Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 02 (MAR-APR, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Biochar: From Waste Material to Soil Resource

* Mummasani Asritha[1], Gourav Sabharwal1, Kotresh D.J.[2], Lokeshwar Kesamreddy[1],
Gokul S[1], Mohammed Shahid S[3] and Lakavath Naveen[4]
[1]Dept. of Agronomy, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu
[2]Department of Agronomy, University of Agricultural Sciences, Bengaluru
[3]Department of Agronomy, IARI Academic Hub CICR -Nagpur
[4]Department of Agronomy, Acharya N G Ranga Agricultural University,
Bapatla, Andhra Pradesh
*Corresponding Author's email: mummasaniasritha@gmail.com

Biochar is a carbon-rich substance made through low-oxygen pyrolysis of biomass, which converts organic waste into a soil amendment that can be sustained over decades. As it is incorporated to soil, it tends to raise the fertility and moisture retention by improving porosity and nutrient storage capacity. Contaminants are also immobilized with the help of biochar, which blocks climatic effects by sequestering carbon and minimizing greenhouse gas emissions. Its efficacy is determined by the methods of application and production conditions, such as feedstock and pyrolysis parameters. This review discusses the definition of biochar, biochar production, physicochemical properties, the advantages of biochar to soil fertility and soil moisture, climate and remediation advantages, limitations, and future research directions.

Defining biochar: Carbon-rich amendment for soil health

Biochar can be defined as a solid with a high level of carbon that is obtained by heating biomass like wood, crop residues, and manure under a low-oxygen atmosphere (Khater et al., 2024). Practically, pyrolysis at approximately 300-700 °C produces biochar, a solid char product, and byproducts such as syngas and bio-oil (Khater et al., 2024; Premalatha et al., 2023). The end product is a biochar that is very porous with a large surface area and aromatic carbon structure, rendering it chemically stable and long-lived in soil (Premalatha et al., 2023). Biochar carbon can stay in the soil for hundreds of years because of the persistent aromatic carbon structure. Biochars are often alkaline, containing basic minerals such as Ca and Mg, and they retain left-over nutrient of the feedstock (Xu et al., 2017). These properties are the foundation of the usefulness of biochar as a soil amendment.

Production pathways: pyrolysis and feedstock selection

Biochar is commonly made through pyrolysis, thermal degradation of biomass in an oxygen-restricted environment. The process may be optimized to reach various outputs: slow pyrolysis with moderate temperature and slow heating will give the largest quantity of char, whereas rapid or high-temperature pyrolysis will give more energy-rich syngas or oil and less char (Al-Rumaihi et al., 2022; Khater et al., 2024). Overall, increasing the pyrolysis temperature reduces biochar yield: experiments indicate that char yield can decrease significantly with an increase in temperature between 400°C and 800°C (Khater et al., 2024)The temperature, heating rate, reactor design, and residence time are all important production parameters that affect biochar stability and the carbon content (Al-Rumaihi et al., 2022). The feedstock selection is also imperative. Biochar has been made out of wood, crop residues, manure, or even blended wastes such as. plastics with biomass (Li et al., 2020). The resulting biochar of each feedstock has different chemistry and ash content. Studies indicate that co-pyrolysis of varied wastes in optimal proportions would lead to higher overall char production and customization of properties (Al-Rumaihi et al., 2022). To conclude, the quality of biochar is determined by the raw material as well as the pyrolysis process.

Physico-chemical properties of biochar

There are numerous physical and chemical properties of biochars, which are based on their source and manufacturing. They are mostly very porous and possess a high specific surface area, which makes them have a high adsorption capacity for water and solutes (Premalatha et al., 2023). Biochars are usually chemically rich in total carbon, usually greater than 30 percent by weight, and alkalinity, with high pH, as a result of mineral ash content (Premalatha et al., 2023). For example, one survey of biochars indicated total carbon of about 33 to 82 percent and ash-based pH of about 8 to 13, based on the feedstock (Premalatha et al., 2023). Aromatic and aliphatic carbon structures and oxygenated functional groups, e.g., carboxyl, phenolic groups that can exchange cations, are present in biochar surfaces (Zhang et al., 2021). A combination of these properties makes biochar have a high cation exchange capacity (CEC) and bind nutrients or contaminants. Biochar's aromatic architecture, porosity, CEC, and ash content are beneficial in immobilizing heavy metals in a contaminated soil setting (Wei et al., 2025). Therefore, biochar is a good soil modifier due to its porous morphology and reactive chemistry.

