ARTICLE

Applications of Biochar: A Comprehensive Review of Production Methods and Potential Uses

Dawod Rasooli Keya[1] and Evin Adin[2]

1 - PhD, Asst. Prof. in Soil and Water Conservation, 2 - Soil Fertility Researcher

Email:

Abstract
Biochar is a carbon-dense material made by heating biomass in low or no oxygen conditions. It is currently receiving attention for the many roles it can play. In this article, we will introduce the main methods of biochar production, such as Slow Pyrolysis, Fast Pyrolysis, Gasification, Hydrothermal, Carbonization and Torrefaction, and then explore biochar applications in agriculture, construction, Energy Production and water treatment. We will explore how biochar's strong structure and unique chemistry can improve soil health, reduce greenhouse gases, strengthen concrete, and trap pollutants in water treatment systems. The article also points out existing barriers and points to future research so that readers can gain a broad and balanced view of what biochar can still achieve.

Keywords: Biochar, Pyrolysis, Soil amendment, Green concrete, Water treatment, Carbon sequestration

Introduction

In the modern era of escalating environmental challenges, the search for sustainable and eco-friendly solutions has become increasingly important. Biochar, a stable, carbon-rich material produced through pyrolysis of biomass under oxygen-limited conditions, represents one of these innovative solutions with potential applications ranging from agriculture to construction and water treatment industries. The importance of biochar lies in two fundamental points: first, as a management method for dealing with biological waste and transforming it into value-added products, and second, as an instrument for reducing carbon and climate change.

. **To cite this article**: Rasooli Keya, Dawod and Evin Adin 2025. "Applications of Biochar: A Comprehensive Review of Production Methods and Potential Uses". *TISHK Center for Kurdistan Studies* .

With these attributes, biochar becomes a promising solution for reaching sustainable development objectives.

Biochar possesses various uses in several fields, including soil fertility, climate stability, water resource management, and energy efficiency. The versatility of biochar is attributed to its physicochemical characteristics, such as high surface area, porosity, and chemical stability.

The objective of this article is to provide a concise review of biochar production methods and examine its applications in three main areas: agriculture, construction, and water treatment. In agriculture, biochar improves soil fertility and productivity while contributing to climate change mitigation. In construction, biochar serves as a sustainable additive for green concrete, enhancing thermal properties and carbon sequestration. In water treatment, biochar is efficient at removing heavy metal ions, inorganic salts, and organic contaminants from industrial, urban, and agricultural wastewater.

Biochar Production Methods

Production of biochar is the thermal decomposition under circumstances of absence or near-absence of oxygen, also known as pyrolysis, of biomass (wood, crop residues, or manure) into a stable carbon-rich material known as biochar. When pyrolysis is conducted, the biomass is exposed to high temperatures, and its organic polymers break down into smaller molecules, resulting in the creation of solid biochar and byproducts like bio-oil and syngas. The step-by-step procedure is possible in different steps: drying (removal of water content), pre-carbonization (degradation of unstable components), carbonization (immediate breakdown and formation of biochar), and calcination (purging of residual volatiles and increase in fixed carbon) (Figure 1). The yield and quality of biochar are specific functions of the pyrolysis conditions, such as temperature, heating rate, and residence time.

