). doi: 10.1002/app.42641
[73] Vidakis N, Petousis M, Velidakis E, et al. On the strain rate sensitivity of fused filament fabrication (Fff) processed pla, abs, petg, pa6, and pp thermoplastic polymers. Polymers. 2020;12(12):2924. doi: 10.3390/polym12122924
[74] Baniasadi H, Äkräs L, Paganelli Z, et al. Can biochar fillers advance the properties of composites? Early-stage characterization and life cycle assessment of novel polyamide/biochar biocomposites. Environ Res. 2025;275:121446. doi: 10.1016/j.envres.2025.121446
[75] Das O, Mensah RA, Balasubramanian KBN, et al. Functionalised biochar in biocomposites: the effect of fire retardants, bioplastics and processing methods. Composites Part C: Open Access. 2023;11:100368. doi: 10.1016/j.jcomc.2023.100368
[76] Rajendran S, Palani G, Veerasimman A, et al. Enhancing carbon fiber composites with fish scale biochar for superior strength and environmental sustainability. Clean Eng Technol. 2025;27:100996. doi: 10.1016/j.clet.2025.100996
[77] Wallace CA, Afzal MT, Saha GC. Effect of feedstock and microwave pyrolysis temperature on physio-chemical and nano-scale mechanical properties of biochar. Bioresour Bioprocess. 2019;6(1):1–11. doi: 10.1186/s40643-019-0268-2
[78] Das C, Tamrakar S, Kiziltas A, et al. Incorporation of biochar to improve mechanical, thermal and electrical properties of polymer composites. Polymers. 2021;13(16):2663. doi: 10.3390/polym13162663
[79] Velmurugan G, Chohan JS, Manikandan T, et al. Evaluation of mechanical, thermal, and flammability properties in biochar-infused polymer composites from bael fruit and cashew shells: a comparative study. Biomass Convers Biorefin. 2025;15(8):12457–12473. doi: 10.1007/s13399-024-06020-3
[80] Nizamuddin S, Hossain N, Qureshi SS, et al. Experimental investigation of physicochemical, thermal, mechanical and rheological properties of polylactide/rice straw hydrochar composite. J Environ Chem Eng. 2021;9(5):106011. doi: 10.1016/j.jece.2021.106011
[81] 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. 2017;139(1):012202. doi: 10.1115/1.4033131
[82] Ahmed K, Hasan M, Haider J. Electrical and mechanical properties of sugarcane bagasse pyrolyzed biochar reinforced polyvinyl alcohol biocomposite films. J Compos Sci. 2021;5(9):249. doi: 10.3390/jcs5090249
[83] Hernandez-Charpak YD, Trabold TA, Lewis CL, et al. Biochar-filled plastics: effect of feedstock on thermal and mechanical properties. Biomass Convers Biorefin. 2022;12(10):4349–4360. doi: 10.1007/s13399-022-02340-4
[84] Zhang Q, Yi W, Li Z, et al. Mechanical properties of rice husk biochar reinforced high density polyethylene composites. Polymers. 2018;10(3):286. doi: 10.3390/polym10030286
[85] Gokulraj S, Saravanan KG, Vijayakumar K, et al. Thermo-mechanical and mechanical performance of interlaced glass fiber epoxy hybrid composites reinforced with almond biochar biofiller. J Polym Res. 2025;32(5):162. doi: 10.1007/s10965-025-04400-5

[86] Hemlata. Mechanical, thermal, morphological, and rheological behavior of recycled polypropylene/pine needle biochar composite: an innovative approach towards circular economy. Polym Compos (Woodhead Publ). 2025;46:8490–8507. doi: 10.1002/pc.29505
[87] Lazzari LK, Neves RM, Kerche EF, et al. Biochar from poultry litter as reinforcement used in epoxy-based composites: mechanical and dynamic mechanical properties. Polym Bull. 2024;81(10):8823–8838. doi: 10.1007/s00289-023-05128-2
