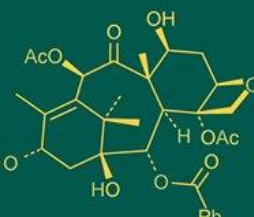


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Role of biochar in sustainable agriculture: Effects on soil properties and plant growth

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Abstract

Nowadays Agriculture land face increasing challenges from soil degradation, nutrient loss, and climate change. The search for sustainable solutions has become more important than ever. Out of variable option Biochar has gained significant attention due to its physiochemical properties and environment friendly nature. It act as a sustainable solution for improving soil health and agricultural productivity. Biochar can be produced using various precursor via different technique. Biochar improves physical, chemical, biological properties of soil by improving water retention, nutrient availability, soil structure, and microbial activity. Biochar also increase the tolerance to the environment stress (draught, salinity). Biochar also act as long term carbon sink and reduce the green house gas emission. In this review we will discuss regarding sources, production methods, physicochemical properties, and agricultural applications of biochar.

Keywords: Biochar, agriculture, pyrolysis, soil, crops yield

Introduction

Sustainable agriculture has came up as an analytical method to satisfy the growing global food demand without environmental degradation and while preserving natural resources [1]. Due to conventional agriculture soil degradation, nutrient depletion, and increased greenhouse gas emissions affect the long-term productivity and ecosystem stability [2]. The integration of carbon rich biochar into agricultural systems has emerge as a promising strategy for enhancing soil structure and nutrient retention [3]. Biochar, a solid carbon rich material produced through the pyrolysis of Biomass, has emerged as a promising amendment for improving soil fertility and mitigating agriculture stressors [4]. As the biochar was derived from various sources like agricultural residues, forestry waste, and animal manure which leads to unique physicochemical properties of Biochar which is highly suitable for soil application [5]. Once biochar was applied in soil it has been reported to enhance soil physical, chemical, and biological properties. It improves soil structure, increases water retention capacity, and enhances nutrient availability [6]. Biochar also assist microbial activity and stabilize organic carbon in soil, which is essential for long-term soil productivity. All this improvement help in plant growth and increase crop yield and help in surviving under too much environmental stress (draught, salinity) [7]. Biochar also help in mitigating the climate change through carbon sequestration and reduction of greenhouse gas emissions [8]. The properties of Biochar depend on various factor (feedstock type, production conditions, and application rate). Nanobiochar was synthesized using Rice husk via pyrolysis (600 °C for 2h) continued with ultra sonication and centrifugation. This process yield 27.5% Biochar and 0.9% nanobiochar. Nanobiochar act as maximum dye removal for waste water dye remediation [9]. Silver embedded wheat straw biochar was produced using pyrolysis at 450-500 °C. In this silver is also extracted from Ligustrum lucidum leaf. It act as an efficient green nano-adsorbent for phenol removal from wastewater through adsorption and sono-adsorption processes [10].

What is Biochar?

Biochar is a recalcitrant, carbon-rich amendment produced through pyrolysis of diverse biomass feedstock, which holds significant potential for optimizing soil physiochemical properties and enhancing agricultural sustainability hence gaining considerable attention in recent years [11].

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Fig 1: Biochar

Biochar-specific properties such as high porosity and large surface area, facilitate improved soil aeration, water retention and bulk density modulation, which are critical for optimal root system development. It is a strong carbon material with a high degree of aromatization ^[12].

Precursor of Biochar

Biochar was mainly produced via wide range of biomass which has strong impact on physicochemical properties of Biochar and effectiveness in agricultural applications ^[13]. There are so many common feedstocks include agricultural residue like rice husk, wheat straw, corn stover, and sugarcane bagasse, These option are widely available and cheap in cost. There are few residue from forest like wood chips, bark, and sawdust it is mainly used due to presence of high percentage of lignin content ^[14].

