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Role of Biochar in Agriculture to Enhance Crop Productivity: An Overview

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Abstract: Biochar is a carbon-rich material with potential applications in agriculture, industry, and the energy sector. It has significant application in agriculture to enhance crop production, soil condition, nutrient uptake, and carbon sequestration due to its unique characteristics like high surface area and pore volume. This review focuses on biochar as an agricultural additive to enhance crop productivity and improve soil health and the potential benefits as a material for growth media and composting. Co-composting of biochar produced from various organic sources can stabilize the soil, repair degraded land, and reduce carbon emissions associated with agriculture. In conclusion, it was found that biochar is also used as growing media for a hydroponic system, which enhances the growth of high-value food crops to meet the increased food demand. Furthermore, the biochar-based soilless alternative to traditional farming may provide a more environmentally-friendly system for growing food and reduce the demand for chemical fertilizers, significantly reducing greenhouse gas emissions.

Keywords: biochar; farm productivity; soil abetments; crop residue; growing media.

1. Introduction

With an increasing population worldwide, the agricultural system is under rising pressure. The constantly growing demand for grains and organic food makes farmers use uncontrolled synthetic fertilizers and chemical inputs to increase production [1–3]. The consequences are hardened soil, reduced soil fertility, contaminated air and water, and greenhouse gas emissions [4,5]. This leads to the production of massive organic waste [6]. The utilization of biowaste to produce biochar could solve the disposal and management of agricultural waste. Biochar is a carbon-rich material obtained by heating biomass in the absence of air [7–10]. The type and composition of the feedstock particle size, reaction temperature, heating rate, and reactor parameters all affect the efficiency of biochar formation from biomass[11]. Unique physical and chemical characteristics of biochar, like large surface area, high pore volume, high cation exchange capacity, and functional groups, make it suitable for a wide range of applications [12,13]. Its applications impact soil characteristics, soil texture, and greenhouse gas emission control [14]. Multiple nutrient inadequacies related to severe soil nutrient deficiency have emerged as the most significant global constraint to agriculture's long-term viability. [15,16]. Biochar applications in the soil improved crop production, soil condition, nutrient uptake, and carbon sequestration [17–19].

The increased need for food demand is met through an improved farming system by combining some controlled environment agriculture such as hydroponics, aquaponics, and aeroponics [20–22]. A soilless alternative to traditional farming may provide a more environmentally-friendly system for growing our food [13,23,24]. Biochar has received greater attention during the past few years due to its potential use in agriculture, the energy sector, and for environmental purposes. To ensure the optimum growth of plants, regulation of growth conditions is one of the key factors in firms adopting soilless agriculture [25]. Biochar has similar physicochemical characteristics to coir and peat and can be utilized as an alternate growing medium [26,27]. Dunlop *et al*. used biochar as a medium for the soilless, hydroponic production of vegetables [28].

In recent years, biochar has been used as an additive to composting and soil remediation to control greenhouse gases and NH_3, humidification, and inactivate heavy and organic pollutants. The application of compost and biochar as soil amendments is affordable and long-lasting, with a positive impact on soil enhancement and the growth of plants [15,29,30]. The different applications of biochar are shown in Figure 1; apart from this, biochar makes a good sustainable fuel [31].

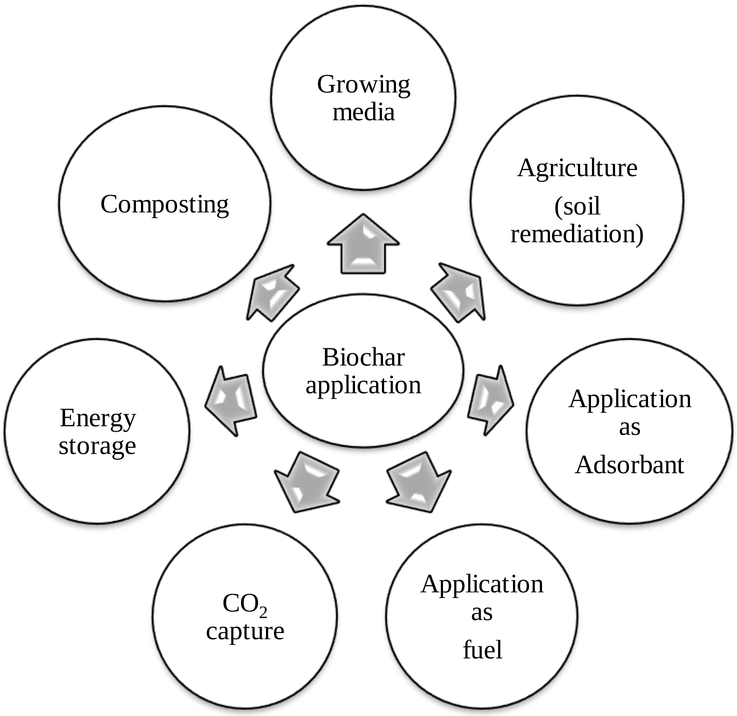

Figure 1. Potential biochar application.

This paper provides an overview of biochar production technology, its application in agriculture to increase production and soil remediation, biochar production methodology in rural areas, the impact of biochar on soil health and crop yield, how biochar is used as a substrate for growing media and as a compost additive, and the environmental impact of biochar after application.

2. Biochar Production Technology

Humans have been producing and using biochar for over 2500 years [32]. Several ancient biochar production methods have been modified as humans have progressed and science has advanced. The two primary categories of biochar production methods, traditional and modern, are shown in Fig. 2 based on their advancements and modernization [6].