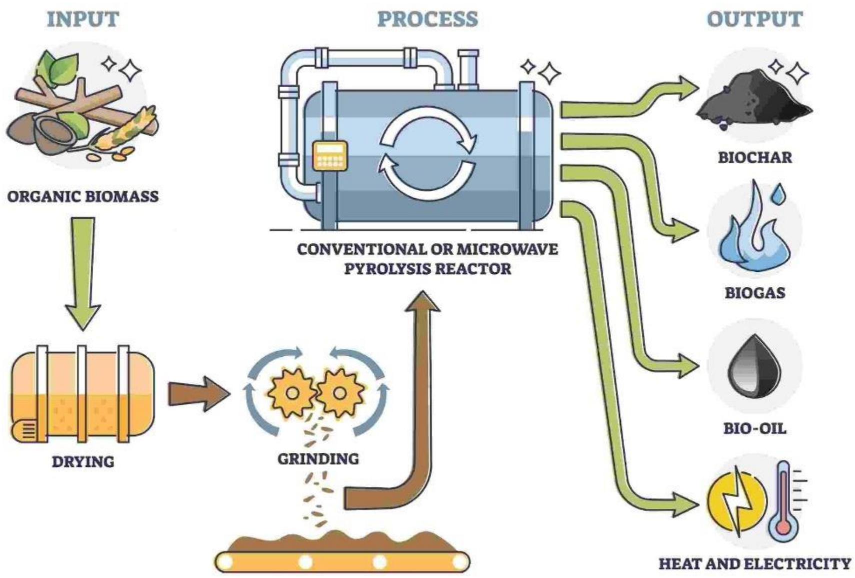

Figure 1. Biomass Pyrolysis Process: From Organic Biomass to Biochar, Bio-Oil, Biogas, and Energy *(Source: https://worldtree.eco)*

Slow Pyrolysis

Slow pyrolysis is marked by low heating flux (0.1–1°C/s), low temperature (277°C–677°C), and long solid residence time (450–550 s). Slow pyrolysis equipment facilitates slow and gradual transformation of the feedstock to biochar in an inert carrier gas and a residence time of 30–60 min. It is the most utilized technique to generate biochar with 25-35% by weight of the original biomass. The resulting biochar is a porous material with a high specific surface area.

Fast Pyrolysis

Fast pyrolysis is between 450°C–650°C with a brief residence time of 0.5–10 s. In fast pyrolysis, biomass is quickly heated to intended temperatures at high rates of heating (100-1000°C/s). Fast pyrolysis will produce more oils and liquids, and slow pyrolysis gives more syngas. Lower biochar yields (15-25%), but liquid bio-oil yields are greater because of short residence time and rapid heating.

Vacuum Pyrolysis

Vacuum pyrolysis is a slow pyrolysis process (low-pressure range: 0.05–0.20 MPa) for the upgrading of biomass materials under all other parameters demanded by the process. This process provides higher control of the pyrolysis environment and is capable of producing biochar of desired characteristics.

Gasification

Gasification procedures produce less biochar in a directly-heated reaction vessel with provided air. The more oxygen a production system can remove, the more biochar it will produce. Oxidant-supported gasification (air or steam) produces the conversion of most feedstock to product gas. This method tends to be at higher temperatures (700-1000°C) and produces mostly syngas with minimal biochar yield (5-15%).

Hydrothermal Carbonization

Hydrothermal carbonization is another novel method of biochar production that uses water at elevated temperature (typically between 180 °C and 250 °C) and pressure. This process facilitates the conversion of wet biomass into carbon-rich solid products and has gained interest because of its potential for the utilization of high-moisture content feedstocks, i.e., agricultural waste and organic waste

Torrefaction

Torrefaction is a milder thermal treatment that is carried out at a temperature of 200 °C to 300 °C in an inert environment. It raises the energy density of biomass and produces solid bio-coal, which can be further processed or directly utilized. The torrefaction solid yield can be high and normally ranges from 60% to 85%, depending on the biomass type and operating conditions.

Co-pyrolysis

Current studies have explored co-pyrolysis; whereby mixed feedstocks are pyrolyzed together to maximize biochar yield and quality. Huang et al. (2017), for example, tried blending sewage sludge with sawdust and found that biochar yield decreased with increasing temperature, demonstrating the effect of feedstock composition on production outcomes. Co-pyrolysis enables the synergistic effects of biomass types, potentially resulting in better yield and quality of the biochar produced.