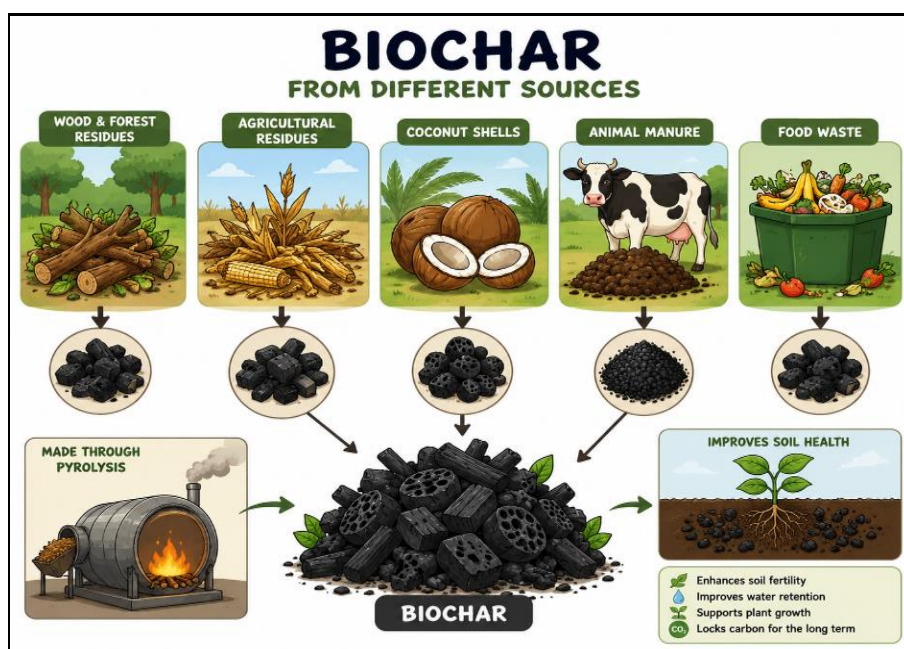


Fig 2: Schematic representation of various biochar feedstock sources.

There are few more option for precursor of biochar like animal manure including poultry litter and cattle dung will produce nutrient rich biochar with high concentration of Nitrogen, Phosphorus, Potassium. If we compare both plant

based biochar and manure based biochar, in plant based biochar it having high carbon stability and other having nutrient availability ^[15].

Table 1: Common Precursors Used for Biochar Production ^[16]

S/No.	Raw material for Biochar	
1.	Industrial waste	Peels
		Fibre
		Textile
		Paper
2.	Aqua waste	Sea weed
		Periwinkle shell
		Fish scale
		Algae
3.	Forest residue	Wood chip
		Saw dust
		Tree bark
		Logging residue
4.	Farming Residue	Rice husk
		Sugarcane
		Manure
		Weed

Production Methods of Biochar

Nowadays biochar production increased using biomass due its various application. There are various method for production of biochar like pyrolysis, gasification, hydrothermal carbonization and torrefaction ^[11]. Biochar produce via pyrolysis (Pyro means fire and lysis means breakdown) is a process defined by the thermochemical decomposition of biomass in oxygen-limited environments, yields a highly porous, carbon rich material capable of sequestering carbon while mitigating soil degradation ^[17].

There are mainly two type of pyrolysis (Slow pyrolysis and Fast pyrolysis) In slow pyrolysis, the process temperature is between 300-500°C with longer times, it help to produce high yield of biochar with high stability carbon and high porosity. It promote sustainable agricultural productivity. In fast pyrolysis, the process temperature are too high, and have short residence time, this process help for bio-oil production instead of Biochar ^[18]. There are various other types of pyrolysis like flash pyrolysis, vaccum pyrolysis and intermediate pyrolysis ^[11].

