



# Agriculture Biochar Production: Applications and Challenges for Crop Improvement

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**Abstract:** The rapid growth of the global population and increasing environmental stress have intensified the need for sustainable agricultural solutions. Biochar, a carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions, has shown promising potential in enhancing soil health. Its application improves soil structure, nutrient availability, water retention, and microbial activity, while also serving as a long-term carbon sink. Biochar can limit the mobility of pesticides and heavy metals, reducing environmental risks, and can also be utilized in composting, livestock feed, and greenhouse gas mitigation. The efficiency of biochar depends on factors such as feedstock type, pyrolysis temperature, soil characteristics, and application rate. Prospects highlight biochar's role in sustainable farming and climate change mitigation; however, challenges remain in optimizing production processes, tailoring biochar properties for specific soils, and ensuring economic feasibility for large-scale adoption

**Keywords:** Rapid pyrolysis, Biomass waste, Microwave pyrolysis, Crop production, Nutrient-rich soils

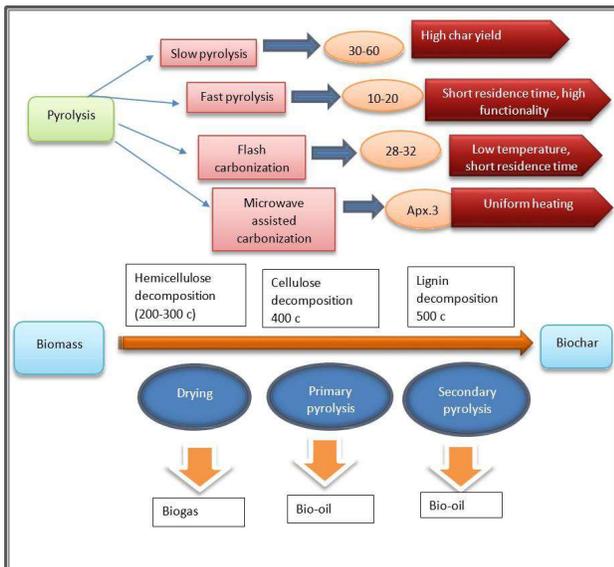
Promising strategies for ensuring food security for a growing world population include increasing production per unit area and sustainably improving agricultural productivity. Research is being conducted around the world on the potential benefits of using biochar as a solution of food security by enhancing crop productivity (Shackley et al., 2012, Vijay et al., 2015, Narzari et al., 2015, Nair et al., 2017). The application of biochar is coherent with modern green development concepts as it plays critical roles in maintaining ecosystem balance, controlling soil pollution, and the sustainable development of the agricultural environment (Zhang et al., 2021). Burning different kinds of fossil-based resources releases huge amount of carbon pollution to the atmosphere which intensifies climate change. To lessen climate change and avoid devastating consequences of global warming and climate problems, using fossil fuels as fuels needs to be pulled in (Dinca et al., 2018, Safarian 2023). In addition to the urgent requirement to reduce conventional energy resources for environmental issues, the war in Ukraine has much more strengthened effort to substitute a large quantity of conventional fuels with instant effects, for instance by using of biochar produced from biomass (Martinopoulos et al., 2018, Chaudhary et al., 2024). Biochar is a carbon-rich and porous material produced through the thermal decomposition of biomass, such as plant residues, agricultural waste, or wood, under controlled oxygen-limited conditions. This process, known as pyrolysis, involves heating the biomass to high temperatures in the absence or near absence of oxygen, preventing complete combustion.

The result is a stable form of charcoal that contains a well-structured network of pores called biochar (Liu et al., 2018, Ali et al., 2023). Biochar is an organic residue that is formed during biomass pyrolysis. Biochar, when added to soil, significantly affects soil fertility by changing the soil's chemical, biological, and physical properties (Awad et al., 2018, Awad et al., 2024). The manufacturing method, soil type and condition, crop type to be planted, and biochar resource could all affect how effective it is. The most common feedstocks used to make biochar are paper goods, animal dung, and agricultural waste. It is crucial to use these wastes to produce biochar since it is an effective method of converting waste into a substance with value (Malghani et al., 2013, Ambaye et al., 2021). The two types of pyrolysis-slow pyrolysis and fast pyrolysis-rely on the heating rate and residence time. Rapid pyrolysis yields more liquids and oils, slow pyrolysis yields more syngas. Slow pyrolysis also produces more charcoal (36%), compared to gasification (12%) and quick pyrolysis (17%) (Makepa et al., 2023). Conventional carbonization, another name for slow pyrolysis, produces biochar by heating biomass to a relatively low temperature over an extended period (days or longer) (Cao et al., 2014). Biochar is made at a higher temperature and has a very short residence period (1 sec) for rapid pyrolysis still. The yields of slow and quick pyrolysis processes are the primary difference between them (Fig. 1). The goal of crop sustainability is to market an environmentally safe alternative to traditional farm inputs, such as chemical fertilizer (Samanta et al., 2025). Pyrolysis is a desirable alternative for using