[88] Vidakis N, Petousis M, Kalderis D, et al. Reinforced HDPE with optimized biochar content for material extrusion additive manufacturing: morphological, rheological, electrical, and thermomechanical insights. Biochar. 2024;6(1):37. doi: 10.1007/s42773-024-00314-5
[89] Rajendran S, Palani G, Arunprasath K, et al. Eco-friendly sugarcane biochar filler for enhanced mechanical properties in S-glass/polyester hybrid composites. Clean Eng Technol. 2024;20:100759. doi: 10.1016/j.clet.2024.100759
[90] Mozrall AM, Hernandez-Charpak YD, Trabold TA, et al. Effect of biochar content and particle size on mechanical properties of biochar-bioplastic composites. Sustain Chem Pharm. 2023;35:101223. doi: 10.1016/j.scp.2023.101223
[91] Zhang Q, Xu H, Lu W, et al. Properties evaluation of biochar/high-density polyethylene composites: emphasizing the porous structure of biochar by activation. Sci Total Environ. 2020;737:139770. doi: 10.1016/j.scitotenv.2020.139770
[92] Behazin E, Misra M, Mohanty AK. Compatibilization of toughened polypropylene/biocarbon biocomposites: a full factorial design optimization of mechanical properties. Polym Test. 2017;61:364–372. doi: 10.1016/j.polymertesting.2017.05.031
[93] Das O, Bhattacharyya D, Hui D, et al. Mechanical and flammability characterisations of biochar/polypropylene biocomposites. Compos Part B Eng. 2016;106:120–128. doi: 10.1016/j.compositesb.2016.09.020
[94] Cappello M, Rossi D, Filippi S, et al. Wood residue-derived biochar as a low-cost, lubricating filler in poly (butylene succinate-co-adipate) biocomposites. Materials. 2023;16(2):570. doi: 10.3390/ma16020570
[95] Ramraji K, Arunkumar K, Senthilkumar R, et al. Mechanical and thermomechanical behaviour of agro-waste almond shell biochar filler interlaced chemically treated flax fibre vinyl ester composites. Biomass Convers Biorefin. 2024;14(24):32163–32176. doi: 10.1007/s13399-023-04840-3
[96] Sahu SK, Sreekanth PS, Praveen Kumar A, et al. Effect of pyrolysis derived coconut shell biochar on the mechanical, thermal, rheological, and water absorption properties of PLA composites. Int J Thermophys. 2025;46(11):1–22. doi: 10.1007/s10765-025-03637-y
[97] Pradeep R, Balavairavan B, Senthamaraikannan P, et al. Enhancement of the functional properties of vinyl ester composites using alkali-treated cocos nucifera shell biochar for sustainable applications. Polym Compos. 2025;47:1523–1537. doi: 10.1002/pc.70233
[98] Natrayan L, Chinta ND, Teja NB, et al. Evaluating mechanical, thermal, and water absorption properties of biocomposites with opuntia cladode fiber and palm flower biochar for industrial applications. Discover Appl Sci. 2024;6(2):30. doi: 10.1007/s42452-024-05660-4
[99] Uram K, Kurańska M, Andrzejewski J, et al. Rigid polyurethane foams modified with biochar. Materials. 2021;14(19):5616. doi: 10.3390/ma14195616
[100] Hoang P, Zhang Z, Ren J, et al. Versatile biochar for wood-plastic composites: improving mechanical properties, dimensional and thermal stability. Polym Compos. 2024;45(11):10349–10364. doi: 10.1002/pc.28477
[101] Venkatesh B, Gandhimathi G, Nagabhooshanam N, et al. Effect of submicron pore sized waste coffee emesis biochar on glass–epoxy composite thermal interface material. Biomass Convers Biorefin. 2025;15(3):4503–4512. doi: 10.1007/s13399-024-05558-6
[102] Papadopoulou K, Klonos PA, Kyritsis A, et al. Synthesis and characterization of PLA/biochar bio-composites containing different biochar types and content. Polymers. 2025;17(3):263. doi: 10.3390/polym17030263