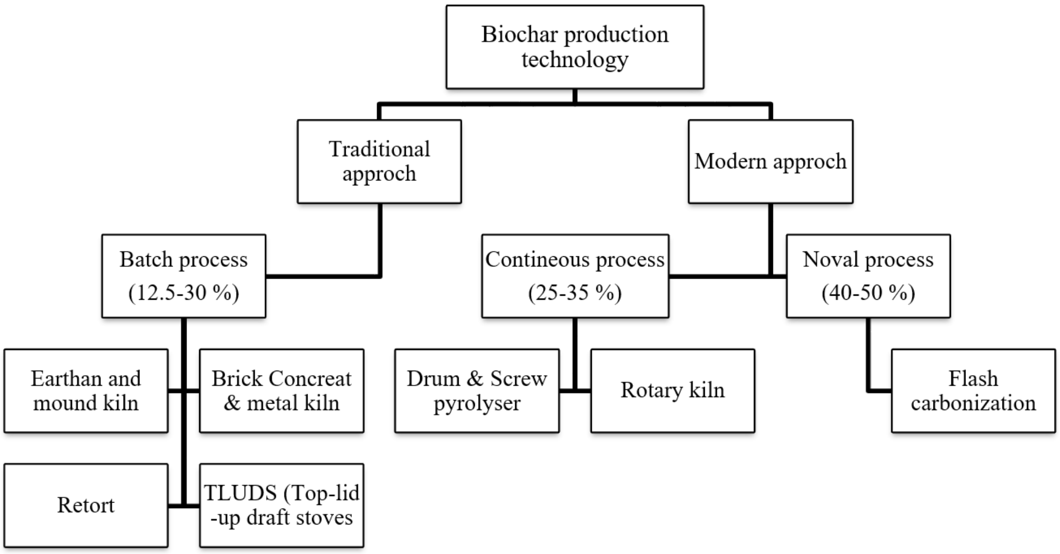

Figure 2. Biochar production technology.

Traditional charcoal production is carried out using batch processes, including earthen and mound kilns and pits [33,34]. Only high-value wood logs are used in kilns and pits, whereas in brick, metal kilns, and retort systems, the feedstock wood can be combined with dry bio-waste materials[35–40]. The biochar yield in the batch process varies from 12.5–30% due to its low operational and construction costs and is still preferred in rural areas [41]. TLUDs (top-lid up-draft stoves) may be used for horticulture or small kitchen gardens but have a limited production capacity [42,43] of 0.5 kg to 10 kg.

In recent years, biochar production methods have undergone several modifications and changes. Flash carbonization, gasification, torrefactions, hydrothermal carbonization, electro-modified techniques, and microwave pyrolysis have been developed to produce biochar. The use of modern practices for biochar production speeds up the process while improving the quality of the biochar [44]. In addition, it can be used to recover high-value products like solid biochar, liquid bio-oil, and volatile compounds [45]. Slow pyrolysis yielded 35% of biochar [46], flash carbonization yielded 37% [47], gasification yielded 10% [48], and torrefaction yielded 80% [49].

3. Biochar Production Process

Biochar production from agriculture residue starts with biomass feeding into the combustion chamber in the absence of air. There are mainly five production stages: drying, conditioning, torrefaction, exothermic pyrolysis, and endothermic pyrolysis at different temperatures. As the temperature rose to 150–180 °C, the biomass conditioning process began, releasing carbon dioxide. The biomass breakdown starts during the torrefaction phase at 180–250 °C, producing carbon dioxide and carbon monoxide. When an exothermic reaction begins at about 250–400 °C, it produces a significant quantity of heat, and condensable vapors such as water, acetic acid, methanol, acetone, etc., and tar are the prevailing products when the temperature rises to 400 °C. When the temperature rises above 450 °C, it is possible to convert biomass to biochar. The biochar production process is practically completed, but biochar contains considerable amounts of tar. To avoid this further, increase the temperature up to 500

°C to complete the carbonization stage [50]. The production process of biochar is shown in Figure 3.