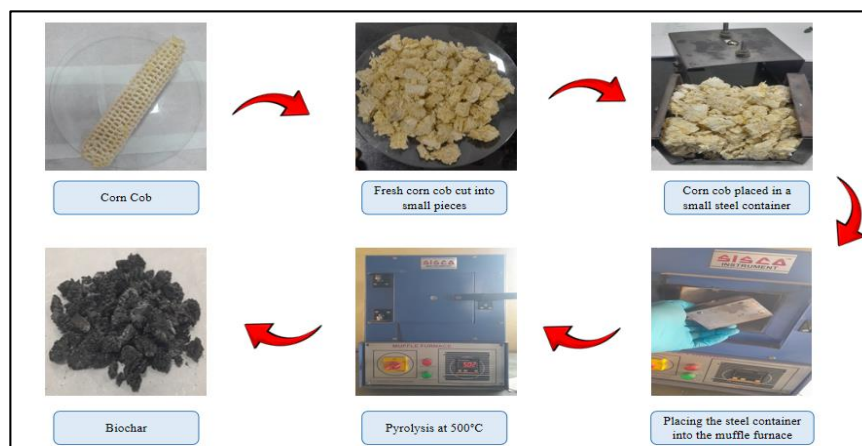


Fig 3: Synthesis of Biochar via pyrolysis

Other than pyrolysis there is another technique named Gassification, This process occur in High temperature always more than 700 °C with presence of gasification agent oxygen. But in this technique also syngas was produced and biochar as side product (in small quantity). Syngas includes Carbon monoxide, Carbon dioxide, Methane, Hydrogen ^[19]. One more technique is torrefaction which is a hydrothermal process where heating at 200-300 °C in low oxygen environment, in this 70% of Biomass remain as solid biochar and remaining came out as gases and condensable side product ^[43]. Biochar yield and quality totally depend on production parameter like Temperature, Heating rate, residence time. During pyrolysis high temperature was provided, It usually help in increasing surface area and aromaticity and functional group ^[20]. Hydrothermal carbonization is a technique occur in 180-300 °C with a residence time 1-16 h. Via this technique biochar production was around 50-80% and bio-oil and syngas produce as side

product ^[21].

Biochar nanodot synthesized from soyabean straw and cattle manure via pyrolysis and continued with hydrothermal treatment using nitric and sulphuric acid. After characterization of nanodot sizes are confirmed as about 4-5nm. It showed potential application in environmental remediation, water treatment, and sustainable agriculture ^[22]. Biochar is synthesized using rice husk by hydrolysis under ambient temperature and pressure with an acid catalyst (H₂SO₄). This technique used as alternate conventional pyrolysis. SiO₂ is a byproduct in this process ^[23]. Biochar was produced using hydrothermal carbonization under optimized condition (187 °C, 8 h reaction time, and 1.19 mol/L H₃PO₄ concentration). The synthesized biochar showed improved adsorption capacity and achieved about 46% removal of 2,4-dichlorophenol (2,4-DCP) from wastewater ^[24].

Table 2: Different Techniques Used for Biochar Production

Technique	Process temperature (°C)	Residence time	Yield%	Reference
Slow pyrolysis	300-700	2 sec	Biochar-35 Bio-oil-30 Syngas-35	[39]
Fast pyrolysis	500-1000	1-24 h	Biochar-12 Bio-oil-75 Syngas-13	[40]
Hydrothermal carbonization	180-300	1-16h	Biochar-50-80 Bio-oil-5-20 Syngas-2-5	[41]
Gasification	700-900	10-20 sec	Biochar-10 Bio-oil-5 Syngas-85	[42]
Torrefaction	200-300	10-60 min	Biochar-80 Bio-oil-0 Syngas-20	[43]
Flash carbonization	300-600	More than 30 min	Biochar-37 Bio-oil- Syngas-	[44]

Physicochemical Properties of Biochar

Biochar is a solid substance produced via carbonization of biomass. It is characterized by a highly porous structure and diverse array of surface functional groups, which fundamentally dictate its interaction with soil matrices and nutrient retention capacity. It will be having Higher carbon content and Energy value and lower hydrogen and oxygen content [25].

Physical property

Biochar has high porosity and it contain macro, meso and micro pores, it act like a sponge. In macropore the pore size is more than 50 nm, these function as pathway for root penetration and habitat for soil microbe. In mesopore the pore size is 2 to 50 nm it usually act as storage space for liquid water and nutrient molecule. In micropore the pore size is less than 2 nm [26]. Biochar have specific surface area, mechanical strength and physical stability, The physical structure of biochar is highly stable due to rigid aromatic carbon matrix so biochar maintain shape in soil for long period of time. Biochar has high water retention property, it trap water within the pores, it help to reduce soil runoff.

Biochar also help in reduce soil compaction and improve root aeration [27].

