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Production and utilization of biochar: A comprehensive review

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Abstract

Biochar has been emerging as an eco-friendly material which has several environmental and agronomic problems to which it can provide solutions. Biochar can be created by applying thermal and chemical processes to organic materials within oxygen-free environments. This material can solve biomass waste management, CO₂ emission, pollution, soil degradation and soil enhancement problems. Important biochar production methods are Pyrolysis, gasification, hydrothermal carbonization and torrefaction, and how the production parameters are related to the biochar physicochemical properties and performance are reviewed. Moreover, the review discusses various applications of biochar in agriculture, environmental management, climate change mitigation, energy and industries. Biochar can be used as an organic amendment to enhance the water-holding capacity, soil quality, nutrient-use efficiency, soil fertility and yield of crops. The porous and highly absorptive nature of biochar allows it to trap pesticides, dyes, heavy metals and other harmful chemicals in soil and water. Last but not least, biochar can help lower the levels of GHG in the atmosphere and increase the carbon stored over the long term. Its effectiveness and commercial viability will improve as the following technological advancements are realized: engineered biochar, Nano-biochar technologies, integration with carbon credit systems and industrial-scale deployment. While biochar holds great potential for sustainable environmental management, the circular economy and resilient agriculture, ongoing research, policy and technological development are crucial for the broad adoption of this technology.

Keywords: Biochar, biomass valorization, carbon sequestration, soil health, environmental remediation, sustainable agriculture, climate change mitigation, waste management, circular economy, pollution control

1. Introduction

In the recent decades, the world has experienced an unprecedented growth in its population, industrial activities and agricultural intensification which has resulted to severe environmental degradation. Climate change, soil infertility, water contamination and the excessive organic waste are global problems. The current waste management strategies and traditional agricultural practices are not enough to solve these problems, therefore there is a great need for sustainable and innovative waste management solutions (Sharma *et al.*, 2024; Kumar *et al.*, 2025) [35, 17].

Biochar has been identified as one of the most versatile materials in this regard due to its special physicochemical properties and environmental advantages. The product is stable carbon-rich and derived from biomass via thermal decomposition of biomass under limited oxygen (Lehmann & Joseph, 2020; Zhao *et al.*, 2021) [20, 49]. Although the concept of biochar is not novel, its scientific and technological significance has significantly grown in recent years, particularly from 2020 to 2026, with its diverse potential applications in carbon sequestration, soil enhancement, and environmental remediation, respectively (Zhang *et al.*, 2025) [47].

Research has shown (Lehmann *et al.*, 2020; Kumar *et al.*, 2023; Zhang *et al.*, 2025) [20, 16, 47] that biochar can be a major climate change mitigation tool, as it can sequester carbon long-term in soil. Biochar retains carbon for a much longer period than raw biomass because of its stability in microbial degradation owing to its aromatic carbon structure (Singh & Cowie, 2020; Zhao & Chen, 2024) [36, 51].

Intensive farming, increased chemical fertilizer usage and soil erosion have caused soil degradation to be a major problem in agricultural systems.

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Biochar has demonstrated remarkable capabilities in promoting soil health through its ability to retain nutrients, hold water and boost microbial diversity (Chen *et al.*, 2021; Singh *et al.*, 2022) [4, 39]. It also helps to mitigate soil acidity and enhance productivity of crops in degraded soils (Sharma *et al.*, 2024) [35].

In addition, models for circular economy have gained a lot of traction and raised more awareness for valorization of biomass waste. The residues from agriculture, forests and urban waste containing organic matter are disposed of or burnt, resulting in pollution of the environment. Biochar production is an effective solution that can help convert this waste into a valuable product, not only by reducing pollution, but also by offering economic benefits (Gupta *et al.*, 2023; Sharma *et al.*, 2025) [11, 32].

Even though biochar has great potential, it still has some problems, including the low production of large-scale industrial production systems, the quality of the products is not consistent and the support of biochar policy in many developing countries is not sufficient (Patel *et al.*, 2024) [30]. Hence, it is important to gain a better understanding of its production techniques, properties and applications to establish its use on a broader scale.

2. Production of Biochar

Biochar is a carbon-rich solid material generated by thermochemical processing of biomass in the absence of or under low oxygen conditions (Lehmann & Joseph, 2020; Zhao *et al.*, 2021) [20, 49]. The properties of its final product, including its carbon content, porosity, stability and yield (Wang *et al.*, 2020) [41], are heavily determined by the method of production. Over the years, several production methods were developed, which varies by temperature range, reaction environment and product distribution (Brown *et al.*, 2021; Zhang *et al.*, 2023) [1, 45].