Table 1. Biochar Production Methods and Key Parameters

Method	Temperature range	Heating rate	Residence time	Biochar yield, %weight	Product quality
Slow Pyrolysis	300-600°C	1-10°C/min	Several hours to days	25-35%	High porosity and surface area
Fast Pyrolysis	450-650°C	100-1000°C/s	0.5-10 seconds	15-25%	Bio-oil and gases
Gasification	700-1000°C	Oxidizing agent: Air or steam	-	5-15%	Syngas ($CO+H_2$)
Hydrothermal Carbonization	180 - 250 °C	Moderate	Several hours	40–70%	Hydrochar, high oxygen content
Torrefaction	200 - 300 °C	Low	10–60 minutes	30–70%	Energy-dense, hydrophobic biochar

Co-pyrolysis

Recent studies have explored co-pyrolysis, where mixed feedstocks are pyrolyzed together to enhance biochar production and properties. For example, Huang et al. (2017) conducted experiments mixing sewage sludge with sawdust and found that the biochar yield decreased with increasing temperature, demonstrating the influence of feedstock composition on production outcomes. Co-pyrolysis allows for the synergistic effects of different biomass types, potentially improving both yield and quality of the resulting biochar.

Feedstock Considerations

Other research has demonstrated that feedstock choice, pyrolysis temperature, and pyrolysis mode influence ultimate biochar physicochemical properties. Common feedstocks include: Agricultural residue (rice husks, wheat straw, corn stalks), Wood waste (wood chips, sawdust, bark), Animal manure (cattle manure, poultry litter), Municipal solid waste, Sewage sludge, Energy crops (switchgrass, miscanthus).

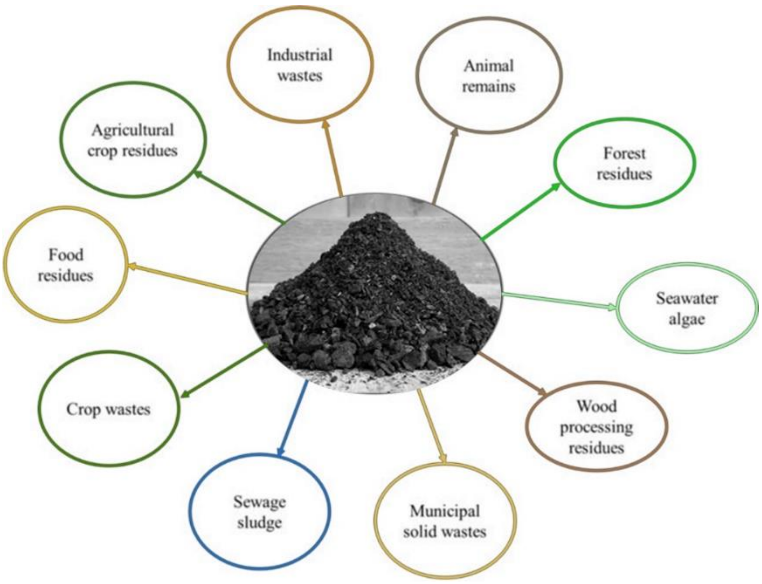

Figure 2. Various types of feedstocks used for the production of biochar *(Content available from Biomass Conversion and Biorefinery)*

Woody biomass, like timber offcuts, bark, will yield low-ash content, high-density carbon biochar, and porous morphology depending on the lignin-based origin. However, due to their non-woody origin, non-woody feedstocks like agricultural wastes (rice straw, flax shives) or animal manure will yield higher ash content (11-36%) as well as water content, leading to biochar with high pH and low surface area. Pre-treatment of feedstocks is also critical: particle size reduction by crushing or sieving increases pyrolysis efficiency, and excessive moisture content above 20% significantly decreases biochar yields. Contaminants in feedstocks like sewage sludge or municipal waste must be evaluated with caution, as they can introduce heavy metals (Zn, Cu, Cr) or polycyclic aromatic hydrocarbons (PAHs) to the product. The feedstock selection has a critical influence on the ultimate biochar characteristics such as ash content, nutrient content, surface area, and pH.

Functional characteristics of biochar are a function of feedstock-pyrolysis conditions. High-ash feedstock like pig manure (36% ash) is slow-pyrolyzed at temperatures between 300-700°C to yield 35-61% biochar, whereas cellulose-derived material like cotton stalks yields as low as 32% under identical conditions

Co-pyrolysis of two feedstocks (e.g., sewage sludge and bamboo sawdust) demonstrates that blending of high-ash and low-ash feedstocks can modulate yield and nutrient levels, though excessive addition of non-woody biomass reduces carbon sequestration potential. Temperature breakpoints also vary depending upon the feedstock: lignin-containing feedstocks require >400°C to completely decompose, while cellulose decomposes at 300-400°C. For agricultural applications, feedstocks with rigid carbon structures (e.g., applewood, green woody waste) pyrolyzed at 450-600°C optimize cation exchange and water retention while minimizing PAH formation.

