AgriCos e-Newsletter
ISSN: 2582-7049
AgriCos e-Newsletter
Open Access Multidisciplinary Monthly Online Magazine
Volume: 04 Issue: 05 May 2023 Article No: 01

Production Techniques of Biochar and Amendment for Global Climate Change Mitigation, Carbon Sequestration and Waste Management

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SUMMARY

Biochar is a carbon-rich material produced from the pyrolysis or gasification of biomass such as agricultural waste, forestry residues, and municipal solid waste. It has gained significant attention in recent years due to its potential as a sustainable solution to various environmental and agricultural challenges. This paper provides an overview of the production techniques, physical, chemical, and biological properties, as well as the advantages of using biochar. The physical properties of biochar such as high surface area, porosity, and water holding capacity make it an effective soil amendment for improving soil fertility and water retention. Biochar also has a high capacity for carbon sequestration, which can help mitigate climate change. Furthermore, biochar can be used for wastewater treatment, as a feedstock for renewable energy, and as a solution to organic waste management. However, further research is needed to fully understand the effects of biochar on soil properties, plant growth, and carbon sequestration.

INTRODUCTION

Biochar, a form of charcoal produced through pyrolysis of organic matter, has gained significant attention in recent years due to its potential as a tool for mitigating climate change and improving soil fertility. Biochar has been used for centuries by indigenous communities in the Amazon basin to improve soil quality and crop yields. More recently, researchers have been studying the potential benefits of biochar in agriculture, forestry, and climate change mitigation. One of the most promising aspects of biochar is its ability to sequester carbon in the soil for long periods of time. Studies have shown that biochar-amended soils can sequester carbon for up to thousands of years, depending on soil type and management practices (Lehmann *et al*., 2015). Carbon sequestration through biochar has the potential to play an important role in reducing atmospheric carbon dioxide levels, as well as mitigating the impacts of climate change. In addition to carbon sequestration, biochar has been found to have a range of other benefits for soil quality and agricultural productivity. Biochar-amended soils have been shown to improve soil fertility, water retention, and nutrient cycling (Jeffery *et al*., 2015). Biochar can also reduce soil acidity and improve soil structure, leading to increased crop yields and improved crop quality. Despite its potential benefits, there are also concerns about the sustainability of large-scale biochar production and the potential for unintended consequences. For example, the production of biochar can release greenhouse gases if not done properly, and there is debate over the carbon footprint of biochar production depending on the source of the feedstock and the energy required producing it (Woolf *et al*., 2010). There is also concern about the potential release of harmful chemicals into the environment if biochar is not produced or applied correctly. Despite these concerns, research on biochar continues to progress, with ongoing studies exploring the most effective ways to produce and apply biochar for agricultural and environmental benefits. Some researchers are also exploring the use of biochar for other applications, such as water filtration and wastewater treatment (Samsuri *et al*., 2018). With continued research and development, biochar has the potential to become a valuable tool for sustainable agriculture and environmental management.

Production techniques

There are several production techniques for biochar, each with its own advantages and disadvantages. The most common techniques include pit burning, slow pyrolysis, fast pyrolysis, and gasification.

Pit burning: Pit burning is a traditional method of producing biochar that involves burning organic materials in a pit, covered with soil or other insulating material to exclude oxygen. This method is still used in some parts of the world, particularly in developing countries, but has several limitations including low efficiency and air pollution (Harrison and Pearce, 2014).

Figure 1- Biochar

Slow pyrolysis: Slow pyrolysis involves heating biomass in the absence of oxygen at temperatures between 350°C and 700°C for several hours. This technique produces biochar with high carbon content and low ash content, making it suitable for agricultural use. However, slow pyrolysis is a slow and energy-intensive process, which can limit its scalability (Mukherjee *et al*., 2014).