2.1 Pyrolysis

Pyrolysis is the most widely studied and widely used technology to produce biochar. During this process, biomass is pyrolysed at a typical temperature range of 300°C to 700°C in an oxygen free environment (Kumar *et al.*, 2023; Liu *et al.*, 2022) [16]. During the absence of oxygen, the biomass doesn't burn completely and produces three products: solid biochar, liquid bio-oil, and gaseous syngas (Chen *et al.*, 2021; Brown *et al.*, 2021) [4, 1]. Slow pyrolysis is especially preferred for biochar production among other pyrolysis processes as it yields the highest amount of solid char and enhances carbon stability (Singh *et al.*, 2022) [39]. This approach uses lower and slower heating rates and longer residence times, leading to the creation of more stable carbon structures and a higher aromaticity for the resulting biochar product (Zhao & Chen, 2024) [51]. Therefore slow pyrolysis biochar is more suitable for long-term carbon sequestration and soil amendment use (Sharma *et al.*, 2024; Wang *et al.*, 2025) [35, 40].

2.2 Gasification

Another thermochemical process of converting biomass into energy and carbon rich residues is gasification. Gasification operates at relatively high temperatures, typically between the range of 700 to 1000 °C, and uses a small amount of oxygen or steam (Liu *et al.*, 2022; Zhang *et al.*, 2023) [24, 45]. The main goal of this process is to generate syngas, which primarily comprises of hydrogen, carbon monoxide and

other minor gases, and is extensively utilized in energy generation (Wang *et al.*, 2020; Singh *et al.*, 2022) [41, 39]. Gasification usually produces much less solid biochar than pyrolysis, because of the high temperature and partial oxidation process. Due to the severe thermal degradation conditions, however, the resulting char is generally more stable and highly carbonized (Zhao & Chen, 2024; Sharma *et al.*, 2025) [51, 32].

2.3 Hydrothermal Carbonization (HTC)

A special thermochemical process was developed for the processing of wet biomass and is called hydrothermal carbonization (Chen *et al.*, 2021; Gupta *et al.*, 2023) [4, 11]. The process is done at a moderate temperature (180°C to 250°C) with self-developed pressure conditions in a closed system (Li *et al.*, 2023; Kumar *et al.*, 2023) [23, 16].

The product from HTC is called "hydro char" whose surface chemistry, porosity and functional group composition are different from biochar (Zhang *et al.*, 2022; Wang *et al.*, 2025) [48, 40]. This approach is especially suitable for converting waste materials, such as agricultural residues, food waste, and sewage sludge, into carbon-rich materials while minimizing energy usage from drying processes (Patel *et al.*, 2024; Sharma *et al.*, 2024) [30, 35].

2.4 Torrefaction

Torrefaction is a mild thermal treatment process that is performed at relatively low conditions (200°C to 300°C) under oxygen limited conditions (Brown *et al.*, 2021; Kumar *et al.*, 2023) [1, 16]. It is usually viewed as a pre-treatment process instead of an entire carbonization reaction (Zhao *et al.*, 2021) [49].

Torrefaction is a process of partial thermal decomposition of biomass, which can be employed to enhance the characteristics of the fuel (Gupta *et al.*, 2023; Singh *et al.*, 2022) [11, 39]. While not as carbonizing as pyrolysis, torrefaction is still an important method of producing solid biofuels and enhancing efficiencies in biomass handling, storage, and transport (Sharma *et al.*, 2025; Wang *et al.*, 2024) [32, 44].

The key factors that influence the quality of biochar.

A number of operational and feedstock parameters have a significant impact on the final properties and performance of biochar (Lehmann & Joseph, 2020; Zhang *et al.*, 2023) [20, 45]. The key considerations are:

- Temperature of production
- The heating rate in the processing.
- The type and composition of the feedstocks.
- Time spent within the reactor.

Of these, temperature is especially important for the determination of biochar properties. Generally, as processing temperature increases, the resultant carbon will be more stable, more aromatic carbon will be formed, and the resistance for microbial degradation will be improved (Wang *et al.*, 2020; Zhao & Chen, 2024) [41, 51]. But this typically leads to reduced overall yield of biochar. Conversely, cooler conditions generally yield a higher biochar production rate, yet also result in less stable carbon structures in the biochar (Chen *et al.*, 2021; Sharma *et al.*, 2024) [4, 35].

3. Utilization of Biochar: Biochar is a versatile product, having several applications in agriculture, environmental

management, energy production and industrial applications. It has a high surface area, porosity, stability, and reactive surface functional groups which makes it a versatile material for practical applications (Lehmann & Joseph, 2020; Zhao *et al.*, 2021) ^[20, 49].

3.1 Agricultural Applications

Biochar has been widely used in agriculture as a soil amendment agent because of its beneficial effects on soil health and longterm productivity. It is used in soil to improve soil fertility through its ability to retain nutrients, which helps to prevent the loss of essential nutrients like nitrogen, phosphorus and potassium from the soil (Chen *et al.*, 2021; Sharma *et al.*, 2024) ^[4, 35].