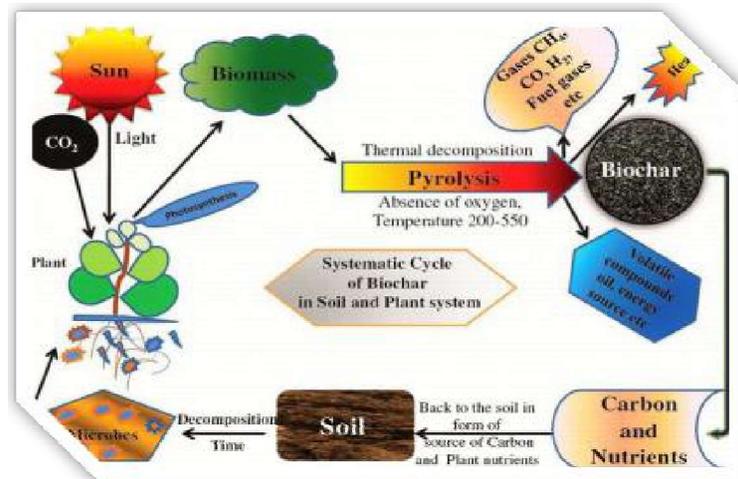
biomass waste. Based on the process parameters and is further classified into three categories that are quick, intermediate and slow. Biochar in solid form and bio-oil in liquid form are the end products of the pyrolysis process. The International Biochar Initiative states that biochar is a carbon-rich solid material obtained from biomass thermochemical conversion under oxygen-free conditions is the most widely recognized and consistent definition of biochar (Begum et al., 2024). The distribution of product yields depends on some factors, including pressure, biomass type, temperature, heating rate, and vapor residence time (Razzak 2024). Lower temperatures and gradual, moderate heating are generally found to promote this technology the biomass volume. In contrast to traditional pyrolysis illustrated that the temperature at the center of the biomass is higher than the material's surface and ambient temperature (Zaker et al., 2019).

**Slow and Fast Pyrolysis**

Slow pyrolysis was performed by placing feedstock into a paint-can fitted with a nitrogen purge (1L/min flow rate) and thermocouple for temperature measurement. The sealed can was placed into a muffle furnace and heated at approximately 15°C/min to 500°C. Corn stover (50 g) was held at 500°C for 30 minutes, switchgrass (125 g) was held at 500°C for 2 hours. The char was then cooled under nitrogen flow and stored in sealed glass jars. Mass yield of char was 33.2% and 41.0% for corn stover and switchgrass, respectively (Brewer et al., 2014). Fast pyrolysis was performed on a 5 kg/hour capacity bubbling fluidized bed reactor optimized for bio-oil production (Lehmann et al., 2011). The sand bed was fluidized with nitrogen pre-heated at 500°C. Char was collected using a high-throughput cyclone catch and cooled under nitrogen before being stored in resealable plastic bags. Therefore, phase transition phenomena and heat and mass transfer processes, as well as chemical reaction kinetics, play a vital role. So, it is important to minimize the exposure of biomass particles with the intermediate temperature to favor formation of charcoal (Brewer et al., 2014). By using microwaves in a novel way, the process is comparatively accelerated. pyrolysis of biomass involves the transfer of energy instead of heat. Pyrolysis that occurs slowly low temperatures, a prolonged residence period, and a slow heating rate are used for slow pyrolysis. Past study reported that 1 kilogram of wood processed by slow at a low heating rate at 400–500 °C will typically provide 30–35% biochar, 45–50% bio-oil, and 20–25% producing gas (Jahirul et al., 2012). In general, 70–80% of biochar is fixed carbon. It has been reported that the slow pyrolysis reactor can be divided into three categories: converters, retorts, and kilns (Garcia-Nunez et al., 2017). Industrial-scale reactors known as retorts are able to extract a volatile fraction and biochar (Fig. 2).