Fast pyrolysis: Fast pyrolysis involves heating biomass to temperatures between 400°C and 600°C for a few seconds to minutes in the absence of oxygen. This technique produces biochar, bio-oil, and syngas. The biochar produced by fast pyrolysis has a lower carbon content and higher ash content compared to slow pyrolysis, but it can still be used for agricultural applications (Demirbas, 2010).

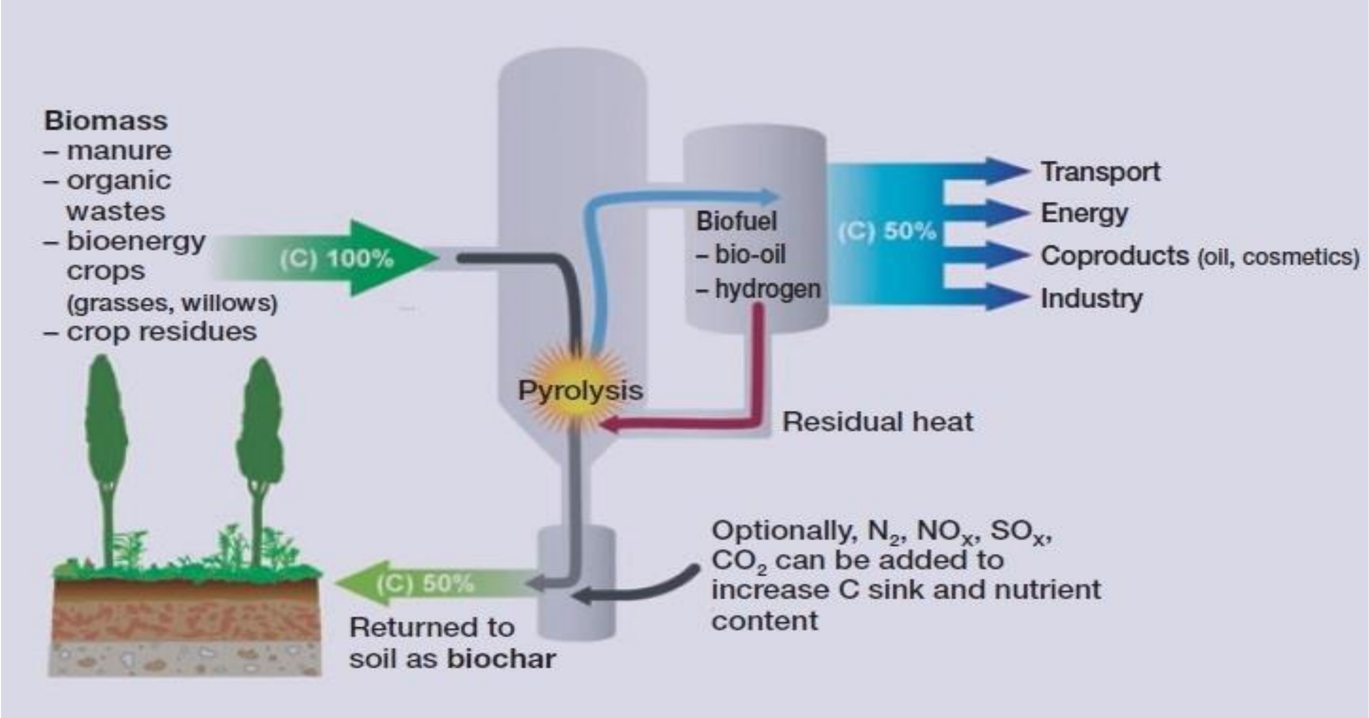

Figure 2. Concept of pyrolysis process with biochar sequestration. Normally, biochar is created from approximately half of the pyrolyzed biomass and may be added back to the soil. (Lehmann, 2007).

Gasification: Gasification involves heating biomass in the presence of a limited amount of oxygen to produce a gas mixture of carbon monoxide, hydrogen, and methane, which can be used for energy production. The biochar produced by gasification has a lower carbon content and higher ash content compared to slow and fast pyrolysis, but it can still be used for agricultural applications (Bridgwater, 2012).

