

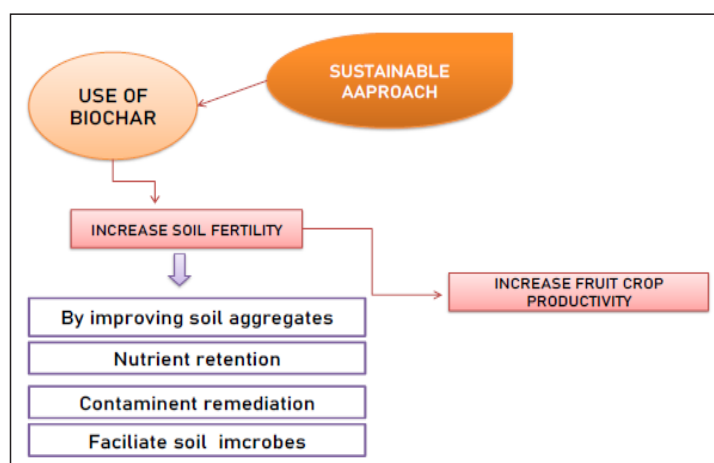
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Innovative solutions are required to meet the urgent problem of sustaining the global food supply for a growing population against the backdrop of expanding desertification and drought brought on by climate change. Traditional synthetic fertilizers have been used to increase agricultural soil productivity for a long time, but they have had negative effects on the environment, including seeping into ecosystems and increasing greenhouse gas emissions. Optimizing soil water retention, encouraging healthy soil bacteria, and improving fertilizer effectiveness are some of the major issues facing the agricultural sector. In this context, the development of biochar—a nutrient-rich material made from biomass—has drawn attention as a potent tool for soil improvement, with an emphasis on the growing of fruit crops and its advantages. Applications of biochar in agriculture have enormous potential. They increase the nutrient content of the soil, increase its capacity to hold water, reduce the need for synthetic fertilizers, strengthen the soil microbiota, and dramatically increase crop yields. Beyond these benefits, biochar has uses in economic, environmental, and prospective applications in carbon credit systems. The use of biochar, also known as biocarbon, is a potential solution to the complex problems that fruit crop agriculture faces in a world that is struggling with water scarcity and desertification brought on by climate change. By realizing its potential, we can advance sustainable agriculture, lessen our negative environmental effects, and improve future food security while supporting international efforts to address climate change. There are obstacles in the way of biochar's potential for global food sustainability because of its varying qualities, dependence on feedstock, and lack of knowledge about its long-term consequences, resulting in the need for more study.

GRAPHICAL ABSTRACT



INTRODUCTION

Since the United Nations Framework Convention on Climate Change was founded in 1992, efforts have been undertaken to address climate change, which is today a serious problem for the entire globe. These programs made an effort to lessen GHG emissions and lessen the effects of climate change. There have been several significant accords made, including the Kyoto Protocol in 1997, the Copenhagen Accord in 2009, and the Paris Agreement in 2015. Despite these accords, the Intergovernmental Panel on Climate Change (IPCC) most recent assessment contends that current decarbonization efforts fall short of the goal of keeping global temperature increases to 1.5°C over pre-industrial levels by 2050. Instead, it is anticipated that the temperature will have increased to 2.7°C by 2050 [5]. Analyzing how climate change is affecting this sector of the economy is crucial. Fruit production is significantly hampered by changing precipitation patterns, rising temperatures, and extreme weather events. The growth, development, and production of fruit crops may be impacted by these changes, which could lead to financial losses and problems with food security. Improved methods and technologies for fruit production must be used to address these problems and comply limit to limit to limit limit limit to limit limit limit to limit limit limit limit limit limit to limit limit limit limit the increase in global temperature. Adopting sustainable farming methods, bolstering