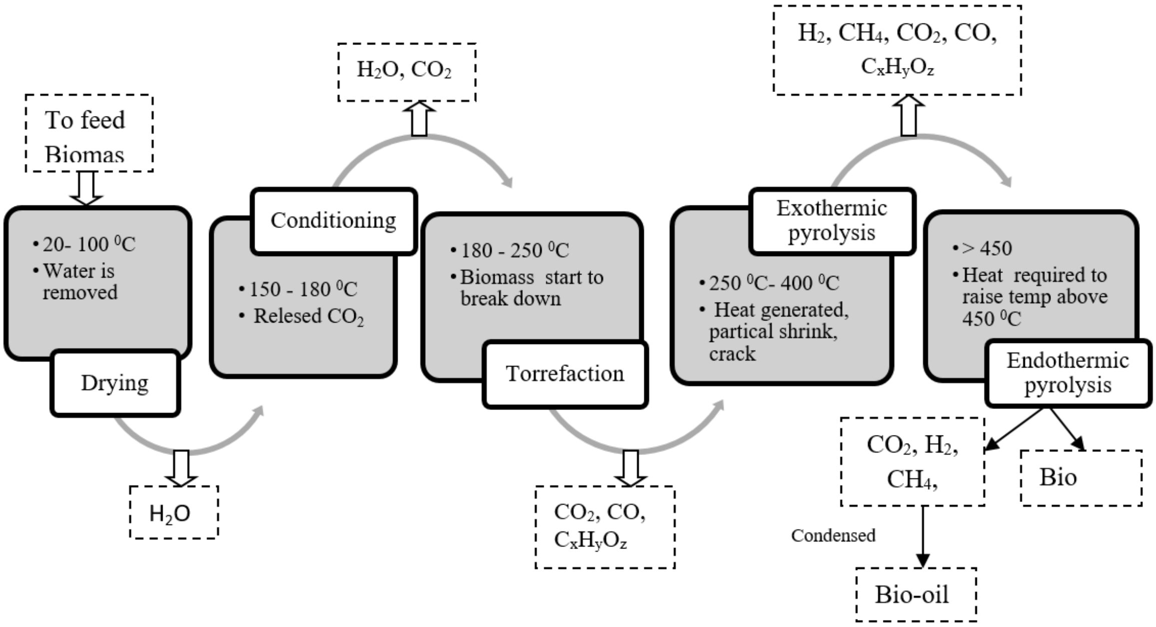

Figure 3. Biochar production process.

4. Impact of Biochar

4.1. Soil health.

Biochar is attracting huge interest due to its significant advantages to agriculture as it can hold soil water [51]. In addition, applying biochar to soil has shown the potential to decrease nutrient leaching, increase yield, and improve nutrient usage efficiency, as shown in Figure 4 [52–54].

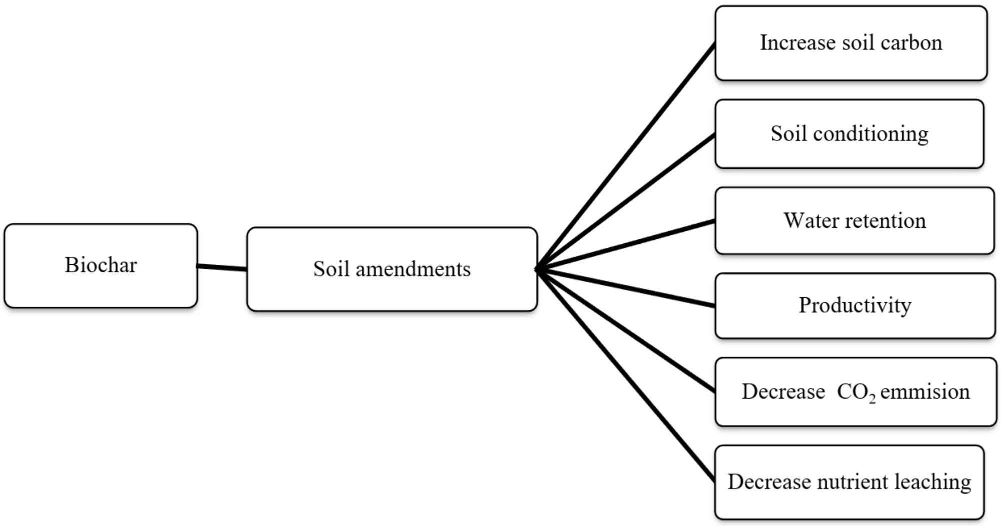

Figure 4. Impact of biochar on soil health.

Furthermore, biochar efficiently sequesters massive amounts of carbon in soil over time, thus increasing soil fertility and crop productivity and mitigating global warming [55,56]. Various parameters such as feedstock type, pyrolysis chamber temperature, soil type, and biotic interactions were discovered to influence the efficiency of biochar application in agricultural environments [57]. Biochar has the capacity to absorb carbon and reduce greenhouse gas emissions in the soil [58]. Tanure *et al*., applied the biochar to a maize crop with two particle sizes (2.0−0.5 and<0.5 mm) at six doses (0, 5, 10, 20, 40, and 60 g/kg) under two soil moisture conditions in a greenhouse environment. It was found that biochar boosted the photosynthesis process, stomatal conductance, moisture retention, pore ratio, reduced bulk density, and fertility when added to soil [59]. Biochar also increases the water-holding capacity of the soil. Singh *et al*. applied biochar on the paddy field to minimize the CH_4 production and showed higher CH_4 consumption because it improves the aeration and porosity of soil [55]. Similarly, Liu *et al*., examine the impact of biochar on yield-scaled greenhouse gas intensity. The results found that biochar considerably reduced yield-scaled greenhouse gas intensity by 29% [60].

