BIOCHAR SYNTHESIS AND APPLICATIONS: A REVIEW OF PRODUCTION ROUTES, PROPERTIES, AND SUSTAINABLE USES

Lepakshi Md. Bhakshu[1], V. Prabhakar Rao[2], C. Aruna[1] and Mohan Behara [3]

1, Department of Botany, Dr YSR Government Degree College, Vedurukuppam Chittoor (Dt) Andhra Pradesh, 517569 India

2, Department of Chemistry, Government Degree College, Puttur, Tirupati (Dt)

3, Department of Botany, Government Degree College, Pakala, Tirupati (Dt)

Abstract: Biochar is a carbon-rich, porous solid produced by thermochemical conversion of biomass under oxygen-limited conditions. Its production links biomass-residue management with carbon storage and the generation of functional materials for agriculture, environmental remediation and emerging industrial applications. This review summarizes major feedstocks and synthesis routes, including slow and fast pyrolysis, hydrothermal carbonization, gasification and post-production activation. The physicochemical properties of biochar—surface area, pore structure, aromaticity, ash content, surface functional groups, pH and cation-exchange capacity—are controlled strongly by feedstock and processing conditions. Applications discussed include soil amendment, nutrient management, carbon sequestration, water and wastewater treatment, soil remediation, composting, catalysis, construction materials and energy-storage electrodes. Particular attention is given to engineered and modified biochars, whose surface chemistry can be tailored for target pollutants. Although biochar offers substantial circular-bioeconomy and climate benefits, performance is application-specific and concerns including polycyclic aromatic hydrocarbons, trace metals, nutrient immobilization, feedstock contamination, energy demand and end-of-life management require careful assessment. Future research should prioritize standardized characterization, long-term field trials, life-cycle and techno-economic assessment, and application-specific quality standards.

Index Terms- biochar; biomass; pyrolysis; hydrothermal carbonization; activation; soil amendment; adsorption; wastewater treatment; carbon sequestration; circular bioeconomy.

I. INTRODUCTION

Biochar has developed from a traditional soil-amendment concept into a broad class of engineered carbonaceous materials. The International Biochar Initiative defines biochar as a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment, with uses that include soil improvement, resource-use efficiency, pollution remediation and greenhouse-gas mitigation [1]. Interest in biochar is driven by the need to manage agricultural and organic residues while producing materials with useful surface chemistry and relatively persistent carbon. Feedstocks include crop residues, forestry wastes, animal manures, food-processing residues and other biomass streams [2,3]. The resulting product is not a single material: its properties vary with feedstock composition, mineral fraction, reactor type, peak temperature, heating rate, residence time and post-treatment [2,4].

1.1 Global status of biochar production

The manufacturing of biochar is expanding rapidly across regions such as North America and Europe. Within Asia, India and China serve as the primary producers of biochar (Anon, 2021). Furthermore, innovative technological advancements are continuously being created to enhance production output. Below is an overview of global biochar generation alongside its projected compound annual growth rate (CAGR) spanning 2021 through 2031.

Figure 1. Global market portion of biochar

(Source: https://www.sciencedirect.com/topics/engineering/biochar-production)

Biochar therefore should be considered a platform material rather than a universal amendment. A biochar optimized for phosphorus retention or acidic-soil liming may not be optimal for adsorption of hydrophobic organic contaminants. Similarly, a highly activated biochar designed for water treatment may be unnecessarily expensive for routine agricultural use. Recent reviews emphasize that matching feedstock and synthesis conditions to the intended application is central to sustainable deployment [5–7, Fig. 2].

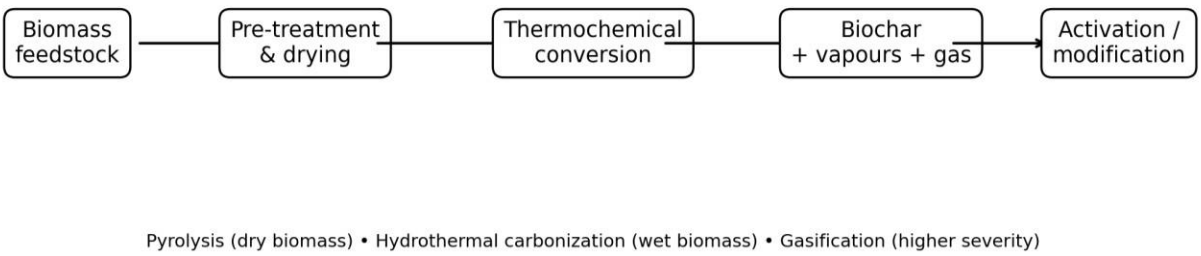

Figure 2. Schematic flow of general routes for biochar synthesis and upgrading.