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water management systems, investing in crop varieties resistant to climate change, and improving post-harvest storage and transportation technology may all be necessary to achieve this. Additionally, strengthening agroforestry systems and safeguarding biodiversity can support the fruit industry's attempts to adapt to and mitigate climate change. Additionally, to lessen the effects of climate change on fruit agriculture, international collaboration and cooperation are essential for the adoption of suitable policies as well as the exchange of knowledge and resources. One example is encouraging collaborations between governments, agricultural organizations, researchers, and farmers to create and implement climate-smart practices and technologies. It is important to support various carbon capture and storage (CCS) technology that can remove CO₂ from the atmosphere or prevent its release to fulfill the Sustainable Development Goals, reduce global warming, and progress towards carbon neutrality. The Food and Agriculture Organisation (FAO) produced a report in 2001 acknowledging the presence of agricultural practices that can increase crop yields while increasing soil's capacity to store carbon. This report recognized the potential of agricultural soils as carbon sinks and storage sites [3]. One potential technology mentioned in the report is the use of biochar, a solid carbonaceous substance produced by the pyrolysis of biomass. The amount of surface area and porosity in biochar varies based on the pyrolysis conditions and the biomass used. Pyrolysis is promoted as a commercially viable method of recovering lignocellulosic waste through the use of biochar. Usually, this trash is burned, which produces greenhouse gas emissions and material losses. On the other hand, the pyrolysis procedure enables the closing of material cycles, which is in line with the guidelines laid out in the European Union's Circular Economy Action Plans for 2015 and 2020. The utilization of pyrolysis to transform lignocellulosic waste into bioproducts including wood vinegar, bio-oil, syngas, and biochar can generate income in the fruit-growing industry. These profits ought to cover the expenses of changing and using these things. Fruit growing can help to mitigate climate change and build a circular economy by utilizing waste materials and reducing GHG emissions. A sustainable and financially viable method of fruit cultivation is possible with the use of charcoal and pyrolysis. The agriculture industry may help with carbon sequestration, GHG emissions reduction, and the shift to a circular economy by implementing these measures [4].

PRODUCTION OF BIOCHAR

Under low oxygen conditions, pyrolysis is a thermo-chemical process that transforms biomass, including plant and crop waste, grasses, manures, agricultural wastes, and wastewater sludge, into valuable goods. Biochar, a high-energy density solid, bio-oil, and a relatively low-energy density gas that is non-condensable are the three main byproducts of this process. During pyrolysis, long-chain polymers found in biomass, like cellulose, hemicellulose, fat, starch, and lignin, break down, producing gases like CO₂, CO, CH₄, and H₂. Condensable gases are created when certain molecules mix, creating liquid fuel and aromatic chemicals. Additionally, the processes of aromatization and polymerization lead to the creation of char. Since biochar's aromatic structure lacks cellular components, it resists deterioration while also delivering extra benefits for a variety of soil uses. This property makes biochar stable and long-lasting for more than a century [8]. Technologies for pyrolysis can be divided into three primary categories: slow

pyrolysis, flash pyrolysis, and quick pyrolysis. In a batch reactor or continuous system, slow pyrolysis entails heating the biomass to temperatures greater than 350°C. Due to its simplicity, this process is extensively employed and typically produces 35% biochar, 30% bio-oil, and 35% gas by mass. Slow pyrolysis systems, often known as "charcoal kilns," have less control, which prevents the separation of the bio-oil and gas, resulting in variances in biochar yields that range from 25% to 60%. In a distillation system, biomass is cooked in batches under moderate to high pressure to perform flash pyrolysis. With typical yields of 60% bio-oil and 40% charcoal and gas, this process is specifically created to maximize the production of bio-oil. By infusing a controlled amount of oxygen into the chamber at temperatures between 800°C and 1,200°C, gasification, on the other hand, strives to produce the most syngas while producing the least amount of biochar and bio-oil. This system has a 5–15% yield potential and can create a mixture of biochar and trace amounts of bio-oil (tar). The temperature is quickly raised to about 700°C within a few minutes during fast pyrolysis. This process results in lower carbon content and higher gas production. Fast pyrolysis typically yields 50–70% bio-oil, 10–30% charcoal, and 15–20% gas as its end products. Generally, when biomass materials are heated at a slow heating rate of 10–20°C/min from 300°C to 750°C, a higher yield of solid product is obtained [13].