Biochar impacts the properties of soil and density because of its highly porous nature and large surface area. The direct benefits of biochar additions to the soil are due to higher potassium, phosphorus, and zinc availability and, to a lesser extent, calcium and copper availability [61]. Biochar enhances soil pH and lowers the exchangeable acidity because of its high magnesium and calcium content [62]. Mohawesh studied the use of biochar to study the soil properties during the cultivation of tomato and bell pepper plants and found that soil pH increased by 1.4% to 7.3%, and electrical conductivity increased by 12.3% and 107.8% after the application of biochar at 8 t/ha and 40 t/ha, respectively [63]. Lucchini *et al*. applied wood biochar in field plants (barley, beans) at the rates of 25 and 50 t/ha and found that it does not raise the metal concentrations in the soil and may be safely utilized for crop production [64]. Cation exchange capacity (CEC) is essential for soil quality, and adding biochar to the soil increases CEC. A higher CEC of soil indicates a high capability for nitrogen fixation, which is crucial for plant growth [65]. The CEC factor is mainly influenced by two different factors: pyrolysis temperature and the type of biomass [63]. Tan *et al*. stated that adding the biochar in the ratio 1:100 increased soil cation exchange capacity by 0.92 cmol kg^{-1} [66]. Further, Berihun *et al*. found the highest germination percentage of garden pea seeds (95.23%), and shoot length was significantly affected at 2 weeks and 4 weeks after biochar application at a rate of 18 t/ha [19]. Biochar can affect soil microbes in terms of pH, pore structure, surface area, sorption behavior, and nutrient content[67–69]. According to recent studies, biochar's growth-promoting effects on soil microbes have been verified [70,71]. Ge *et al*. studied the addition of biochar at a 5 t/ha rate within 10–20 cm of soil depth and increased microbial biomass [70]. The effect of wheat and miscanthus straw biochars added at 1 and 2 percent on soil enzymatic activity and the microbe count was studied, and it found that adding 1% biochar increased the number of bacteria and fungi by 380 and 26%, respectively [72]. The inclusion of biochar into acidic mine materials reduces hazardous element concentrations, improves soil characteristics, and increases microbial populations and activity [73]. Huang *et al*. observed that using biochar for extended periods can improve internal nitrogen use efficiency and crop yield [74]. Chen *et al*. examined the effect of biochar on the hydraulic characteristics of sandy soil. The study revealed that higher rates of biochar (3 and 5%) were added to the sandy soil. The results showed that water retention capacity improved [75]. In addition to this, Glab *et al*. examined small biochar particles with a diameter of fewer than 0.5 m but increased the bigger pore volume diameter in the range between 0.5 and 500 m, and their implementation enhanced the accessible moisture content, especially when the tiniest fraction (0.064 cm3cm−3) was used [17]. The positive effect of biochar on soil amendment is presented in Table 1.

Table 1. Impact of biochar amendment on soil properties

Sr no	Biochar feedstock	Effect on soil properties	References
1	Bamboo	Increasing soil moisture and soil	[70]

Sr no	Biochar feedstock	Effect on soil properties	References
		microbial biomass	
2	Wood	Increasing soil organic carbon content and soil pH	[76]
3	Pinus tabu-laeformis Carr and Robinia pseudoacacia L	Biochar application rate with an increasing in the soil organic content increased, and soil bulk density decreased	[77]
4	Hardwood	Increasing available potassium and soil organic carbon content by 300% and 37%, respectively.	[78]
5	Maize straw	Increasing fungi/bacteria ratios and soil organic carbon	[79]
6	Maize straw	Decreasing bulk density and enhancing plant available water and soil aggregate stability	[80]
7	Rice straw	Increasing soil pH	[81]
8	Rice husk	Enhanced macro and micro aggregates	[82]
9	Woody biomass	Biochar increased soil cation exchange capacity	[83]

4.2. Crop productivity

Biochar applications to soils have been demonstrated to increase net primary crop production, grain yield, and biomass production. The biochar application rates in the field, greenhouse, plot, and pot are collected and displayed in Table 2. This table summarises crop biomass and yield changes for the following biochar application rates.

The rice yield increased by 8.5-10.7% when the application rate of rice straw biochar was about 4.5 t/ha [84]. In addition to this, applying the same biochar in greenhouses at the rates of 10, 25, and 50 t/ha increased the rice and wheat yields by 12% and 17%, respectively [85]. In some studies, maize grain improved by 20% in the first year and 12.5% in the second year [86], 6% [87] by applying the biochar rate of about 10 to 25 t/ha. Similarly, biochar application had some positive effects on grain yield, such as wheat at 10% [87], 28% [88], 6.2-24.2 % [89], 17% [85], corn at 5-20% [90], common bean at 46% [91]. Further, Usman *et al.* applied biochar in a greenhouse for the tomato crop and increased the fruit yield by 14–43% [92].

Biochar produced from different organic materials on crop yield has shown a positive effect on crop yield on hardwood [87,93–96], wood [97,98], cow manure [99–101], poultry litter [102], rice husk [84,85,90]. The biomass yield increased by 50 to 300 % [87,88,103–105] by applying the biochar rate of about 10 to 60 t/ha. Some authors also revealed no impact of biochar on yield and biomass production [84,106–110].

Some authors found that the higher dose rate of biochar at 50t/ha for 21 days in a maize crop induced a severe negative effect on plant growth [98]. In addition, pine sawdust biochar was applied to sorghum crops at a rate of 45t/ha and was found to decline plant growth at higher applications [105].

Table 2. Effect of biochar application on crop yield.

S. No.	Biomass & process	Application rate	Crop grown	Effect on yield	Reference
A	**Field crop**				
1	Hardwood 500 ^{0}C	10, 20, and 30 t/ ha	Cocoyam	Increase yield 8.1, 7.8, and 5.5 %, respectively	[95]
2	Willow wood pyrolysis, 600^{0}C	10-25 t/ ha 1 crop cycle	papaya banana	Reduced banana yield by 18-24% and neutral for papaya	[97]
3	Rice straw BC (RBC) 550 °C	4.5 t /ha for two crop season	Rice	Grain yield increases by 8.5–10.7%	[84]
4	Acacia biochar 400–500 °C	25- 50 t/ ha	Maize	Increased yields in 1st year by 20% and after 2nd year by 12.5%.	[86]