1.2 Feed stocks and Biochar Synthesis

1.2.1 Feedstock selection

Feedstock selection determines the initial cellulose, hemicellulose, lignin, protein and mineral composition and therefore influences char yield, ash content, pH and surface chemistry. Woody biomass commonly produces relatively carbon-rich chars with low ash, whereas manures and some crop residues can generate chars richer in minerals and nutrients. Sludge and contaminated biomass require particular caution because inorganic contaminants and persistent organic compounds can become concentrated in the char [2,8]. Pre-treatment commonly includes sorting, size reduction and drying; washing may be used when soluble salts or undesirable contaminants need to be reduced.

1.2.2 Pyrolysis

Pyrolysis is the most widely discussed route for biochar production (Fig. 3). Biomass is heated in the absence or near-absence of oxygen, producing a solid char together with condensable vapours and permanent gases. Slow pyrolysis generally favors solid production through relatively long residence times, while fast pyrolysis favors liquids and shorter vapor residence times. Temperature is a major control variable: increasing temperature generally increases carbonization and aromaticity and can increase surface area and microporosity, while reducing many oxygen-containing functional groups [2,4,6]. The optimum temperature is application-dependent rather than universal.

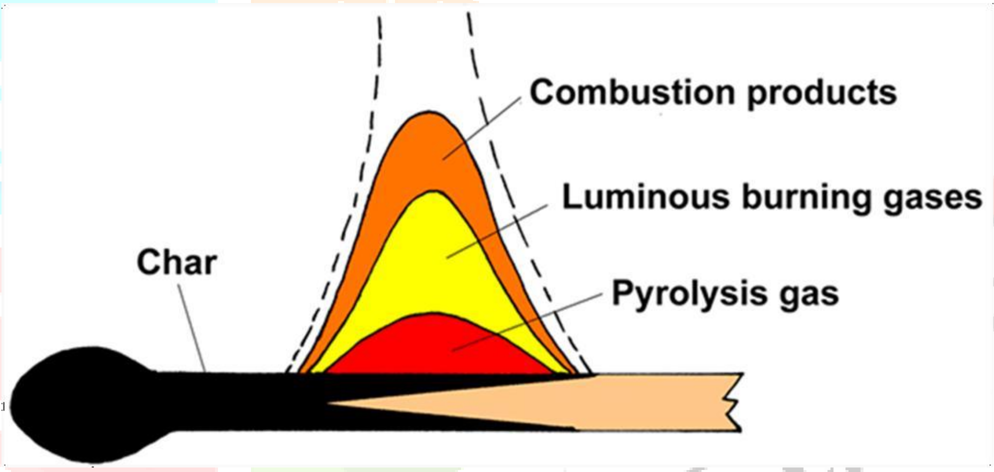

Figure 3. Pyrolysis of wood for biochar production

(Source: https://biochar-international.org/about-biochar/how-to-make-biochar/biochar-production-technologies/)

1.2.2 Hydrothermal carbonization and gasification

Hydrothermal carbonization (HTC) is particularly attractive for wet feedstocks because it can operate without energy-intensive drying. Water at elevated temperature and autogenous pressure promotes hydrolysis, dehydration and decarboxylation, producing hydrochar with properties that differ from conventional pyrolysis biochar. Gasification uses more severe thermal conditions and limited oxidant to maximize combustible gas formation; the resulting char fraction can be smaller and more mineral-rich. Pyrolysis, gasification and HTC are therefore complementary rather than interchangeable technologies [4,6,9].

1.2.3 Activation and Engineering of Biochar

Raw biochar can be modified physically, chemically or biologically to improve application-specific performance. Physical activation using steam or carbon dioxide develops pore volume at elevated temperature. Chemical activation may employ alkaline, acidic or oxidizing treatments to create or expose functional groups and increase accessible surface area. Other strategies include impregnation with iron, manganese, calcium, magnesium or other phases; loading with nanoparticles; ball milling; and composite formation [5,10]. Modification can improve adsorption of metals, nutrients, dyes, pharmaceuticals and other contaminants, but it can also increase cost, generate secondary waste streams or introduce new environmental risks. Consequently, activation should be justified by a measurable performance gain.