Hydrothermal carbonization (HTC): HTC is a process that involves heating organic materials in the presence of water under high pressure and temperature. The process produces a solid carbon-rich material known as hydrochar, along with a liquid byproduct that can be used as a biofuel or fertilizer. HTC has several advantages over other biochar production methods, including a shorter processing time and the ability to process a wide range of feedstocks, including wet materials (Titirici et al., 2016). However, the process is energy-intensive and may require additional drying steps before use (Bridgwater *et al*., 2012).

Microwave pyrolysis: Microwave pyrolysis is a process that involves heating organic materials in a microwave oven in the presence of a catalyst, producing a biochar with high surface area and porosity. The process is relatively fast and energy-efficient, and can produce biochar with high yields and uniform properties (Liu *et al*., 2021). However, the process may require additional processing steps to remove ash and impurities from the final product (Chen *et al*., 2021). The choice of production technique depends on several factors, including the type of biomass, the desired properties of the biochar, and the intended use. Other factors that should be considered include the cost and scalability of the production process, the energy required, and the environmental impact.

Table 1. The reaction conditions and product distribution of various modes of pyrolysis (Qambrani *et al*., 2017).

Process	Temperature (°C)	Residence time	Yields %		
			Biochar	Bio-oil	Syngas
Slow pyrolysis	300–700	hour-days	35	30	35
Intermediate pyrolysis	~500	10–20 sec	20	50	30
Fast pyrolysis	500–1000	< 2 sec	12	75	13
Gasification	~750–900	10–20 sec	10	5	85
Hydrothermal carbonization (HTC)	180–300	1–16 hr.	50-80	5-20	2-5
Torrefacation	~290	~10–60 min	80	0	20

Factors Affecting Product Yield of Biochar

Type of feedstock: The yield of biochar production varies depending on the type of feedstock and the production technique used. Generally, the yield of biochar production ranges from 20% to 60% of the dry weight of the feedstock (Gul *et al*., 2021).

Pyrolysis Process: The yield of biochar production from slow pyrolysis ranges from 20% to 35%, with higher yields obtained from woody biomass and lower yields from herbaceous biomass (Lehmann *et al*., 2011). Fast pyrolysis typically produces higher yields of biochar, ranging from 30% to 60%, with lower yields of bio-oil and syngas (Demirbas, 2010).

Gasification: The yield of biochar production from gasification ranges from 10% to 30%, with higher yields obtained from woody biomass and lower yields from herbaceous biomass (Bridgwater, 2012).

Temperature: The yield of biochar production can also be affected by the processing conditions, such as the temperature, heating rate, and residence time. Increasing the temperature and residence time can increase the yield of biochar production, but can also decrease the quality of the biochar (Gul *et al*., 2021).

Overall, the yield of biochar production depends on several factors, including the type and quality of the feedstock, the production technique used, and the processing conditions.

Properties of Biochar

Biochar is a carbon-rich material produced from the pyrolysis or gasification of biomass such as agricultural waste, forestry residues, and municipal solid waste. It has a wide range of potential applications, including as a soil amendment, as a feedstock for renewable energy, and as a carbon sequestration tool.

Physical Properties of Biochar

Particle size: The particle size of biochar can vary widely depending on the feedstock and production process. Generally, biochar particles range in size from less than 1 mm to over 10 mm. (Kloss *et al*., 2012)

Porosity: Biochar has a highly porous structure with a large surface area, which can range from 50 to 800 m2/g depending on the production process and feedstock. (Lehmann and Joseph, 2015)

Density: The density of biochar can range from 200 to 800 kg/m^3 depending on the feedstock and production process. (Kloss *et al*., 2012).
Water holding capacity: Biochar has a high water holding capacity due to its porous structure. The water holding capacity of biochar can range from 30 to 200% depending on the feedstock and production process. (Lehmann and Joseph, 2015).
Surface chemistry: Biochar has a complex surface chemistry that can influence its interaction with other substances in the environment, including nutrients, metals, and organic compounds. The surface chemistry of biochar is influenced by factors such as the feedstock, production process, and post-processing treatments. (Lehmann and Joseph, 2015).