S. No.	Biomass & process	Application rate	Crop grown	Effect on yield	Reference
5	Pine needle and Lantana biochar slow pyrolysis	2 and 5 t / ha	Wheat, rice	Increased wheat yield by 6.2–24.2%. Neutral rice yield.	[89]
6	Orchard pruning PY, 500 ^{0}C.	22 - 44 t / ha for 4 years.	Grape	Increases productivity by up to 66%	[111]
7	Hardwood biochar at pyrolysis temp 500 ^{0}C	30 and 60 t/ha 2 crop cycle	Durum wheat	Increased up to 30% biomass production and yield	[93]
8	Poultry litter biochar	10,25,50and 100 t/ha		10% increase in the yield	[102]
9	Mixed hardwood pyrolyzed 500 ^{0}C	10 t/ha for 1 crop cycle	Durum wheat and maize	Increase yield by 10% and maize by 6 %	[87]
10	*Eupatorium adenophorum* pyrolysed at 680-700 ^{0}C	750 kg/ha for 17 weeks	Pumpkin	Increase fruit yield (85-300)%	[112]
11	Rice Straw and Corn Stalk	1, 2, and 4 ton/ha	Corn, peanut, and sweet potato	Increase yield by 5-15 % when biochar is applied 1 or 2 t/ha. 20% by applying 4 t/ha	[90]
12	Zambia, Maize cob, and mixed softwood pyrolysis at , 400 ^{0}C	4 t/ ha 2 crop cycles	Maize	Biomass yield by 233-322%	[113]
B	**Greenhouse crop**				
13	Cow Manure 600 ^{0}C	0, 10, 15, and 20 ton/ha	Maize	Increased Maize crop yield	[101]
14	Conocarpus Pyrolysed at 400 ^{0}C	Apply 4-8% (w/w) for 11 weeks	Tomato	Increase tomato yield by 14-43%	[92]
15	Rice Husks 450 ^{0}C	0, 10, 25, and 50 t/ha in	Rice and wheat	Increased rice and wheat yield by 12% and 17%, respectively	[85]
16	Cow manure pyrolysis at 500 ^{0}C	0, 10, 15, and 20 t/ 12 weeks	Maize	Increased maize grain yield by 150 and 98% by applying 15 and 20 t ⁄ ha rate biochar, respectively.	[99]
17	Natural grass-cutting pyrolysis at 400 ^{0}C	10 t/ h 8 weeks	Red clover, red fescue, and plantain	Increase biomass (8-30)% in single crop & 28-50% in mixed cropping	[114]
C	**Plot and pot crop**				
18	Pine sawdust is used in Fast pyrolysis at 400 ^{0}C	45 t / ha 9 weeks	Sorghum	Plant growth declined at a higher application rate	[105]
19	Maize stalks biochar, 400 ^{0}C	16 t/ ha for 1 year	Soybean, wheat	Increase grain mass per plant of soybean by 11% and wheat by 28 %, and Biomass increase by 32%	[88]
20	Pine sawdust used in Fast pyrolysis at 400^{0}C	22 t / ha 8 weeks	Sorghum	Increase 18-22% biomass.	[105]
21	Wood, paper sludge & sewage sludge pyrolyzed at 500-600 ^{0}C	10, 20, and 40 t/ha 79 days	Ryegrass	Increase biomass yield by 67-333 %	[104]
22	Mixed wood chips pyrolysis at , 450 ^{0}C	50t\ ha 21 days	Maize	Higher application rates have negative effects on plant growth.	[98]

5. Application of Biochar as Growing Media

Conventional farming has a number of disadvantages, including high water and land requirements, high use of pesticides, soil degradation, and nutrient runoff [115]. When comparing hydroponics to conventional agriculture, the former is preferred because of its ability to sustainably meet future food demands [116]. In a study by Barbosa *et al*., when conventional agriculture and hydroponics systems were evaluated using spinach as a test plant, the hydroponics system produced an 11-fold higher yield than conventional practices. A controlled environment agriculture system can effectively perform aquaponics or hydroponics, which is soilless agriculture [21,117]. For optimal crop growth, this system effectively utilizes moisture and minerals. Hydroponics showed a significant increase in plant growth and productivity as well as better agricultural water management [116,118]. Hydroponic systems help plant cultivation in areas without soil or where plant cultivation is inefficient. It reduces soil fatigue and enables continuous production.

Furthermore, soil-borne diseases and pests are eliminated, saving water and fertilizer. Biochar has recently gained popularity for soil nutrient management. Many researchers suggest that biochar has similar physicochemical characteristics to other growing media (like peat and coir) and enhances high-value crop production. [119,120].

Generally, organic additives are used to enhance soil's physical and chemical characteristics. Bio-additives have effectively replaced soil as a growing medium. Electrical conductivity and pH are important factors to consider when using materials for the growing media because too high or too low pH and electrical conductivity can inhibit plant development. Plant growth is influenced by the physical characteristics of the growing medium, particularly pore size and density, which have an impact on the amount of available water [121]. Peat and aggregates (perlite and vermiculite) are commonly used as growing media, but their negative environmental impact and high cost necessitate using different alternatives [120]. According to Sanjuan-Delmás *et al*., hydroponic growth media has a nutrient retention gap due to possible volatilization, which could be a primary source of nutrient loss [122]. According to Hashida *et al*., nitrous oxide accounts for 16% of nitrogen loss [123]. Coco-peat is the most widely used medium in soilless cultivation, although it has a pH range of 4-5, which is insufficient for the plant to absorb the most minerals [124]. The stability of the growing medium is another important parameter for potted plants' production because its physicochemical characteristics are usually preferred to hold steady throughout the growing period [125].