Biochar Applications

Soil Amendment and Fertility Enhancement

Biochar is a stable fertilizer for adsorption and mineralization, and also is a fertilizer for the improvement of biomass. Biochar-mediated improvement of biomass and soil can improve productivity and fertility.

Table 2. Benefits of Biochar Application on Soil Physical, Chemical, and Biological Properties

Physical Properties	Chemical Properties	Biological Properties
• Improved water retention capacity • Enhanced soil structure and aggregation • Increased porosity and aeration • Reduced bulk density	• Increased cation exchange capacity (CEC) • Enhanced nutrient retention (N, P, K) • pH buffering capacity • Reduced nutrient leaching	• Enhanced microbial activity and diversity • Improved soil enzyme activity • Increased earthworm abundance • Better mycorrhizal associations

However, the application of biochar in the soil is a strong method to make a significant impact on the pesticide behavior of the soil. Specifically, biochar affects the bioavailability processes of the contaminants in the soil, such as adsorption, desorption, degradation, and leaching. The adsorptive property of biochar makes it effective in the remediation of pollutants in the soil. Biochar has been found to effectively reduce CH_4 emissions from various sources such as livestock dung, rice fields, and landfills. It is believed that the mechanism of this reduction is the adsorption of CH_4 onto the surface of biochar, which is later put through microbial oxidation.

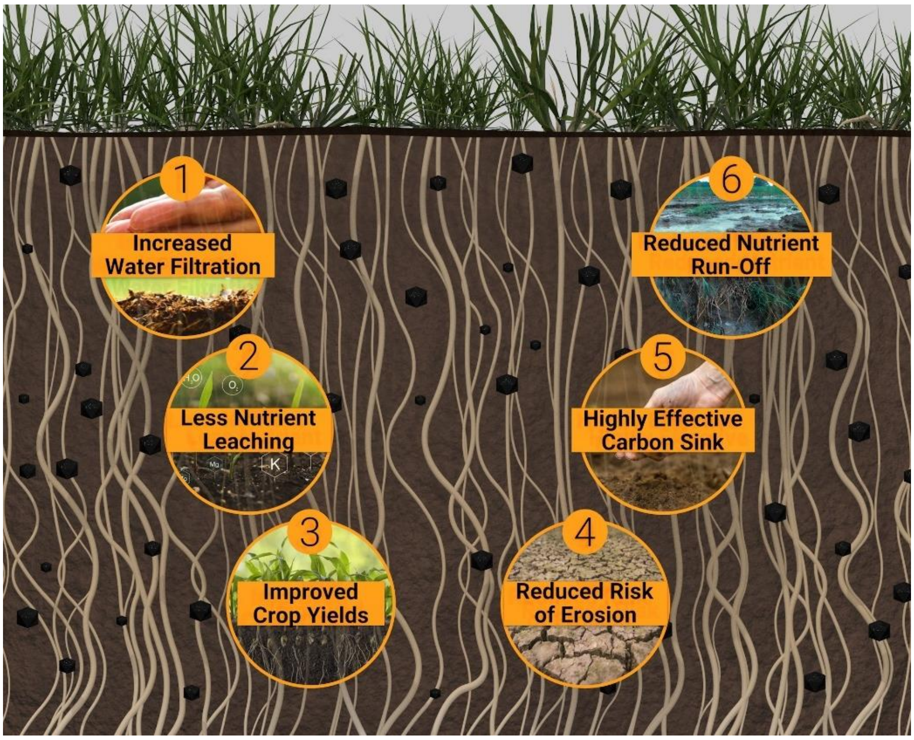

Figure 3. Biochar benefits for soil *(Content available from https://stronga.com)*

Construction Applications: Green Concrete

Uses of biochar in construction revolve primarily around its incorporation in concrete as a green ingredient. Green Concrete has to face a series of challenges, from obtaining the optimal mix ratios to ensuring material performance, maintaining constant quality control and standardization on different projects, and maintaining complete cost-effectiveness measures to regulate performance against costs. Furthermore, long-term performance also must be evaluated, as this helps determine whether and how materials and methods remain safe, durable, and effective in the long term. Overcoming these issues is necessary for attaining effective, efficient, and sustainable construction results.