**Fig. 1.** Pyrolysis & biomass formation



**Fig. 2.** Biochar production and applied as a soil amendment (Saha et al., 2022)

### Microwave Pyrolysis (MP)

Microwave based technology is an alternative heating method and has already been successfully used in biomass pyrolysis for biochar and biofuel production thanks to its fast, volumetric, selective and efficient heating. Previous review mainly focused on production and analysis of bio-oil and gas instead of biochar. The current paper provides a review of microwave-assisted pyrolysis (MP) of biomass and its biochar characteristics, including product distribution and biochar yield, biochar properties, microwave absorbers (MA) and catalysts commonly used in MP, as well as comparison of biochar derived from MP and conventional pyrolysis (Li et al., 2016). It has reported that microwave heating (MH) technique offers several advantages over conventional heating based on previous research, such as more controllable, high-energy efficiency and cost effectiveness (Sun et al., 2016). MH offers a potentially attractive alternative to CP systems owing to its energy transfer rather than heat transfer, non-contact and rapid heating, selective and volumetric heating, high level of safety, as well as quick startup and shutdown. Numerous results have shown that MH is better than conventional. The biochar products can be widely applied in various environmental fields, such as carbon capture and sequestration, soil amendment, adsorption of contaminants in soil, water, and air, and energy production. Nevertheless, challenges remain for these new trends, such as the increase in cost for the installation and operation, the lack of knowledge of the mechanism involved during pyrolysis, the difficulty in scaling up, etc. Further studies are recommended to facilitate the application of these new trends, such as pilot tests or field experiments to evaluate the real effects of biochar products prior to large-scale applications or their long-term risk during use, or prediction of properties of biochar and their impact on environmental applications using modeling or machine learning approaches (Jahirul et al., 20012).

It is a crucial factor to select feedstock selection for biochar affecting soil CH<sub>4</sub> emissions. Biochar from manure or straw has a low C/N ratio and contains many low-molecular-weight organic compounds, leading to increased available C for methanogenesis and ultimately increasing CH<sub>4</sub> production (Lehmann et al., 2011, Mallik et al., 2024). In contrast, wood/cellulose-derived biochar decreases CH<sub>4</sub> emissions due to the greater porosity resulting from preserving the pore structure during pyrolysis due to lignin's stability (Fungo et al., 2014). Soil aeration can be better by excessive porosity. Biowaste biochar amendments decrease CH<sub>4</sub> emissions have been utilized in the process of biochar production (Fig. 3).

**Biochar properties:** Biochar porosity and its surface affect

metal sorption capacity. When pyrolyzing bio-mass material, micro-pores are formed in biochar because of water loss in the dehydration process (Yin et al., 2016). Biochar has different pore sizes, if the size is below 2.00 nm, then they are micro, if is above 50.00 nm then it is macro-pores and nano if it is less than 0.900 nm, respectively. Its porosity and surface area changes significantly with pyrolysis temperature. Increasing the temperature from 500 to 950°C, the porous structure of biosolids biochar increases between 0.059 and 0.1 cm<sup>3</sup>/g, the surface area also increases from 25.7 to 68.9 m<sup>2</sup>/g (Zhou et al., 2017).

**Biochar benefits:** Biochar significantly reduces nutrient leaching and nitrous oxide (N<sub>2</sub>O) emissions. Research indicates that N<sub>2</sub>O emissions can decrease by approximately 83% following biochar application, which also contributes to reduced gaseous nitrogen losses. These benefits, coupled with its role as a soil conditioner and organic fertilizer, enhance carbon sequestration, soil fertility, microbial activity, pH levels, nutrient recycling, and water-holding capacity, while also mitigating soil contamination (Dong et al., 2017, Nguyen et al., 2019,). Bulk density and porosity are affected by water storage capacity, such soil characteristics are affected by biochar application (Fig. 4). Biochar affects nutrients holding basically for acidic, hydrophilic characteristics. It also increases nutrient retention. It is effective in soil conditioning. Due to agricultural activities, organic carbon merely deteriorates daily (Xia et al., 2017). For the agricultural yields, the presence of carbon is very important. Biochar can be used in removing toxic pollutants from soil. Organic carbon that presents in biochar depends on the source of materials. Carbon sequestration applications are increasing. The ability of biochar to increase