Soil fertility enhancement and nutrient retention

Usually, biochar increases the fertility and the efficiency of nutrient use in soil. Its porous char matrix and surface charges enhance soil CEC, which serves to retain important nutrients, particularly NH_4^+,K^+ and micronutrients, and minimize leaching losses (Khater et al., 2024). The nutrient-rich biochar can serve as a slow-release fertilizer, as the nutrients on the surface of biochar can be made available to the plants slowly (Premalatha et al., 2023). The basic ash minerals of biochar, such as calcium and magnesium, can increase pH in acidic soils to enhance the availability of nutrients to plants (Premalatha et al., 2023). Soil benefits have been documented in numerous studies as a result of biochar addition, especially where the original soils were either low in nutrients or organic matter. A meta-analysis discovered that exchangeable potassium and total nutrient retention increased concomitantly with biochar additions (Hosseini et al., 2022). However, the advantages vary depending on the context. In case the soil is already fertile, or the biochar is applied excessively, biochar might occasionally inhibit nitrogen availability or alter the pH balance excessively (Bangwei et al., 2025). Overall, biochar, when used correctly, improves nutrient retention and soil fertility to support plant growth.

Moisture regulation and soil structure improvement

With biochar addition, the physical structure of soil and water relations can be significantly enhanced. Because of the porous character of biochar and its lightness, incorporating biochar enhances the overall porosity of the soil and reduces the bulk density (Premalatha et al., 2023). Increased porosity and aggregation enhance water infiltration and soil aeration. Research has demonstrated that biochar can enhance the soil porosity by tens of percent and decrease the bulk density by 10 to 30 percent with usual application rates (Hoque et al., 2025). As a result, biochar-enriched soils are capable of retaining an increased amount of plant-available water (Fig. 1). For example, the application of biochar has been reported to approximately increase the water-holding capacity of coarse (sandy) soils by a factor of two with 20 percent application levels (Hoque et al., 2025; Premalatha et al., 2023). Such modifications make soils resistant to drought stress and soil erosion. The response is dependent on the soil texture: biochar can increase the moisture retention capacity of sandy soils, and in heavy clay soils, the reaction is usually smaller or even negative (Premalatha et al., 2023). To conclude, biochar can improve the availability of moisture in soils and the physical stability by adjusting the distribution of pore sizes and aggregation.

Carbon sequestration and climate mitigation role

Biochar is useful in the mitigation of climate change by stabilizing carbon in the soil. Most of the biomass carbon is sequestered in refractory aromatic structures that are very slow to break down in soil during the thermal conversion process (Ali et al., 2025). Biochar has been estimated to be able to sequester approximately 0.7 to 1.8 gigatons of CO_2 each year in large-scale applications, making it a substantial carbon sink. In lab and field experiments, biochar amendment also tends to decrease soil nitrous oxide and methane emission, with average decreases reported to be from 20-40%, due to enhanced soil aeration and nutrient dynamics changes (Kaur et al., 2023). In such a way, the net climate benefit of biochar is twofold, with direct elimination of CO_2 from the carbon cycle and indirect reduction of the other greenhouse gas emissions (Hoque et al., 2025). Combined with the reality that biochar generation can displace the consumption of fossil fuels through bio-oil and syngas byproducts, biochar application in agriculture potentially can significantly reduce GHG emissions.

Remediation of contaminated soils and waste management

Biochar has been extensively explored as a means of soil remediation. It can be useful in immobilizing heavy metals and organic contaminants because biochar can adsorb Cd, Pb, As, and other toxic ions, and decrease their bioavailability in soil (Wei et al., 2025). The remediation processes are varied, such as physical adsorption to biochar surfaces, electrostatically binding to charged surfaces, precipitation of metals by biochar ash minerals, ion exchange, and complexation by functional groups. Also, biochar may also indirectly contribute to the process of remediation by enhancing the soil fertility and triggering microbial degredtion on the contaminants (Wei et al., 2025) Biomass residues on the waste management side can be useful as agricultural wastes, forestry by-products, manure, or even municipal organics, and some plastics can be used to make biochar, rather than being disposed of in landfills or burned. This waste-to-biochar strategy does not just divert waste from disposal, but also has an energy coproduct, syngas or bio-oil, and a soil conditioner (Khater et al., 2024). Altogether, biochar is an example of a circular-economy solution since it presents a possibility to convert waste products into a useful soil product that can rehabilitate polluted soils.