Table 3. Key Benefits of Incorporating Biochar in Concrete Production

Thermal Properties	Mechanical Properties	Environmental Properties
• Enhanced thermal insulation • Reduced thermal conductivity • Improved temperature regulation • Energy efficiency in buildings	• Potential strength enhancement with proper particle size • Improved workability in certain mix designs • Reduced concrete density • Enhanced durability under specific conditions	• Carbon sequestration in concrete • Reduced cement content requirements • Waste material utilization • Lower carbon footprint of concrete production

Energy Production

Biochar has also found an application in the area of energy production. It can be combusted to generate heat and electricity, and as a result, it is a source of renewable energy. Its high surface area and electrical conductivity also make it suitable for use in batteries, particularly lithium-ion batteries, and as a catalyst in the production of materials like graphene.

Water Treatment Applications

Biochar has high potential for the remediation of soil and water, especially through its unique adsorption and chemical properties that can trap and immobilize pollutants such as metalloids, organic pollutants, and toxic emerging pollutants such as microplastics.

Biochar performs wonderfully in water treatment owing to its large surface area and abundance of functional groups, which enable it to adsorb heavy metals such as lead, cadmium, chromium, and copper with removal efficiencies ranging from 60% to 99%. In addition to heavy metals, biochar can also remove a wide range of organic pollutants (including pesticides, pharmaceuticals, dyes, VOCs, and PAHs) from various sources of wastewater. Moreover, biochar also facilitates the regain of nutrients via phosphorus and nitrogen trapping and their recycling in agriculture, thus advancing a circular economy approach to waste management.

Table 4. Contaminant Removal and Nutrient Recovery with Biochar in Water Treatment

Heavy Metal	Organic Pollutant	Nutrient Recovery
• Lead (Pb) • Cadmium (Cd) • Chromium (Cr) • Copper (Cu)	• Pesticides and herbicides • Pharmaceutical compounds • Dyes and colorants • Volatile organic compounds (VOCs) • Polycyclic aromatic hydrocarbons (PAHs)	• Phosphorus recovery from wastewater • Nitrogen capture and slow release • Nutrient-enriched biochar for agricultural applications • Circular economy approach to waste management

Conclusions

This comprehensive review demonstrates that biochar is a multifaceted and sustainable solution to various environmental and industrial challenges. Optimization of the production parameters, feedstocks, and application-specific modifications is required for effective applications in biochar.

The future of biochar technology lies in addressing current constraints through increased research, the development of regulatory frameworks, and market entry. Biochar's potential to enable sustainable development in different sectors makes it a technology worth continued investment and development.

Subsequent research will need to be aimed at defining standard measures of quality and performance in long-term studies to effectively assess the efficacy of emerging materials and technologies across the range of applications. Economic feasibility testing and determining methods of transferring these advancements to existing processes in industry will also be critical for productive use. Establishing supportive policy frameworks will also be instrumental in enabling widespread adoption and fostering sustainable industry growth.