1.3 Characterization of Biochar

Characterization connects synthesis conditions to performance. Proximate analysis measures moisture, volatile matter, ash and fixed carbon, while ultimate analysis provides C, H, N, O and sometimes S content. Brunauer–Emmett–Teller (BET) analysis estimates surface area; pore-size analysis distinguishes micro-, meso- and macroporosity. FTIR identifies surface functional groups, XRD reveals crystalline mineral phases, SEM provides information on morphology, and Raman spectroscopy can assess graphitic/disordered carbon structures. Thermogravimetric analysis helps evaluate thermal stability, while solid-state NMR can provide detailed information on carbon structures [2,4].

Important application-specific measurements include pH, electrical conductivity, cation-exchange capacity, elemental ratios, nutrient concentrations, dissolved organic carbon and contaminant screening. Because biochar is heterogeneous, a small set of measurements may not adequately predict field behavior. Standardized reporting of feedstock, peak temperature, heating rate, residence time, reactor atmosphere and post-treatment is therefore essential [1,7 Fig. 4].

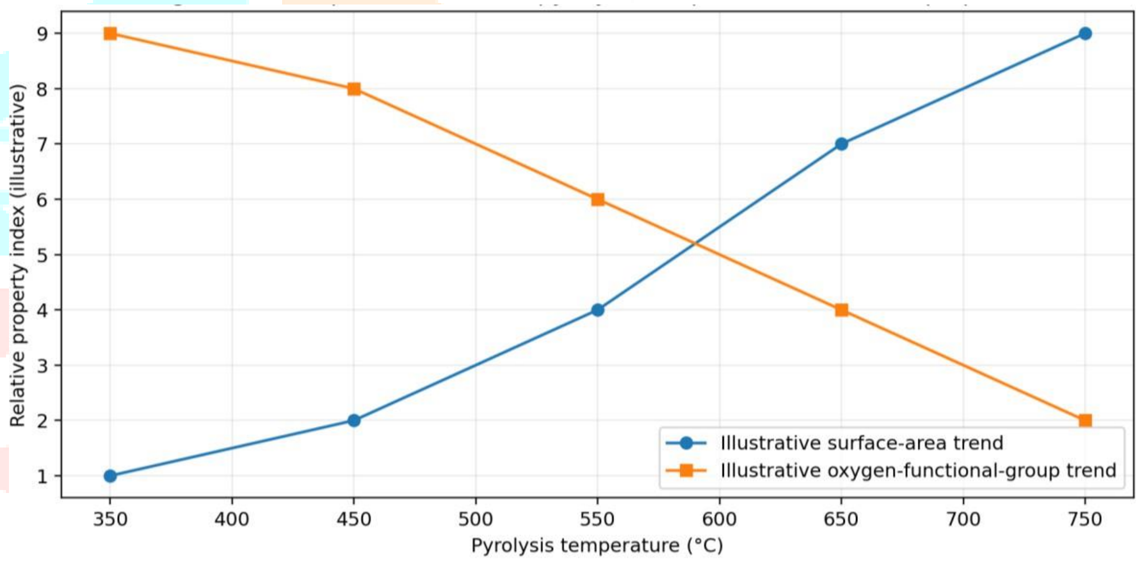

Figure 4. Conceptual relationship between pyrolysis temperature and selected biochar properties. Trends are illustrative, not universal.

II Major Applications

2.1 Agriculture and soil improvement

Biochar can alter soil physical and chemical properties by adding stable carbon, increasing water-holding capacity in some soils, modifying pH, retaining nutrients and providing habitat for microorganisms. Effects are strongly dependent on soil texture, climate, biochar properties and application rate. In nutrient-poor or acidic soils, nutrient-rich or alkaline biochars may be useful, whereas excessive application can increase salinity or alter nutrient availability. Meta-analyses indicate that biochar can increase soil organic-carbon stocks, but responses vary substantially among systems [11,12].