Another crucial step in the biomass gasification process is pyrolysis, in which biomass is oxidized with a controlled amount of oxygen to maximize the production of flammable syngas. The type of biomass used as feedstock, temperature, reaction time, and the pyrolysis equipment employed all have an impact on the yield of different pyrolysis products and the performance of biochar. Fruits that are frequently grown include apples, oranges, bananas, strawberries, grapes, and mangoes. These fruits are grown in orchards or specialized farms using a variety of agricultural techniques to promote maximum development and productivity [29].

PROPERTIES OF BIOCHAR

The effects of biochar on soil are strongly correlated with porosity, water-holding capacity, sorption capacity, redox properties, liming capacity, and nutrient retention [18]. The physical characteristics of biochar are typically assessed using pore-size distribution, surface area, surface structure, water-holding capacity, and particle density [47]. For instance, the size of biochar particles and the presence of larger macropores (pores with a diameter of more than 50 m) on the surface of biochar might affect the soil's hydrology, particle size distribution, and microbial habitat.

On biochar surfaces, variables of relevance include sorption capacity, pH, cation exchange capacity (CEC), total carbon-to-nitrogen ratio (C/N), nutritional content, electrical conductivity, elemental composition, surface molecules, and organic coatings [33; 2; 11; 42; 46]. Biochar frequently promotes plant development and microbiological activity because of its positive effects on soil properties. However research has revealed that biochar can release dangerous compounds, leading to biochar toxicity [17]. Biochar toxicity may result from the characteristics of the feedstock used and the manufacturing temperature, which can change the material's pH, electrical conductivity, levels of polycyclic aromatic hydrocarbons, and heavy metal content. These substances might harm organisms if they seep into the ecosystem.

When it comes to determining biochar field performance in the

context of fruit crop cultivation, its distinctive physicochemical properties are crucial. It is crucial to properly describe biochar before adding it to the soil in scenarios where fruit crops are being grown. Understanding these characteristics enables farmers and researchers to maximize the use of biochar to enhance the quality of the soil, the availability of nutrients, the retention of water, and the microbial activity, ultimately enhancing the growth and productivity of fruit crops.

Plants, especially those grown for fruit, can be significantly impacted by acidity, alkalinity, salinity, and nutrient deficiency. The ability of plants to absorb the nutrients necessary for growth may be compromised when the pH of the soil is high (more than 8). Sodicity, on the other hand, is brought on by an excess of sodium ions relative to other significant ions like magnesium (Mg), calcium (Ca), and potassium (K). Salinity, on the other hand, is brought on by high salt concentrations in the soil.

Salinity endangers plant growth by causing osmotic stress, which harms crop development as a whole. On the other side, sodicity directly limits root growth, which may have a detrimental effect on the entire crop production cycle [36]. The overall production of crops is impacted by these chemical restrictions. An essential component of these chemical characteristics is the charge density per unit surface of organic matter, which defines the cation exchange capacity. When it comes to storing and releasing the essential cations (positively charged ions) for plant absorption, soil organic matter serves as a cation exchanger. Organic matter's capacity to retain cations is improved by having a higher charge density per unit surface, which increases the availability of nutrients to plants. To maintain appropriate soil conditions and promote healthy plant growth, understanding and controlling these chemical constraints is essential in the context of fruit development. Analyzing and analyzing the soil can help identify pH, salinity, sodicity, and nutritional deficiencies. According to the research, suitable soil amendments, such as the addition of organic matter or the use of specific fertilizers, can be implemented to reduce these restrictions and create an environment that is more advantageous for fruit crops. By removing chemical constraints and improving soil conditions, fruit growers can boost nutrient availability, reduce the detrimental effects of salt and sodicity, and eventually improve crop yields and quality. The overall effectiveness and sustainability of fruit cultivation practises are supported by regular monitoring and adjusting of these chemical components.