[103] Dias JO, Conceição AO, Siqueira R, et al. Investigation of the thermal, physical, and microstructural properties of polymeric composites bio-reinforced with charcoal fines. Polymers. 2025;17(10):1370. doi: 10.3390/polym17101370
[104] Özgün Mİ., Erci V, Madenci E, et al. The effect of nano-biochar derived from olive waste on the thermal and mechanical properties of epoxy composites. Polymers. 2025;17(10):1337. doi: 10.3390/polym17101337
[105] Day R, Adhikari S, Peng Y. Properties of polylactic acid and biochar-based composites for environment-friendly plant containers. Clean Eng Technol. 2024;23:100850. doi: 10.1016/j.clet.2024.100850
[106] George J, Gaidukovs S, Bhattacharyya D. Pinewood biochar antistatic polymer composites: an investigation of electrical, mechanical, rheological and thermal properties. Int J Sustain Nanotechnol Mater. 2024;15(4):767–785. doi: 10.1080/19475411.2024.2408013
[107] Alghyamah AA, Elnour AY, Shaikh H, 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(4):101409. doi: 10.1016/j.jksus.2021.101409
[108] Mao J, Zhang K, Chen B. Linking hydrophobicity of biochar to the water repellency and water holding capacity of biochar-amended soil. Environ Pollut. 2019;253:779–789. doi: 10.1016/j.envpol.2019.07.051
[109] Badgayan ND, Sahu SK, PS RS. Investigation of wetting behavior of HDPE reinforced with nanoscopic 1D/2D filler system using contact angle goniometry. Mater Today Proc. 2020;26:331–334.

[110] Zhang R, Peng H, Li S, et al. Effect of biochar content and particle size on mechanical and water absorption properties of landscaping waste/polylactic acid composites. Ind Crops Prod. 2025;223:120163. doi: 10.1016/j.indcrop.2024.120163
[111] Muthukumarasamy S, Karthik K. Experimental analysis of biochar filler effects on the mechanical, water absorption, and viscoelastic properties of novel caryota fiber reinforced polymeric composites: the role of biodegradable reinforcements concentration. Polym Compos. 2025;46(S2):S119–S134. doi: 10.1002/pc.29830
[112] Srivastava S. Investigation of mechanical and water absorption characterization of chitosan and rice bran reinforced biochar-based composites. Iran Polym J. 2025;34(7):1029–1038. doi: 10.1007/s13726-024-01431-5
[113] Zhu S, Guo Y, Chen Y, et al. Low water absorption, high-strength polyamide 6 composites blended with sustainable bamboo-based biochar. Nanomaterials. 2020;10(7):1367. doi: 10.3390/nano10071367
[114] Srivastava S. Mechanical and water absorption characterization of rice husk and coconut coir reinforced biochar composites. Int J Polym Anal Charact. 2024;29(6):398–409. doi: 10.1080/1023666X.2024.2375254
[115] Gurusamy M, Thirumalaisamy R, Karuppusamy M, et al. Pistachio shell biochar as a reinforcing filler in short turkish hemp fiber composites: a path toward sustainable materials. J Polym Res. 2025;32(4):1–26. doi: 10.1007/s10965-025-04338-8
[116] Vengadesan E, Muralidharan S, Das D, et al. Rice husk and bamboo biochar-reinforced polylactic acid hybrid composites: evaluation of mechanical, thermal, and physical properties. Express Polym Lett. 2025;19(8):822–842. doi: 10.3144/expresspolymlett.2025.63
[117] Bellanthudawa BKA, Nawalage NMSK, Handapangoda HMAK, et al. A perspective on biodegradable and non-biodegradable nanoparticles in industrial sectors: applications, challenges, and future prospects. Nanotechnol Environ Eng. 2023;8(4):975–1013. doi: 10.1007/s41204-023-00344-7