There is a constant search for new materials with more suitable properties for plant growth. The use of biochar to replace peat [119] and vermiculite [126] substrate in growing media improves nutrient retention and is also disease and drought-resistant [127]. Haraz *et al*. analyzed the effect of adding biochar to peat moss growth media with ratios of 0%, 5%, 25%, and 50% on electrical conductivity and pH. They found that electrical conductivity reduced as the biochar rate increased and pH increased by 1.5 units with increased biochar to growth media ratio [128]. Biochar has similar physicochemical characteristics to coir and peat and can be used as an alternative growing medium [26]. The efficacy of rice straw biochar alone and in conjunction with perlite as substrates was investigated in nutrient film techniques (NFT) for cultivating crops such as cabbage, red lettuce, dill, and mallow [129]. In addition to this Karakas *et al*. suggest using olive stone biochar as a growing medium for aquaponics in greenhouse systems rather than perlite or coir materials [130]. Further, Dunlop *et al*. suggested that biochar be used as a medium for hydroponic systems, enhancing high-value food crops' growth [28].

Similarly, Haraz *et al*. studied the effect of coconut biochar used as substrate in closed hydroponics systems and recommended biochar percentage has a major role in growth and yield quality [128]. Altland and Locke produced the biochar tomato crop green waste and used it in a hydroponic system for the production of tomato crops. They evaluated that adding biochar to aquaponics boosted microbial activity while lowering nutrient leaching [131]. The biochar in container substrate changes the characteristics of container substrates, such as bulk density, pore volume, container capacity, availability of nutrients, pH, electrical conductivity, and cation exchange capacity[132]. The effect of biochar on plant growth's physical and chemical properties in container substrates and hydroponic systems is shown in Tables 3 and 4.

Table 3. Summary of biochar used in container substrates.

Sr no	**Properties**	**Results**	**References**
1	Porosity	Increased microspores after biochar incorporation, combining 50 percent (by volume) biochar with peat enhanced container capacity when compared to peat substrates containing 100 percent peat.	[133]
2	Electrical conductivity	Biochar added 50% (by volume) to peat moss media increased electrical conductivity significantly.	[119]
3	Cation Exchange Capacity (CEC)	The CEC was found to be significantly higher in a 25 percent biochar and 75 percent peat moss mixture (by volume) than in a 100 percent peat moss mixture	[126]
4	Microbial activity	Mycorrhizal colonization was found to be higher in containers containing sand and clay in a 3:1 (by volume) ratio with activated biochar (2 g per container)	[134]
5	Plant growth	When compared to peat substrates alone, a 50 percent mix of biochar and peat increased total biomass and leaf surface area.	[119]

Table 4. Summary of biochar used in the hydroponics system.

Sr no	**Biochar feedstock**	**Results**	**References**
1	Tomato crop green waste	Electrical conductivity decreases to <0.5 mS·cm^{-}1, and Ph increases.	[28]
2	Rice husk : perlite (1 : 1)	When compared to leafy vegetable plants grown in perlite substrate, the combination of rice husk and perlite (1:1) substrate resulted in increases in shoot length, number of leaves, and fresh/dry masses that were approximately 2-fold.	[129]
3	Olive stone biochar	Tomato seedlings grew 3–41% faster than other solid media materials.	[130]
4	Coconut shell biochar 5%, 25%, and 50% addition to peat moss	Electrical conductivity decreased as the biochar rate increased, and pH increased by 1.5 units as the biochar to growth media ratio increased.	[128]
5	Palm kernel shell	Improvements in water quality parameters, as well as catfish and lettuce growth rates, are achieved using palm kernel shell biochar.	[135]

6. Biochar Used as Composting

Composting is a simple method to turn biodegradable materials into a humus-like product that can be used as a soil addition or bio-manure [136,137]. However, manure fertilizers have some significant drawbacks in terms of greenhouse gas emissions and nitrogen loss [138,139]. Biochar boosts soil nutrient supply, microbial growth, soil organic matter, moisture retention, and plant growth while reducing fertilizer use, greenhouse gas emissions, nutrient loss, degradation, pollutant migration, and pollutant bioavailability [140], due to its unique properties such as chemical recalcitrance, porosity, adsorption capacity and large surface area [30]. Biochar has received increased attention as a composting and soil remediation amendment due to its positive effects on each other's properties. Some of the benefits of using biochar as a compost amendment include enhancing microbial activity through aeration, decreasing soil bulk density, increasing compost temperature, decreasing nutrient losses and ammonia volatilization, improving water holding capacity through leaching, lowering greenhouse gas (GHG) emissions, and increasing the degree of humidification [137,141] shown Figure 5

Zhang and Sun studied the impact of various biochar percentages on the characteristics of composted green waste. They determined that the most effective combination enhanced the particle-size distribution, reduced pH and electrical conductivity, and regulated the bulk density, porosity, and water-holding capacity to ideal ranges [142]. When Awasthi *et al*. added up to 10% biochar to poultry manure during composting, C loss was reduced by 394%, and N loss was 40.94% [143]. In addition, Miguel tested biochar-blended compost for its ability to improve soil fertility and found that it could increase 25% organic carbon in the soil, 44% nitrogen, and 26% increase in soil respiration. Furthermore, biochar-blended compost also increased significant crop quality parameters, such as fruit weight, diameter, and hardness, by 16%, 9%, and 8%, respectively [144]. Further, Chowdhury *et al*. tested the efficacy of biochar in composting hen fertilizer and barley straw at low flow rates and found that biochar effectively minimized cumulative NH3-CH4 losses. Compared to barley straw added alone, the total greenhouse gas emissions were reduced by 27–32% [138]. The combination of compost and biochar improves soil fertility, microbes, and moisture retention capacity in cropland [145], and biochar compost combined with fertilizer improves soil nutrients, organic carbon content, moisture retention capacity, and maize production[146].