Chemical Properties of Biochar

Carbon content: Biochar is primarily composed of carbon, which makes up 50-90% of its mass, depending on the feedstock and production process. (Lehmann and Joseph, 2015)
Elemental composition: Biochar also contains small amounts of other elements, including hydrogen, nitrogen, oxygen, sulfur, and ash. The elemental composition of biochar can vary widely depending on the feedstock and production process. (Kloss *et al*., 2012)
Surface area: Biochar has a highly porous structure with a large surface area, which can range from 50 to 800 m^2/g depending on the production process and feedstock. (Lehmann and Joseph, 2015)
pH: The pH of biochar can range from acidic to alkaline depending on the feedstock and production process. Generally, biochar produced from woody feedstocks tends to be more acidic, while biochar produced from agricultural residues tends to be more alkaline. (Lehmann and Joseph, 2015)
Electrical conductivity: Biochar has a low electrical conductivity due to its high carbon content. The electrical conductivity of biochar can range from 0.1 to 1.0 dSm^{-1} depending on the feedstock and production process. (Lehmann and Joseph, 2015)
Cation exchange capacity (CEC): Biochar has a high CEC due to its ability to adsorb cations. The CEC of biochar can range from 20 to 600 meq/100 g depending on the feedstock and production process. (Lehmann and Joseph, 2015)
Functional groups: Biochar contains a variety of functional groups on its surface, including carboxyl, hydroxyl, and phenolic groups. These functional groups can influence the chemical and physical properties of biochar, including its ability to adsorb and desorb nutrients and contaminants. (Lehmann and Joseph, 2015)

Biological Properties of Biochar

Microbial activity: Biochar can influence soil microbial communities by altering the physical and chemical properties of the soil. Some studies have shown that biochar can increase microbial biomass and diversity, while others have shown a decrease in microbial activity. (Lehmann and Joseph, 2015)
Nutrient availability: Biochar can improve nutrient availability in soil by adsorbing and desorbing nutrients such as nitrogen, phosphorus, and potassium. The extent of nutrient adsorption and desorption by biochar depends on the feedstock and production process. (Jeffery *et al*., 2015)
Water retention: Biochar can improve soil water retention by increasing the water holding capacity of soil. This can be beneficial for plant growth and can also reduce the amount of irrigation needed in agriculture. (Jeffery *et al*., 2015)
Plant growth promotion: Biochar can promote plant growth by improving soil structure, increasing nutrient availability, and stimulating soil microbial activity. Studies have shown that biochar can increase crop yields in a variety of agricultural systems. (Lehmann and Joseph, 2015)
Contaminant immobilization: Biochar can immobilize contaminants such as heavy metals and organic pollutants in soil by adsorbing them onto its surface. This can be beneficial for soil remediation and can reduce the potential for contaminants to enter the food chain. (Jeffery *et al*., 2015)

Advantage of Biochar for Sustainable Development

Biochar is a carbon-rich material produced from the pyrolysis or gasification of biomass such as agricultural waste, forestry residues, and municipal solid waste. It has a wide range of potential applications, including as a soil amendment, as a feedstock for renewable energy, and as a carbon sequestration tool. Here are some agricultural and environmental advantages of biochar.

Improved soil fertility and Productivity: Biochar has been shown to improve soil fertility and increase crop yields in a variety of agricultural systems. A meta-analysis of 67 studies found that biochar application increased crop yields by an average of 10.8%, with the largest increases seen in tropical regions and in soils with low fertility (Jeffery, 2017). Biochar can improve soil fertility by increasing soil organic matter, improving nutrient retention, and promoting beneficial soil microbial activity. These improvements can lead to increased crop yields and improved soil health, which can ultimately benefit food security.