Biochar can also be combined with compost or fertilizers. Such combinations may reduce nutrient losses and provide a slower-release nutrient environment. Modified biochars have been investigated for targeted nutrient retention and for immobilization of toxic metals. However, agricultural recommendations should be based on multi-season field trials rather than short laboratory incubations alone [6,13]. Integrating biochar into nutrient-poor or degraded soils boosts crop yields by 10% to 30%. It enhances soil water retention by 10% to 25%, helping crops remain resilient against heatwaves and severe droughts.
https://www.drishtiias.com/daily-updates/daily-news-analysis/biochar-and-its-applications

2.2 Carbon sequestration and climate mitigation

Thermal conversion transfers part of biomass carbon into a relatively persistent aromatic solid. When sustainably produced and placed in stable reservoirs such as soil or long-lived materials, this can contribute to carbon removal. A 2024 global review and meta-analysis reported a significant increase in soil carbon sequestration following biochar application, while effects on total CO_2 flux and microbial respiration were less conclusive [11]. Life-cycle performance nevertheless depends on feedstock sourcing, transport, reactor energy requirements, co-products, application pathway and permanence. Biochar should therefore not automatically be treated as carbon-negative without system-level accounting.

2.3 Water and wastewater treatment

Biochar is increasingly studied as a low-cost adsorbent for water and wastewater. Pollutant removal can involve pore filling, electrostatic attraction, ion exchange, surface complexation, hydrogen bonding and π–π interactions. Target contaminants include heavy metals, dyes, pharmaceuticals, pesticides and nutrients such as phosphate, nitrate and ammonium [5,8,9]. High-temperature chars may provide greater hydrophobic surface area for some organic pollutants, while lower-temperature chars may retain more oxygen-containing functional groups useful for interactions with ionic contaminants [2,8].

Practical deployment requires attention to competing ions, pH, natural organic matter, hydraulic conditions, regeneration and disposal of spent biochar. Batch adsorption capacity alone does not establish suitability for a continuous treatment system. Recent work emphasizes integration with other treatment technologies and evaluation of regeneration and resource recovery [9,14; Fig. 5].

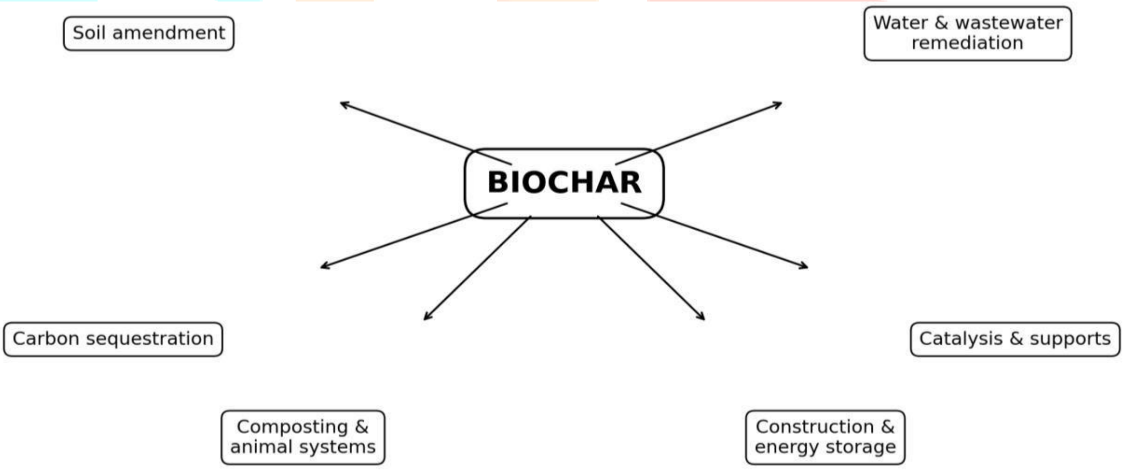

Figure 5. Major application domains of biochar

2.4 Soil and sediment remediation

Biochar can immobilize metals and metalloids in contaminated soils by adsorption, precipitation, ion exchange and complexation, thereby reducing their mobility and bioavailability. It can also sorb hydrophobic organic contaminants. Engineered biochars containing mineral or metal phases can further enhance remediation [5,10]. Yet immobilization is not equivalent to destruction: contaminants remain in the system and may be remobilized when environmental conditions change. Long-term monitoring is therefore necessary.

2.5 Composting, animal systems and anaerobic digestion

Biochar can be co-composted with organic residues, where its porous structure may influence moisture, aeration, microbial activity and nutrient retention. Reviews also describe applications in animal farming and anaerobic digestion, including potential effects on gas production and process stability [3]. These uses require application-specific evidence and careful consideration of feedstock safety, animal exposure pathways and contaminant transfer.