Chemical property

Biochar is alkaline in nature (7 to 10), due to this basic nature it is very helpful in neutralizing acidic soils for cultivation. Lime is globally used to manage the acidic soil. High cost and its scarcity reduced the usage in many area. To overcome this issue biochar produced using rice husk and corn cob is very much helpful to tackle soil acidity [28]. Biochar are having high cation exchange capacity, it hold on positively charge nutrient like Calcium, magnesium and potassium. It also contain functional group like hydroxyl group, carboxyl group, phenolic group. It has high carbon content, it consist fixed carbon. Biochar contribute nutrient to the soil, it also adsorbs toxic substance like heavy metals. In one study it was seen that biochar synthesis using peanut shell and cattle manure are very much helpful in decrease in exchanging Al and H ion and increase the cation exchange capacity [29]. Biochar synthesis using pecan shell at temperature below 700 °C having neutral pH (7.2) and high surface area (222 m²/g), with 92% carbon content [45].

Table 3: Properties of Biochar [30]

Property Type	Key features	Benefit in soil
Physical	High porosity Low density	Improves water retention & aeration
Chemical	Alkaline Ph High cation exchange capacity	Enhances nutrient availability
Structural	Functional group Carbon stability	Long-term soil fertility & carbon storage

Effect of Biochar on Soil Fertility

Biochar refine soil fertility by boost the physical, chemical, and biological properties of soil. If we talk about physical improvement. Biochar application in soil upgrade the structure of soil, increase porosity, bulk density reduce and aeration will improve and filtration of water. For sandy soil, Biochar help to hold water and maintain the nutrient and for clay soil biochar help in improving the drainage and reduce compaction [31].

Chemically, Biochar help in maintaining soil pH because pH of biochar is alkaline so it help in neutralizing the pH of soil especially in acidic soil [28]. Even Biochar help reducing aluminum toxicity and improving nutrient availability. Biochar also help improving cation exchange capacity, which help soil maintain essential nutrients such as potassium (K), calcium (Ca), magnesium (Mg), and ammonium (NH₄⁺). Biochar has ash and mineral nutrient which support soil fertility [29].



Fig 4: Enhancement of soil fertility through the physical, chemical, and biological properties of biochar.

Biologically, Biochar support favourable environment for beneficial soil microorganisms (nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi). The micropores in biochar act as microhabitat for growth and nutrient cycle of microorganisms by protecting them from

environmental stress and predators [32]. Microbial activity improve soil health and fertility by improving decomposition and nutrient mineralization. Biochar application in soil increase microbial biomass and diversity. Biochar also improve soil enzyme activity in carbon,

nitrogen, and phosphorus cycling. Better soil enzyme activity increase decomposition and nutrient mineralization processes [33]. As biochar adsorb toxic chemical and heavy metal, it help microbe for there growth by providing more favourable environment and reducing stress [34].

Effect of Biochar on Plant Growth and Crop Yield

Effect of biochar application on plants show positive effect through multiple mechanism. Biochar improve nutrient

availability, better water retention, enhanced microbial activity, and improved soil structure which sustain healthy plant growth [35]. Biochar enhance seed germination by holding up the water, maintaining moisture in soil and aeration condition. Biochar also help in root development by reducing soil compaction. Root growth allow palnt to absorb water and nutrient. Soil with poor nutrient, after biochar application in soil lead to yield improvement [36].

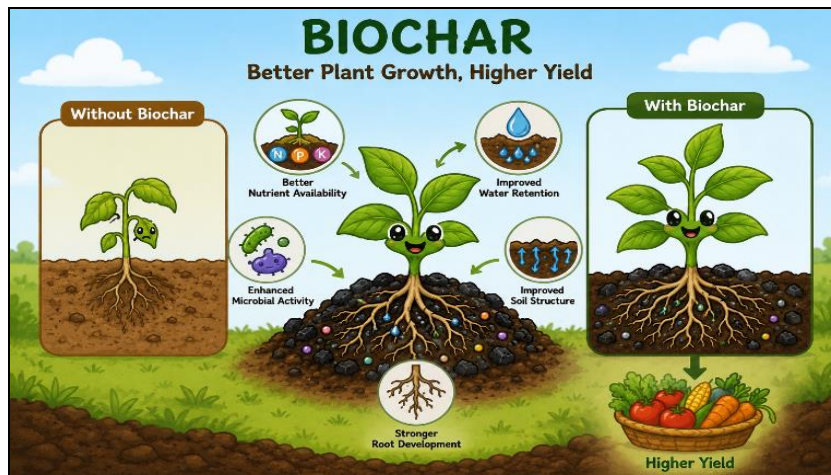


Fig 5: Effects of biochar application on plant growth and crop yield.