Biochar also enhances water holding capacity of soil which is particularly beneficial in drought prone and semi-arid areas. Substantial porosity enables it to hold water and release it gradually to the plant roots ensuring uniform crop growth (Singh *et al.*, 2022) ^[39].

Moreover, biochar lowers the loss of fertilizers due to irrigation and precipitation which alleviates the nutrient-use efficiency and minimizes reliance on chemical fertilizers. The application of biochar has been shown to significantly enhance the productivity of various crops, including rice, wheat, maize, and vegetables, in recent studies (2020-2026) (Gupta *et al.*, 2023; Wang *et al.*, 2025) ^[11, 40].

3.2 Environmental Remediation

Biochar has been receiving a lot of interest for its high adsorption ability and chemical stability in environmental remediation. Due to its porous structure and functional groups on the surface, it has the ability to adsorb and fix a variety of environmental pollutants (Zhang *et al.*, 2022) ^[48].

It is especially good for removing heavy metals like lead, cadmium and arsenic from polluted soils and water systems. Moreover, biochar can also effectively adsorb organic pollutants such as pesticides, dyes and pharmaceutical residues (Kim & Lee, 2021; Chen & Li, 2023) ^[13, 5].

In the field of wastewater treatment, biochar is an affordable adsorbent that can be used to treat wastewater and decrease the concentration of contaminants. These engineered biochars, such as magnetic and chemically modified biochar, have also improved the adsorption efficiency of biochar (Liu *et al.*, 2024; Li *et al.*, 2023) ^[25, 23].

3.3 Climate Change Mitigation

The potential for biochar to sequester carbon in a stable form for long periods makes it one of the most important mitigation measures for climate change. In biomass conversion process, a large amount of carbon is converted into highly resistant aromatic structures with very slow degradation process in soil environment (Wang *et al.*, 2020; Zhao & Chen, 2024) ^[41, 51].

This long-term capability of storing carbon helps mitigate atmospheric carbon dioxide level, which in turn helps to mitigate global climate change. Additionally, biochar has been found to lower the emission of greenhouse gases like methane (CH₄) and nitrous oxide (N₂O) when applied to agricultural soil, due to its ability to enhance soil aeration and microbial activity (Sharma *et al.*, 2025; Singh & Cowie, 2020) ^[32, 36].

3.4 Energy Sector Applications: Biochar production is closely associated with bioenergy generation systems in the

energy sector. In addition to solid biochar, thermochemical conversion of biomass, like pyrolysis, generates useful by-products such as bio-oil and syngas (Brown *et al.*, 2021; Kumar *et al.*, 2023) ^[1, 16].

These byproduct can be used as renewable energy sources for generating heat, electricity or used as alternative fuel. This comprehensive energy recuperation method boosts the process efficiency and promotes sustainable bioenergy development (Zhang *et al.*, 2023) ^[45].

In recent years, new uses of biochar have also been found in energy storage devices and catalyzing energy conversion processes, in addition to its conventional use within biomass applications (Kim *et al.*, 2024) ^[12].

3.5 Industrial Applications

In addition to the environmental and agricultural applications, the use of biochar is being investigated for a number of industrial applications. It is found to be stable in carbon structure and highly reactive on the surface, thus acting as catalyst support material in various chemical and industrial applications (Patel & Kumar, 2024) ^[30].

In addition, biochar is being used extensively in environmental remediation, especially in the remediation of contaminated sites and industrial wastewater treatment processes (Wang & Liu, 2024) ^[44]. It is used in material science as a component of composites with enhanced mechanical features, thermal stability, and durability (Li *et al.*, 2024) ^[21].

Moreover, biochar-based materials are being explored for their applications in the construction industry, filtration applications, and polymer composites; thus, demonstrating the potential of using biochar as a sustainable industrial resource (Sharma *et al.*, 2024; Gupta *et al.*, 2025) ^[35, 10].

4. Limitation of Biochar technology

Even though the technology has many environmental and agricultural advantages, it has some practical and scientific challenges that limit its scale-up and uptake in various parts of the world (Sharma *et al.*, 2024; Kumar *et al.*, 2025) ^[35, 17]. Advanced pyrolysis systems or engineered biochar processes are two of the major challenges as the production cost is high in this case. Large scale production is difficult due to the need for specialized reactors, controlled conditions and energy input, particularly in developing countries (Brown *et al.*, 2021; Patel *et al.*, 2024) ^[1, 30].

Furthermore, there is lack of standardization in the production and assessment of biochar (lack of standardization). The properties of biochar varies depending on the feedstock used, the process of biochar production is a process that varies depending on the conditions, so it's difficult to define universal quality standards. Variability in performance can impact its reliability for agricultural and environmental use (Zhao *et al.*, 2021; Zhang *et al.*, 2023) ^[49, 45].