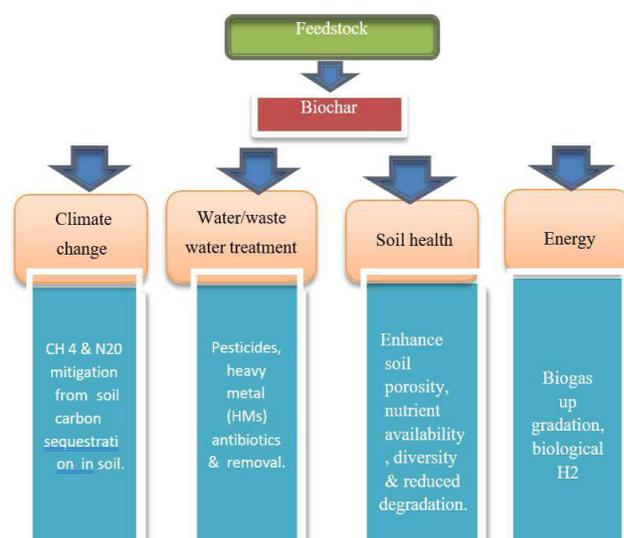


Fig. 3. Factor influences on biochar production

crop yield may decline over time, which may be attributed to nutrients being taken up by plants or leached out of the biochar (Alkharabsheh et al., 2021) and the microporous structure of the biochar becoming rougher and gradually collapsing which may leads to decrease rates of ammonium (NH<sub>4</sub><sup>+</sup>) - nitrogen (N<sub>2</sub>) fixation and nitrification (Xu et al., 2024). In India most of the work on biochar is concentrated to its application in agricultural sector to improve soil quality and as a sustainable method for waste management (Godwin et al., 2019). Nevertheless, some research has reported effect biochar application in production of catalysts, their activation

and their analyses for potential use in removal of toxic elements from soil and water (Jin et al., 2025, Islam et al., 2024). Past study has also reported conversion of a problematic aquatic weed to charcoal by pyrolysis for energy production (Kataki and Kataki, 2022.).

**Impact on crop productivity and soil health:** Biochar applications may substantially improve soil fertility and crop productivity. For, instance, biochar application (68 t ha<sup>-1</sup>) increased biomass in rice (*Oryza sativa* L.) and cowpea (*Vigna unguiculata* (L.) Walp) by 20 and 50 %, respectively, and at 136.75 t ha<sup>-1</sup> increased cowpea biomass by 100 % (Adekiya 2022). Biochar addition improved biomass and grain yields in durum wheat (*Triticum durum* L.) by up to 30 %, but there was no effect on grain N content (Vaccari et al., 2011). Past study also reported that increases of 91% and 44 % in grain and biomass yield, respectively, in maize (*Zea mays* L.) on charcoal-amended soils when compared with adjacent field soils in Ghana (Yeboah et al., 2022). Likewise, in Kenya, maize yield in degraded soils doubled with the addition of Eucalyptus-derived biochar (Borah et al., 2020). Several studies have indicated the strong potential of biochar application for improving crop yields, particularly on nutrient-poor soils (Van-Zwieten et al., 2010, Zhang and Ok 2014). The effect on crop yields, particularly in nutrient-rich soils, remains uncertain. Several other studies have revealed only small improvements or even reductions in grain yield with