IMPACT OF BIOCHAR ON FRUIT CROPS

MANGO (*Mangifera indica*)

Mango fruit production has shown that biochar may have advantages, affecting factors related to plant growth, soil health, and fruit quality. Biochar amendment enhances soil fertility by enhancing nutrient retention and accessibility. It prevents leakage from the root zone by acting as a storage space for essential nutrients. Mango trees may have healthier development and provide more fruit by increasing nutrient intake [31; 10]. The soil's porous texture improves its capacity to hold water. It helps retain moisture, especially in sandy soils, which reduces watering requirements and the stress that dryness puts on mango trees. A sufficient quantity of soil moisture is associated with improved fruit quality and yield [1; 30]. These bacteria are essential for the soil's overall health, the control of disease, and the cycling of nutrients. Improved mango tree health and fruit quality can result from increased microbial

activity [23]. It has been demonstrated to inhibit fungus and nematodes, two types of soil-borne diseases. This can make mango trees healthier and produce fruit of higher quality by reducing the prevalence of diseases that damage them [6]. The size, weight, color, hardness, and shelf life of mangoes are all improved by applying biochar to mango orchards, according to numerous research. The increased nutrient availability, enhanced hydration retention, and disease control of biochar lead to superior fruit quality [24; 30]].

CITRUS (*Citrus* spp.)

Citrus plants have been found to benefit from biochar's increased nutrient availability, which improves soil fertility. It enhances the soil's cation exchange capacity (CEC) and nutrient retention, which benefits plant nutrient uptake. [14]. By adding biochar to citrus orchards, critical minerals like nitrogen, phosphate, and potassium become more readily available, promoting better plant growth and fruit quality. Citrus orchard soils that have been amended with biochar can better retain water and lose less water to leaching. It boosts the soil's capacity to hold water, making water more readily available to citrus trees during dry spells [22]. Citrus farming can use less water by reducing the frequency and amount of irrigation required as a result of improved water retention [21]. In citrus orchards, biochar has shown promise in controlling soil-borne illnesses and pests. Its porous design and large surface area can serve as a habitat for advantageous microorganisms, helping to prevent disease and enhance soil health [14]. According to studies, biochar amendment improves overall plant health and productivity by decreasing the prevalence of root rot and Phytophthora-related illnesses in citrus plants [20]. Studies have shown that the use of biochar can improve the qualities of citrus fruit, including larger fruits, improved color, improved flavor, and higher vitamin C content [39]. Citrus orchards with biochar amendments have also seen an increase in fruit yield. Increased tree vigor and productivity are a result of biochar's improved nutrient availability, water retention, and disease suppression [28].

GUAVA (*Psidium guajava*)

Based on its impacts on plant development, nutrient uptake, fruit quality, and yield, biochar can have an impact on guava fruit. An experiment on the effects of biochar on guava growth, yield, and nutrient usage efficiency was carried out [15]. The findings showed that the use of biochar was associated with an increase in plant height, stem diameter, and canopy volume. Compared to control treatments, biochar also increased nutrient uptake, especially for nitrogen (N) and phosphorus (P), which increased fruit yield. The effects of biochar on the physical characteristics and water status of a calcareous loamy soil beneath guava trees as well as the effects of biochar on guava orchards reported that the biochar incorporation into the soil improved soil physical properties, such as increased porosity and decreased bulk density [34]. These changes contributed to enhanced water infiltration and water-holding capacity, providing favorable conditions for guava tree growth and development. Researchers looked into how biochar affected the soil's fertility and ability to absorb nutrients in guava orchards. The application of biochar increased soil fertility, as evidenced by improved pH, increased organic matter content, and enhanced cation exchange capacity. They also looked at biochar application rates, soil fertility parameters (pH, organic matter, and cation exchange capacity), and nutrient concentrations in

plant tissues. The greater nutrient contents in the tissues of biochar-treated guava plants further suggest improved nutrient absorption and utilization [41].