Limitations

There are significant drawbacks to the use of biochar, despite its promise. Biochar properties depend greatly on the feedstock and pyrolysis, which makes it difficult to regulate its properties (Hoque et al., 2025). There is no predictability in the effects of inconsistently produced biochars. Biochar made from contaminated feedstocks is an issue, as metals present in sewage sludge or industrial wastes might be concentrated in the char and may be subsequently leached into the soils. Excessive use of biochar may also interfere with soil processes. An example is that excessive amounts of biochar can lead to nitrogen immobilization or excessive alkalinity in the soil that could be detrimental to plant growth (Bangwei et al., 2025). There have even been studies that have cited adverse impacts on soil biota, in certain circumstances (Premalatha et al., 2023). Another challenge is the economic and logistical considerations of large-scale pyrolysis in the form of energy input and the required equipment (Ahmad et al., 2012). All these, combined, imply that attention to selecting feedstock, regulated production, and adequate dosing is necessary to prevent counterproductive outcomes.

Future perspectives in biochar applications

Biochar research is advancing at a fast rate to overcome its current obstacles. The development of advanced biochars and composites is one of the directions. For example, biochars with metal-organic frameworks or fertilizers can be used to enable slow release of nutrients and capture specific contaminants. Researchers are also exploring biochar designed for a particular soil, crop, or climate to maximize the benefits (Zhang et al., 2021). Future work is vital to incorporate long-term field testing in the most realistic agronomic system. This will validate laboratory findings and polish the regulations of its application (Ali et al., 2025). Also, the production of biochar can be combined with renewable energy generation or waste processing to capture pyrolysis gases and use them to produce heat or power, further enhancing sustainability and cost-effectiveness (Al-Rumaihi et al., 2022). With these advances, biochar will become an indispensable tool in sustainable agriculture and climate-conscious soil management.