Biochar for Carbon Sequestration and Climate Change Mitigation

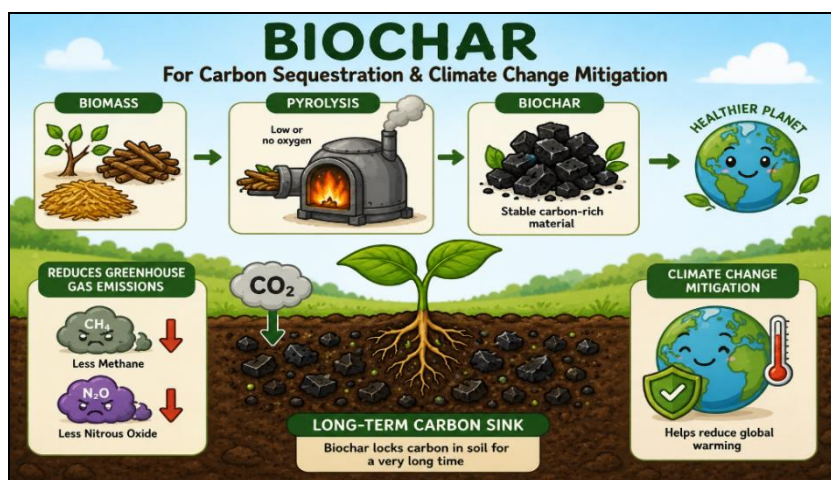


Fig 6: Role of biochar in carbon sequestration and climate change mitigation.

Biochar is a effective tool for carbon sequestration and climate change mitigation [37]. Biochar is produced through a thermochemical process by converting biomass into stable carbon-rich material under no or less oxygen [17]. In this process few portion of carbon becomes resistant to microbial decomposition, due to this biochar remain in soil for a very long period of time. Biochar application in soil act as a long-term carbon sink by hindering the fast release of CO₂ into environment. Biochar can reduce the emission of greenhouse gases (Methane, nitrous oxide). So Biochar contribute to climate mitigation [38].

Conclusion

To solve the agriculture land issue Biochar came up as a best solution that fulfil the gap between productivity and environment safekeeping. Biochar benefit are not only limited to agriculture field. Biochar improve soil fertility

and crop performance to mitigating climate change through carbon sequestration. The material which is once accepted as waste can now be transformed into valuable resource with lot of benefit as supporting future food security. Biochar is a one stop resolution for all different issue.

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Authors' Contributions

Ayithe Santhosh Chandra Balaji (ASCB) conducted the literature survey, compiled and analysed the scientific information, and prepared the initial draft of the manuscript. Dr. Kiranmai Chadipiralla (KC) conceptualized the review topic, provided academic guidance, supervised the work, and critically reviewed the manuscript.

Ms. Ankita Nandi (AN) contributed to literature collection, scientific discussions, manuscript editing, and interpretation of the reviewed studies.

Dr. Jagadeesh U (JU) provided technical guidance, reviewed the manuscript critically for intellectual content, and approved the final version for publication.

All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflict of interest.

Ethical Approval

This article is a review article and does not contain any studies involving human participants or animals performed by any of the authors. Therefore, ethical approval was not required.

Informed Consent

Not applicable.

Declaration of Generative AI and AI-Assisted Technologies

The authors used generative artificial intelligence (AI) tools during the preparation of this manuscript for language refinement and the creation of illustrative figures included in the review article. The authors carefully reviewed, edited, and validated all AI-generated content and images to ensure their scientific accuracy, originality, and appropriateness. The authors take full responsibility for the content of this publication.

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