Another important one is (Feedstock variability). The properties of biochar are strongly dependent of the type of biomass used, such as agricultural residues, forestry waste or municipal organic waste. The inconsistent product quality may be due to variations in lignin, cellulose and minerals content, which make it difficult to predict the performance in field applications (Chen *et al.*, 2021; Singh *et al.*, 2022) ^[4, 39].

Moreover, biochar technology is not fully adopted (at large scale). Although large laboratory and small-scale field trials

were conducted, its implementation is still limited to specific economic constraints, absence of policy incentives, and awareness among the farmers and industries (Sharma *et al.*, 2025; Gupta *et al.*, 2023) [32, 11]. Also, its field performance is still being built up over long-term, under various climatic conditions, thus hindering its widespread acceptance.

In conclusion, although biochar has significant potential as a sustainable resource, several challenges must be overcome for its widespread adoption on a global scale, including technological development, policy support, and standardization efforts (Lehmann & Joseph, 2020; Wang *et al.*, 2025) [20, 40].

5. Future Scope of Biochar

In light of the increasing focus on sustainability, climate change mitigation, and circular economy models around the world, the potential for biochar research and application is immense (Sharma *et al.*, 2024; Kumar *et al.*, 2025) [35, 17]. Continuous innovations in material science and environmental engineering are likely to bring bigger and better opportunities in the old and new biochar markets.

One of the most important future directions is the development of engineered biochar. Chemical activation, doping, or physical modification can be used to adjust the properties of biochar for specific applications, including pollutant removal, soil improvement, and catalytic reactions. Recent research indicates that (engineered biochar) has a much greater adsorption efficiency and functional performance than (raw biochar) (Zhang *et al.*, 2023; Liu *et al.*, 2024) [45, 25].

One of the booming fields is (nano-biochar applications). The particle size of nano-biochar is extremely small resulting in a high surface area and increased reactivity, as well as improved interaction with soil and contaminants. This makes it very suitable for advanced applications such as precision agriculture, wastewater treatment, and environmental remediation systems (Li *et al.*, 2023; Gupta *et al.*, 2025) [23, 10]. However more research is required to assess its potential long term environmental safety and ecological impact.

The integration of biochar into carbon credit systems is also attracting the attention of the international community. Because of the potential for biochar to permanently store carbon in soils, it could be an important component of carbon trading markets and greenhouse gas reduction programs. It has been demonstrated in several recent studies to have the potential to contribute to the adoption of net zero emission targets by offering measurable carbon storage pathways (Zhao & Chen, 2024; Patel *et al.*, 2024) [51, 30].

Furthermore, large-scale industrial use of biochar is projected to rise in the years to come due to a growing trend in the adoption of sustainable waste management and utilization of renewable resources by governments and industries. This will require the development of standard production methods, making the technology more economically viable, and support from policy initiatives to scale up biochar systems to a global level (Sharma *et al.*, 2025; Wang *et al.*, 2025) [32, 40].

In general, the potential for biochar is in technological innovation, policy integration, and scale-up commercialization, which can enable biochar to be a central element in sustainable environmental and agricultural

systems (Lehmann & Joseph, 2020; Kumar *et al.*, 2025) [20, 17].

6. Conclusion

Biochar is known to be highly versatile and sustainable, and has great potential to solve multiple environmental challenges at the global level (Lehmann & Joseph, 2020; Sharma *et al.*, 2024) [20, 35]. Its ability to contribute to carbon sequestration, improve soil health, support waste

It is a crucial part of the new generation of green and sustainable technologies in management and pollution control, and is widely used in the waste-water treatment industrial sector, as well as in various agricultural fields (Wang *et al.*, 2020; Zhao *et al.*, 2021) [41, 49].

Biochar can help mitigate climate change by stabilizing carbon in a long-lasting form and enhance soil physicochemical properties contributing to sustainable agriculture (Singh & Cowie, 2020; Chen *et al.*, 2021) [36, 4]. Furthermore, it is crucial for circular economy models in applications such as environmental remediation and resource recovery, as detailed by (Gupta *et al.* 2023) [11] and (Patel *et al.* 2024) [30].

Despite all these benefits, there are still some challenges and opportunities that need to be explored. Further research is needed to optimize production techniques, assess long-term environmental impacts, and enhance application efficiency in various ecological conditions (Sharma, *et al.*, 2025; Kumar, *et al.*, 2025) [32, 17]. Furthermore, improved policy measures and standardized production processes are crucial for the commercialization and global diffusion of biochar technologies (Zhang *et al.*, 2023; Wang *et al.*, 2025) [45, 40].

In conclusion, biochar has a tremendous potential for sustainable environmental management, but more research, economic viability and regulatory support are needed to realize its potential (Lehmann *et al.*, 2020) [20].

7. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

8. Acknowledgement

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