[118] Amalina F, Abd Razak AS, Krishnan S, et al. Biochar production techniques utilizing biomass waste-derived materials and environmental applications–A review. J Hazard Mater Adv. 2022;7:100134. doi: 10.1016/j.hazadv.2022.100134
[119] Kacprzak M, Kupich I, Jasinska A, et al. Bio-based waste substrates for degraded soil improvement—Advantages and challenges in european context. Energies. 2022;15(1):385. doi: 10.3390/en15010385
[120] She D, Dong J, Zhang J, et al. Development of black and biodegradable biochar/gutta percha composite films with high stretchability and barrier properties. Compos Sci Technol. 2019;175:1–5. doi: 10.1016/j.compscitech.2019.03.007
[121] Papadopoulou K, Klonos PA, Kyritsis A, et al. Synthesis and study of fully biodegradable composites based on poly (butylene succinate) and biochar. Polymers. 2023;15(4):1049. doi: 10.3390/polym15041049
[122] Wang X, Sotoudehniakarani F, Yu Z, et al. Evaluation of corrugated cardboard biochar as reinforcing fiber on properties, biodegradability and weatherability of wood-plastic composites. Polym Degrad Stab. 2019;168:108955. doi: 10.1016/j.polymdegradstab.2019.108955
[123] Musioł M, Rydz J, Janeczek H, et al. (Bio) degradable biochar composites–studies on degradation and electrostatic properties. Mater Sci Eng B. 2022;275:115515. doi: 10.1016/j.mseb.2021.115515
[124] Kolya H, Kang CW. Eco-friendly polymer nanocomposite coatings for next-generation fire retardants for building materials. Polymers. 2024;16(14):2045. doi: 10.3390/polym16142045
[125] Gayathri V, Khan T, Gowtham M, et al. Functionalized conductive polymer composites for tissue engineering and biomedical applications-a mini review. Front Bioeng Biotechnol. 2025;13:1533944. doi: 10.3389/fbioe.2025.1533944
[126] Amirapu SL, Nelapati GS, Yalamanchili H, et al. HDPE based polymeric nanodiamond nanocomposite for total knee arthoplasty: a finite element based approach. Mater Today Proc. 2022;56:1622–1628. doi: 10.1016/j.matpr.2022.03.290
[127] Sun Y, Li X, Du B, et al. Customized copolymer composite coatings for carbon capture environments: corrosion inhibition and CO2 barrier synergy. J Colloid Interface Sci. 2025;692:137519. doi: 10.1016/j.jcis.2025.137519
[128] Li X, Hu P, Jiang J, et al. High-temperature polymer composite dielectrics: energy storage performance, large-scale preparation, and device design. Adv Mater. 2025;37(9):2411507. doi: 10.1002/adma.202411507
[129] Mokhtar A, Asli B, Abdelkrim S, et al. Polymer/Clay nanocomposites as advanced adsorbents for textile wastewater treatment. Minerals. 2024;14(12):1216. doi: 10.3390/min14121216
[130] Mandal P, Palai D, Goel P. Polymer composites for environmental solutions and remediation In: Hybrid composite materials: experimental and theoretical analysis. Singapore: Springer Nature Singapore; 2024. p. 67–90. doi: 10.1007/978-981-97-2104-7_3
[131] Sahu SK, Rama Sreekanth PS. Multiscale RVE modeling for assessing effective elastic modulus of HDPE based polymer matrix nanocomposite reinforced with nanodiamond. Int J Interact Des Manuf (IJIDeM). 2024;18(9):6371–6380. doi: 10.1007/s12008-022-01080-z
[132] Sanaka R, Sahu SK, Sreekanth PR, et al. A review of the current state of research and future prospectives on stimulus-responsive shape memory polymer composite and its blends. J Compos Sci. 2024;8(8):324. doi: 10.3390/jcs8080324
[133] Sahu SK, Badgayan ND, Samanta S, et al. Dynamic mechanical thermal analysis of high density polyethylene reinforced with nanodiamond, carbon nanotube and graphite nanoplatelet. Mater Sci Forum. 2018;917:27–31. doi: 10.4028/www.scientific.net/MSF.917.27