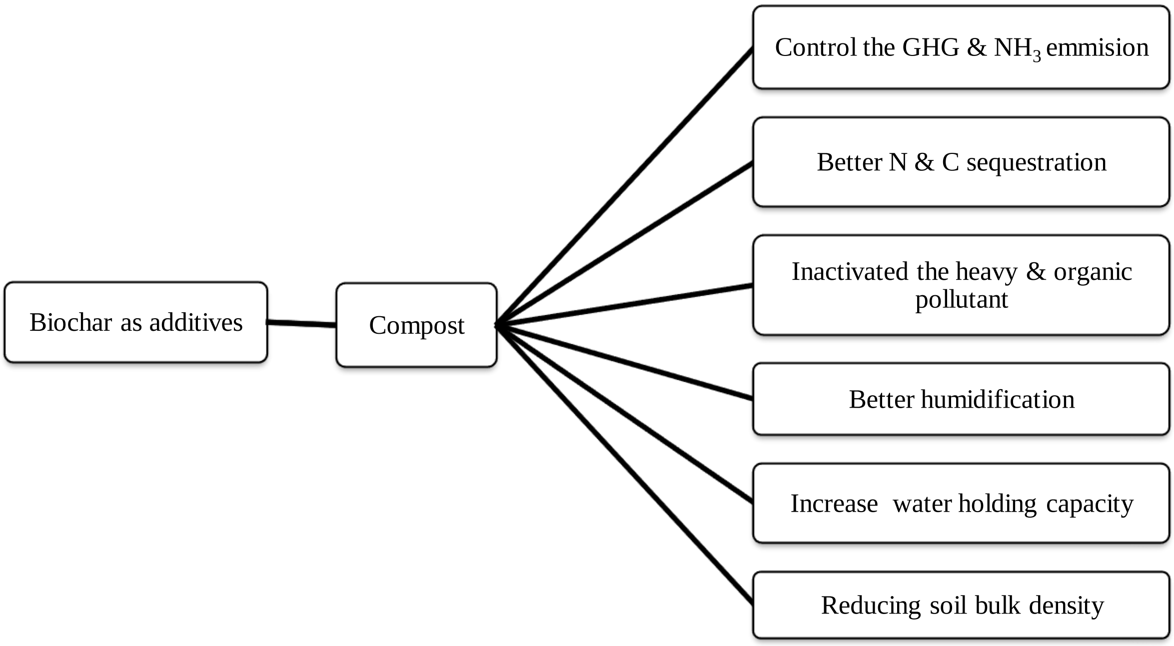

Figure 5. Biochar used as an additive to compost.

7. Income Enhancement

Bio-economy refers to the research and application of bio-resources, as well as the use of biotechnology to develop innovative economic bio-products [147]. Soil erosion, soil acidity, and low fertility constitute a risk to food security and create serious economic restraints. Therefore, there is a need to study and develop value-added additives for upgrading soil productiveness [67]. Biochar is a valuable product with uses in cropland and energy. As a result, biochar can generate additional income by improving crop productivity and providing additional revenue opportunities, which leads to economic and agricultural benefits [147] under various biotic and abiotic stresses [56]. Kroeger *et al*. examined whether biochar could save water costs after the application of biochar in soil and found that about 37 percent reduced irrigation water use [148]. Furthermore, Zheng *et al*. investigated the application of biochar compound fertilizer to the soil. They discovered that it increases agronomic nitrogen efficiency use by 43.1 percent and net income by 12% when compared to inorganic compound fertilizers [149]. Applying biochar to the soil increases the carbon level and provides a long-term benefit to the crop. Aller *et al*. studied the biochar application rate of about 0 to 90 Mg/ha to increase the carbon level from 8 to 115 %. Due to this, corn yields increased from –2.6 to 0.6 %. Overall, the applied rate of 22 Mg/ha was found to be more cost-effective and provides for the long-term reduction of 50% of maize residue for 32 years, making it beneficial for producers even with minimal impact on grain yield [150].

The cost of transportation is a significant part of the economics of biochar generation. Palma *et al*. describe the expense of generating biochar in one location and transporting it to another. They explored two different numbers of biochar kilns in three different states that travel at flexible periods to determine the economic viability of mobile pyrolysis facilities. They discovered that the net profit of biochar increases with the number of mobile pyrolysis units [151]. In addition, Homagain *et al*. analyze the complete life cycle cost and economic impact of biochar-based bioenergy generation and biochar land application. He reported that the pyrolysis process accounts for 36% of the total cost of the production system.