2.6 Catalysis, construction and energy storage

Because biochar can be converted into porous carbon and can host catalytically active phases, it has been investigated as a catalyst support, adsorbent and activator. Engineered biochar-based carbons are also being explored in electrodes for supercapacitors and batteries, where conductivity, surface area and heteroatom/mineral doping are important [4,6]. In construction, biochar has been incorporated into cementitious and composite materials for potential functional benefits and long-term carbon storage [3]. These emerging applications need stronger durability, safety, cost and end-of-life evidence before broad commercialization.

2.6 Environmental Safety and Limitations

Biochar is not inherently risk-free. Feedstocks contaminated with metals or industrial chemicals may produce chars with elevated contaminant concentrations. Thermal processing can also generate polycyclic aromatic hydrocarbons (PAHs), and their formation depends on feedstock and process conditions. A 2024 review emphasized the need to assess PAH formation and fate when biochar is used environmentally [15]. Potential risks also include excessive pH or salinity, nutrient immobilization, release of dissolved organic carbon, dust exposure, and unintended effects on soil or aquatic organisms.

Another limitation is variability. Two chars with the same nominal production temperature may behave differently because of feedstock chemistry and reactor design. Standardized certification and transparent product labeling are therefore important. The IBI standards provide a framework for reporting physicochemical properties and safety-related characteristics, while recognizing that suitability depends on local conditions and intended use [1].

2.6.1 Environmental Impact

- Air Pollution Mitigation: Processing agricultural stubble into biochar diverts part of India's 500+ million tons of annual crop waste from open burning, significantly curbing hazardous smoke and particulate pollution.
- Waste Diversion: Biochar systems convert organic municipal solid waste (over 50% of urban garbage in India) and sewage sludge, preventing landfill accumulation.
- Long-Term Carbon Sequestration: Biochar locks carbon into a stable soil matrix for centuries, with every ton sequestering roughly 2.5 to 3 tons of CO_2 equivalent.
- Water Remediation: Engineered pristine biochar serves as an effective filtration medium to remove toxic heavy metals (e.g., chromium, arsenic, lead) during wastewater treatment.

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2.6.2 Economic & Utility Value

- Carbon Credit Revenues: Certified biochar yields 2 to 2.8 tonnes of CO_2-equivalent credits per tonne, creating direct financial returns for rural farming communities and cooperatives.
- Energy & Fuel Generation: Pyrolysis yields 20–30M tonnes of syngas (capable of producing 8–13 TWh of electricity) and 24–40M tonnes of bio-oil (replacing 12–19M tonnes of imported fossil fuels and cutting emissions by >2%).
- Sustainable Construction Materials: Adding 2–5% biochar into concrete boosts mechanical strength, increases thermal resistance by 20%, and sequesters around 115 kg of CO_2 per cubic meter.

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III Future Perspectives

Future biochar research should move from proof-of-concept studies toward application-specific design and field validation. Priority areas include:

(i) standardized characterization and interlaboratory testing
(ii) long-term soil, water and material durability studies
(iii) life-cycle assessment and techno-economic analysis

(iv) safe use of difficult feedstocks such as sewage sludge and mixed wastes
(v) regeneration and end-of-life management of spent adsorbents
(vi) integration of biochar production with heat, power and chemical co-products and
(vii) development of decision-support tools that match feedstock, process and end use [6,7].

An important research direction is multifunctional biochar: one production system may generate a char for soil use while recovering heat and valuable chemicals from vapours and gases. Such integrated biorefineries could improve economic viability and reduce the environmental burden of stand-alone production. At the same time, claims of climate benefit should be supported by transparent carbon accounting and monitoring of permanence.

IV Conclusion

Biochar is a versatile carbonaceous material that can convert biomass residues into products with value in agriculture, environmental remediation, carbon management and emerging industrial applications. Its performance is governed by the interaction of feedstock, thermochemical conditions, post-treatment and application environment. Pyrolysis remains the dominant synthesis route, while HTC and gasification provide useful alternatives for particular feedstocks and objectives. Activation and functionalization can improve targeted performance but must be balanced against cost and environmental impacts. The strongest pathway toward sustainable biochar deployment is therefore not universal application, but deliberate design: select a safe feedstock, control the synthesis process, characterize the product, match it to a defined end use, and verify performance and environmental safety over the long term.

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