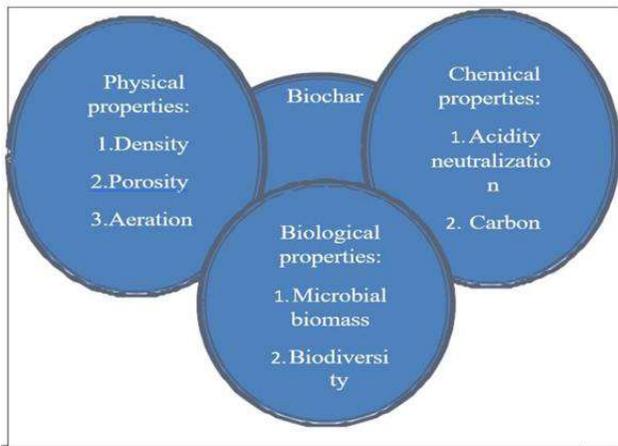


Fig. 4. Properties of biochar

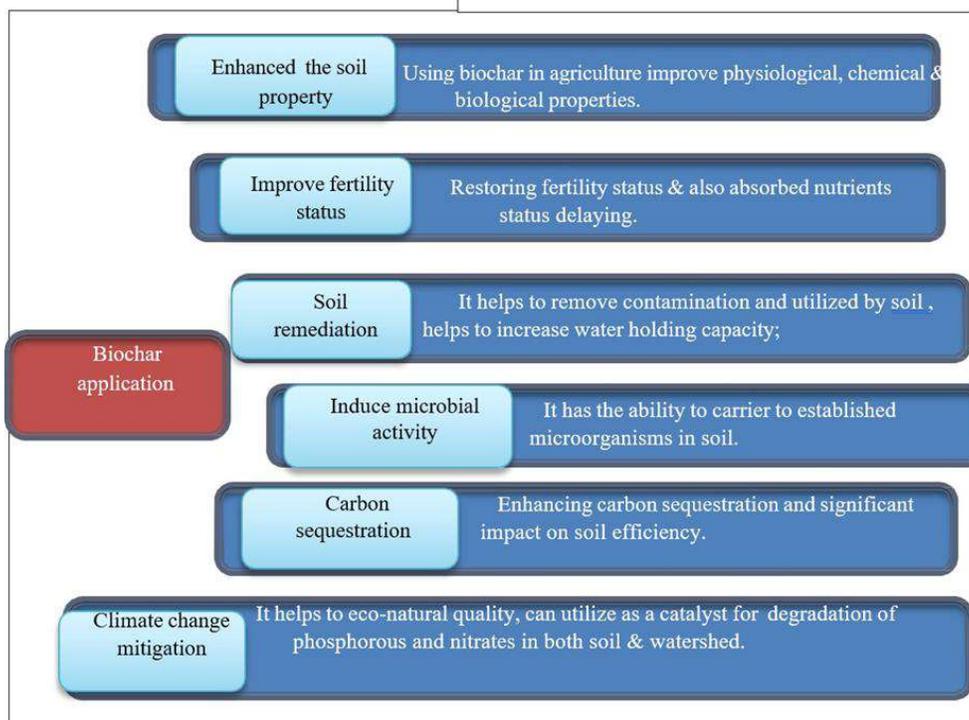


Fig. 5. Different applications of biochar in crop production

biochar application in nutrient-rich soils (Hussain et al., 2017). It has also been reported that there is a linear decrease in grain yield with increasing rates of biochar application (Huang et al., 2019). Biochar is known to improve physical, chemical, and biological properties in soil. The effect of biochar application on soil physicochemical properties, nutrient availability, and soil biota is discussed in the following sections (Fig. 5). Addition of biochar in soils improved soil stability due to improved soil aggregation (Novotny et al., 2015, Rafi et al., 2022). Increased soil carbon stock is the most pronounced effect of biochar soil application (Lehmann et al., 2011, Zhang and Ok 2014). Merging bioenergy production with the application of pyrolysis by-product biochar in soil removes CO<sub>2</sub> from the atmosphere, as more carbon is sequestered than emitted (Roberts et al., 2010). It has also been reported that 20 % more CO<sub>2</sub> is captured from the atmosphere and sequestered by biochar soil amendment (Mulabagal et al., 2017). However, certain risks such as the potential source of toxicants, retention of heavy metals, and the suppression of the efficacy of applied pesticides due to retention and ecotoxicology effects on soil microbes are linked with biochar addition to arable land (Alengebawy et al., 2021) As the biochar are in the dust form, they may be dangerous to humans during their application to agricultural soils. For example, rice husk biochar pyrolyzed at higher temperatures may possess toxic crystalline materials, e.g., silica which are very harmful to human health, and they can affect the respiratory system if they enter during the biochar application process in soil.

### CONCLUSIONS

In developing countries, crop residue has traditionally been used as animal feed. When not used as animal feed, it becomes a huge surplus biomass, and farmers burning it create a hazy and smoky environment. Conversion of such surplus biomass into biochar circumvents this problem and creates employment and economic opportunities. Quality biochar with high fixed carbon content can be produced by maintaining a reactor temperature between 400 and 600 °C. As a carbon sink, biochar also contributes to atmospheric carbon sequestration, particularly when its oxygen-to-carbon molar ratio is below 0.2, promoting its longevity in the soil. While short-term studies indicate positive impacts on crop yield, the long-term effects on soil health warrant further investigation. Our findings demonstrate biochar's efficacy as a soil amendment in Alentejo, offering a strategy to mitigate environmental concerns within agricultural practices. However, broader adoption and societal benefit necessitate increased efforts to promote its use and capitalize on its positive externalities. The biomass-to-biochar conversion

process, encompassing cultivation, collection, transport, and pyrolysis, involves considerable energy and CO<sub>2</sub> emissions, with pyrolysis being a major contributor. Enhancing the efficiency of this process, particularly pyrolysis, is crucial for minimizing the carbon footprint associated with biochar production and maximizing its environmental benefits from pyrolysis, so improving its efficiency could notably shrink the carbon footprint.

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