On the other hand, land application, feedstock collection, and conveyance account for 14%, 11%, and 9% of the overall generation cost, respectively [152]. Similarly, Dickinson *et al*. compare present total expenses versus present total benefits as a function of biochar performance lifespan to compute the net present value (NPV). Using biochar was shown to have a beneficial impact on cereals cropping, with the biochar effect on yield expected to last for 30 years [153]. Mohammadi *et al*. investigated rice production's economic returns after applying biochar compared with traditional farming practices. They found that the maximum benefit at 18 Mg ha-1 biochar addition enhanced rice's net present value (NPV) by 12% and lowered the conventional energy production by 27%, compared to after eight years of application. By crediting greenhouse gas emissions abatement in low and high carbon price scenarios, the variation in NPV values across generation systems grew to 23% and 71%, respectively [154]. Keske *et al*. studied the process of biochar produced from biomass and found stable and floating costs of \$505.14 Mg^{-1} and \$499.13 Mg^{-1}, respectively. Biochar production was economical when applied to beets at the midpoint, with an expected yearly income of \$4,953 ha^{-1} and a maximum yearly expected income of \$11,288 ha^{-1} above various expenses [155]

Biochar generation might be profitable if the earnings according to the above values cover the expense of producing, harvesting, trucking, and storing the biomass feedstock and the costs of pyrolysis, transportation, and biochar application. According to the study, the net profitability of generating biochar might be enhanced with more affordable inputs and a viable process [156].

8. Environmental Impact of Biochar

Several studies are available for the positive application of biochar, such as removing harmful pollutants from agricultural lands [29], soil remediation [147], natural adsorbent [157], material waste management, and climate change mitigation. In the study of Yang *et al*., 920 kg of CO2e (CO2-equivalent) is sequestered by biochar soil storage and biofuel use by converting

1 tonne of crop residues into biochar. Biochar decreases annual national carbon emissions by about 4.5 percent [158]. Unfortunately, for each of the listed benefits above, a counterargument or drawback has been found for biochar, such as the production of toxicants [159], increased dust emission [160] facility to pollution migration [161,162], and production of polycyclic aromatic hydrocarbons (PAHs) [163,164]. The presence of hazardous organic chemicals increased due to biochar production processes, leading to significant health risks [51,165]. Heavy metals, volatile organic compounds (VOCs), dioxins, and furans are some native toxicants that can be created during biochar formation. Pollutants are normally found in biomass feedstock [166]. Slow pyrolysis with a long retention period yielded lower PAH yields than fast pyrolysis with a shorter retention period [66]. According to Li *et al*., dust emission increased with increasing biochar addition rate during mechanical cleaning [167].

Furthermore, the type of biochar microparticle associated with PM10 was a major source of concern for human health [159]. Carbon black, a substance related to biochar, has been observed to exhibit increased cytotoxicity in mice and human cells as the size of the material decreases [168]. Biochar acts as a sink for a variety of contaminants in the soil. Biochar has also been found to be an excellent agent for immobilizing organic contaminants due to its high aromaticity, large surface area, and microporosity [169,170]. Together, these studies indicate that biochar has both a positive and negative impact on the environment, as shown in Figure 6.

To minimize the negative impact of biochar-induced dust emissions and their risks [159,171]. It is suggested that to reduce dust emission, biochar application should be avoided on windy days, and applying biochar with high water content. In addition, Major outlines different biochar production processes and suggests integrating biochar replenishment with other on-farm operations to save resources and reduce dust emissions [172].

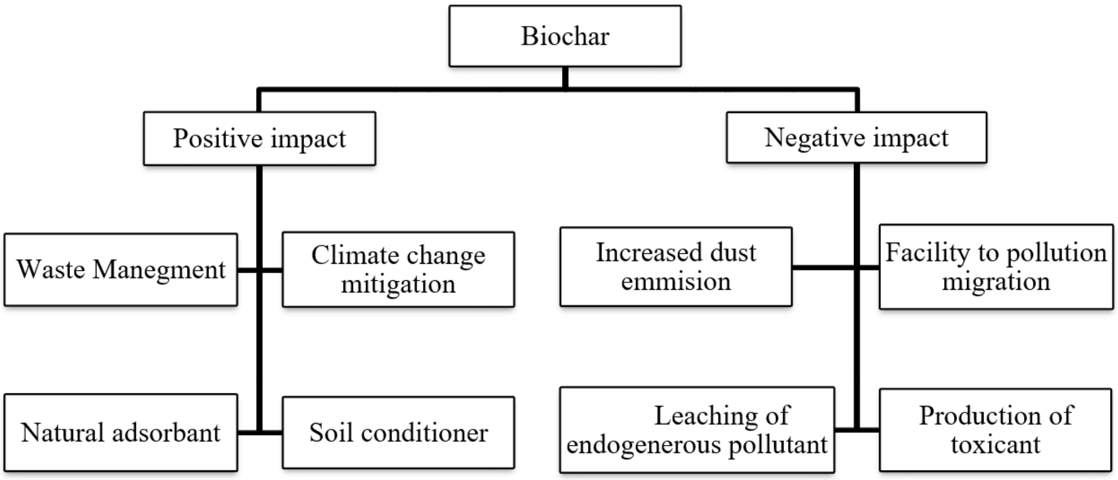

Figure 6. Environmental impact of biochar.

9. Conclusions

Biochar is carbon-rich material obtained by the thermal decomposition of organic material in the absence of air. Biochar can provide a good solution to agricultural issues such as cropland deterioration due to acidity, salinity, and nutrient shortages. Adding biochar to the soil significantly reduces nutrient leaching and increases yields and nutrient use efficiency. However, the agricultural advantages of biochar are solely dependent on using specific biochar at the optimal field application rate under suitable soil types and parameters. It has been recommended that co-composting biochar made from various alternative feedstocks can be used to improve soil health, rehabilitate land resources, and reduce carbon output related to agriculture. Biochar can replace soil as a growing medium to meet the ever-increasing food demand and generate additional income by improving crop productivity and providing other revenue opportunities, leading to economic and agricultural benefits.

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