References

1. Barszcz, W., Łożyńska, M. & Molenda, J. 2024. Impact of pyrolysis process conditions on the structure of biochar obtained from apple waste. Sci Rep 14, 10501. https://doi.org/10.1038/s41598-024-61394-8
2. Biochar International. (2023). Biochar Production Technologies. Retrieved from https://biochar-international.org/about-biochar/how-to-make-biochar/biochar-production-technologies/
3. Crombie, K.; Mašek, O. Pyrolysis biochar systems, balance between bioenergy and carbon sequestration. GCB Bioenergy 2015, 7, 349–361
4. Fryda, L.; Visser, R. Biochar for Soil Improvement: Evaluation of Biochar from Gasification and Slow Pyrolysis. Agriculture 2015, 5, 1076-1115. https://doi.org/10.3390/agriculture5041076
5. Hassan, M., et al. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, 2, 421–438. https://link.springer.com/article/10.1007/s42773-020-00067-x
6. Kavan Kumar V, N L Panwar, Pyrolysis technologies for biochar production in waste management: a review, *Clean Energy*, Volume 8, Issue 4, August 2024, Pages 61–78, https://doi.org/10.1093/ce/zkae036
7. Li, S., et al. (2022). Biochar for the removal of contaminants from soil and water: a review. *Biochar*, 4, 19. https://doi.org/10.1007/s42773-022-00146-1
8. Maryam Afshar, Saeed Mofatteh. 2024. Biochar for a sustainable future: Environmentally friendly production and diverse applications. *Results in Engineering*, Volume 23, https://doi.org/10.1016/j.rineng.2024.102433
9. Minnesota Pollution Control Agency. (2023). Biochar and applications of biochar in stormwater management. *Minnesota Stormwater Manual*. https://stormwater.pca.state.mn.us/index.php?title=Biochar_and_applications_of_biochar_in_stormwater_management
10. Nepal Jaya, Ahmad Wiqar, Munsif Fazal, Khan Aziz, Zou Zhiyou, 2023. Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science,* Volume 11. DOI=10.3389/fenvs.2023.1114752

11. ScienceDirect Topics. (2024). Fast Pyrolysis - an overview. https://www.sciencedirect.com/topics/chemical-engineering/fast-pyrolysis
12. Shyam, S., Ahmed, S., Joshi, S.J. et al. 2025. Biochar as a Soil amendment: implications for soil health, carbon sequestration, and climate resilience. Discov. Soil 2, 18. https://doi.org/10.1007/s44378-025-00041-8
13. Singh, H., et al. (2024). Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: a scientometric review. *Environmental Sciences Europe*, 36, 59. https://enveurope.springeropen.com/articles/10.1186/s12302-024-00859-z
14. Verma, M., et al. (2023). Biochar production from slow pyrolysis of biomass under CO2 atmosphere: A review. *Environmental Research*, 214, 113851. https://www.sciencedirect.com/science/article/abs/pii/S2213343723007480
15. Yanfei Yuan, et al, 2023. Biochar as a sustainable tool for improving the health of salt-affected soils, Soil & Environmental Health, Volume 1, Issue 3, https://doi.org/10.1016/j.seh.2023.100033

[1] **Dr. Dawod Rasooli** is Assistant Professor of Soil and Water Conservation in the Department of Crop Production. He received his Ph.D. in 2020 from Salahaddin University - Erbil (SUE). In 2009, he joined the Polytechnic University of Erbil, where he worked as a lecturer in the Department of Crop Production and as a researcher. His research is in the field of soil conservation, estimation of soil erosion, rainfall characteristics, evapotranspiration (ETo) and crop water requirements. His main research interests include Erosivity Index and Rainfall Energy Measurement (REM). Dawod teaches several courses on Fundamentals of Plane Surveying, Fundamentals of Soil Science and Soil Fertility, Irrigation Systems, Computer Essentials, Watershed Management and Landscape Engineering. Dawod has also conducted seminars and symposia on Soil and Water Sciences for academics and professionals in collaboration with EPU. He has published 4 books on Soil and Water Science in Kurdish and English.

[2] **Evin Adin** is a researcher in Soil Fertility and Bio-engineering and is a dedicated researcher in the fields of soil health, sustainable agriculture, and ecosystem restoration. With a focus on nutrient management and soil ecology, Evin's work emphasizes environmentally sound practices that promote biodiversity and long-term agricultural productivity. Evin has contributed to several research projects aimed at enhancing soil fertility through natural methods, including bioengineering techniques; epically using the Biochar that improve soil resilience and ecological balance. An advocate for ecological sustainability, Evin is passionate about developing innovative solutions to address soil degradation and promoting regenerative practices in agriculture.