Carbon sequestration and Climate change mitigation: Biochar has the potential to sequester carbon in soils for hundreds to thousands of years, which can help mitigate climate change by reducing atmospheric CO_2 concentrations. A global analysis estimated that biochar application to soils could sequester up to 4.4 gigatons of CO_2 per year, which is equivalent to approximately 12% of current annual global emissions (Woolf *et al*., 2016). Biochar production can also reduce greenhouse gas emissions by capturing and storing carbon that would otherwise be released into the atmosphere during biomass decomposition. Additionally, biochar can reduce emissions of other greenhouse gases such as nitrous oxide and methane by improving soil conditions.

Reduced Greenhouse Gas Emissions: Biochar production can also reduce greenhouse gas emissions by capturing and storing carbon that would otherwise be released into the atmosphere during biomass decomposition. Additionally, biochar can reduce emissions of other greenhouse gases such as nitrous oxide and methane by improving soil conditions. (Lehmann and Joseph, 2015).

Water Conservation: Biochar can improve water conservation by increasing soil water retention, reducing water runoff, and decreasing the need for irrigation. This can be particularly beneficial in arid and semi-arid regions. (Jeffery *et al*., 2015)

Soil Remediation: Biochar has the potential to remediate contaminated soils by immobilizing pollutants such as heavy metals and organic pollutants. This can help protect human health and the environment. (Lehmann and Joseph, 2015). A study conducted in China found that the addition of biochar to soil reduced the bioavailability of heavy metals such as cadmium, lead, and copper, thereby reducing their uptake by plants and decreasing the risk of human exposure (Lin *et al*., 2018).

Renewable Energy: Biochar can be used as a feedstock for renewable energy production through gasification or combustion. A study conducted by the International Energy Agency estimated that the use of biochar in energy production could replace up to 20% of global coal consumption by 2050, leading to significant reductions in greenhouse gas emissions (IEA, 2011).

Water Quality Improvement: Biochar has the potential to improve water quality by reducing nutrient runoff and increasing water holding capacity in soils. A study conducted in Australia found that the addition of biochar to soil reduced the leaching of nutrients such as nitrogen and phosphorus, thereby reducing the risk of algal blooms in nearby waterways (Laird, 2010). Biochar has the water filtration potential to improve water quality by adsorbing pollutants such as heavy metals and organic contaminants. A study published in the journal Environmental Science & Technology found that biochar reduced the concentration of contaminants in stormwater runoff by up to 90% (Novak *et al*., 2010).

Waste Management: Biochar can be produced from various types of organic waste, such as agricultural residues and food waste, thus providing a sustainable solution to waste management. A study published in the journal Waste Management found that biochar production from sewage sludge could reduce the volume of waste by up to 80% (Abdelhafez, 2020).

CONCLUSION

Biochar is a versatile material with numerous potential applications in agriculture, energy production, and environmental remediation. Biochar has emerged as a promising solution to various environmental and agricultural challenges. Its production techniques, physical, chemical, and biological properties have been extensively studied in recent years. The physical properties of biochar make it an effective soil amendment for improving soil fertility, water retention, and carbon sequestration. Biochar has also shown potential for wastewater treatment, as a feedstock for renewable energy, and as a solution to organic waste management. Future research on biochar could focus on developing sustainable and cost-effective production techniques, improving our understanding of the long-term effects of biochar application on soil health and productivity, and identifying new applications and markets for biochar. The potential use of biochar for mitigating climate change by sequestering carbon and reducing greenhouse gas emissions also warrants further investigation. Finally, efforts to promote the adoption of biochar as a sustainable solution to environmental and agricultural challenges could involve policy incentives, education and outreach, and collaboration among stakeholders in different sectors.

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