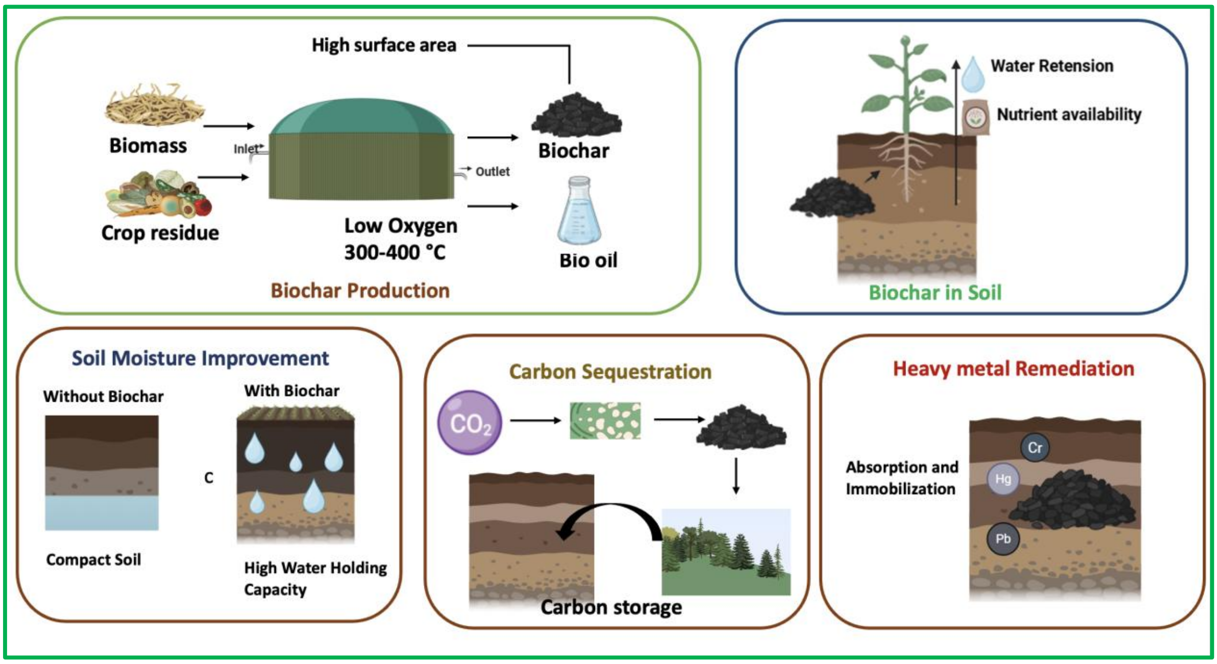

Fig.1: Biochar production and its applications

References

1. Ahmad, M., Lee, S. S., Dou, X., Mohan, D., Sung, J., Yang, J. E., & Yong, O. S. (2012). Effects of pyrolysis temperature on soybean stover- and peanut shell-derived biochar properties and TCE adsorption in water. Bioresource Technology, 118, 536–544. https://doi.org/10.1016/j.biortech.2012.05.042
2. Ali, A., Jabeen, N., Chachar, Z., Chachar, S., Ahmed, S., Ahmed, N., Laghari, A. A., Sahito, Z. A., Farruhbek, R., & Yang, Z. (2025). The role of biochar in enhancing soil health & interactions with rhizosphere properties and enzyme activities in organic fertilizer substitution. Frontiers in Plant Science, 16, 1595208. https://doi.org/10.3389/fpls.2025.1595208
3. Al-Rumaihi, A., Shahbaz, M., McKay, G., Mackey, H., & Al-Ansari, T. (2022). A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. Renewable and Sustainable Energy Reviews, 167, 112715. https://doi.org/10.1016/j.rser.2022.112715
4. Bangwei, Z., Liu, C., Li, Q., Ye, J., Lin, Y., Wang, Y., & Burton, D. L. (2025). Evaluating the effect of biochar rate and combination with fertilizer on the dynamics of soil nitrogen supply in tea plantation. Scientific Reports, 15, 3135. https://doi.org/10.1038/s41598-025-87942-4
5. Hoque, Md. M., Saha, B. K., Scopa, A., & Drosos, M. (2025). Biochar in Agriculture: A Review on Sources, Production, and Composites Related to Soil Fertility, Crop Productivity, and Environmental Sustainability. C, 11(3), 50. https://doi.org/10.3390/c11030050
6. Hosseini, S., Omidvar, N., Gallart, M., Kämper, W., Tahmasbian, I., Farrar, M. B., Singh, K., Zhou, G., Muqadass, B., Xu, C., Koech, R., Li, Y., Nguyen, T. T. N., & Zwieten, L. (2022). Combined effects of biochar and fertilizer applications on yield: A review and

meta-analysis. Science of the Total Environment, 808, 152073. https://doi.org/10.1016/j.scitotenv.2021.152073

7. Kaur, N., Kieffer, C., Ren, W., & Hui, D. (2023). How much is soil nitrous oxide emission reduced with biochar application? An evaluation of meta-analyses. GCB Bioenergy, 15(1), 24–37. https://doi.org/10.1111/gcbb.13003
8. Khater, E.-S., Bahnasawy, A., Hamouda, R., Sabahy, A., Abbas, W., & Morsy, O. M. (2024). Biochar production under different pyrolysis temperatures with different types of agricultural wastes. Scientific Reports, 14, 2625. https://doi.org/10.1038/s41598-024-52336-5
9. Li, X., Zhao, Y., Liu, Y., Liu, S., & Gong, J. (2020). Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis. Science of the Total Environment, 744, 140714. https://doi.org/10.1016/j.scitotenv.2020.140714
10. Premalatha, R. P., Poorna Bindu, J., Nivetha, E., Malarvizhi, P., Manorama, K., Parameswari, E., & Davamani, V. (2023). A review on biochar’s effect on soil properties and crop growth. Frontiers in Energy Research, 11, 1092637. https://doi.org/10.3389/fenrg.2023.1092637
11. Wei, Y., Ma, J., Liu, K., Zhang, S., & Wang, J. (2025). Biochar-Based Remediation of Heavy Metal-Contaminated Soils: Mechanisms, Synergies, and Sustainable Prospects. Nanomaterials, 15(19), 1487. https://doi.org/10.3390/nano15191487
12. Xu, X., Zhao, Y., Sima, J., Zhao, L., Mašek, O., & Cao, X. (2017). Indispensable role of biochar-inherent mineral constituents in its environmental applications: A review. Bioresource Technology, 241, 887–899. https://doi.org/10.1016/j.biortech.2017.06.023
13. Zhang, P., Duan, W., Peng, H., Pan, B., & Xing, B. (2021). Functional Biochar and Its Balanced Design. ACS Environmental Au, 2(2), 115–127. https://doi.org/10.1021/acsenvironau.1c00032