GRAPES (*Vitis vinifera*)

Biochar additions have been shown to increase the nutrients' availability in grapevine soils. Grapevine nutrient availability and retention are benefited by the porous nature of biochar, which provides a habitat for beneficial bacteria and increases the soil's capacity to exchange cations [16]. Adding biochar to the soil can improve its capacity to hold onto water, especially in sandy soils. Because of its high porosity and water-holding capabilities, biochar helps grapevines with water stress by ensuring adequate water availability during critical growth phases [7; 22]. Biochar serves as a stable type of organic material in the soil that promotes the buildup of soil organic carbon. This can enhance soil fertility, microbial activity, and general soil health, all of which are favorable for grapevine development and productivity, according to studies by [25] and [49]. Studies have shown that biochar has positive effects on the growth parameters of grapevines, such as enhanced shoot length, leaf area, and root development. These improvements in vegetative development typically result in higher grape yields [32; 12]. It has been linked to greater phenolic component accumulation [26] and improved sugar content, two characteristics of grapefruit quality [9]. Additionally, using biochar can lessen the uptake of heavy metals in grapefruit [44].

PAPAYA (*Carica papaya*)

Papaya plant growth and yield have benefited from the use of biochar. Its integration into the soil can boost the availability of nutrients, increasing the uptake of those nutrients by papaya plants. As a result, fruit quality and yield are enhanced [27]. According to experiments, soil supplemented with biochar produces more papaya fruit and has a greater average fruit weight and total soluble solids (TSS) content than soil that hasn't been amended [38]. It can absorb and hold onto nutrients, extending the time over which they are accessible to plants. As a result, papaya agriculture may use nutrients more effectively [32]. Application of biochar has been shown to increase nutrient content in papaya leaves, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), which are essential for plant growth and fruit development. By increasing soil organic matter content and cation exchange capacity, fostering beneficial soil microbial activity, and encouraging nutrient cycling, biochar addition can increase soil fertility. [53].

STRAWBERRY (*Fragaria × ananassa*)

Numerous studies have indicated that biochar has favorable benefits on strawberry fruit production and have produced encouraging results. Adding biochar to the soil greatly enhanced the amount of strawberries that could be harvested. According to the study, using biochar at a rate of 20 tonnes per hectare increased fruit yield by 24% when compared to the control group. The soil's availability of nutrients can be improved by using biochar [51]. According to a study by [45], adding biochar to soil raised the concentrations of vital nutrients like nitrogen (N), phosphorus (P), and potassium (K) in strawberry plants, which enhanced the quality of the fruit. The ability of the soil to store water can be improved with biochar, which is essential for the best plant growth. According to a study, adding biochar to the soil increased its ability to retain water, which reduced water

stress on strawberry plants and encouraged greater fruit development. Certain soil-borne illnesses have been demonstrated to be suppressed by biochar, making strawberry plants healthier as a result [35]. According to research, strawberry plants' vigor and fruit quality were enhanced by the application of biochar, which greatly decreased the prevalence of root rot and crown rot diseases. According to several research, using biochar improves the strawberry fruit quality qualities [43].

APPLE (*Malus × domestica*)

Apple fruit can be significantly impacted by biochar, which can change different elements of fruit output, quality, and tree health. To get insight into the possible advantages of biochar application, several research have examined its impacts on apple orchards. It has been demonstrated that biochar increases nitrogen uptake by apple trees and increases nutrient availability in the soil. It serves as a storage for nutrients, slowly releasing them over time when the plants require them [19]. This may result in apple trees using nutrients more effectively and more quickly. The fertility and structure of soil in apple orchards can be improved by adding biochar. It increases soil aeration, decreases the bulk density, and increases soil's ability to hold onto water [52]. These modifications may enhance fruit quality by encouraging root development, nutrient uptake, and overall tree health. According to certain reports, biochar possesses anti-disease qualities that can help reduce soil-borne pathogens and lower the prevalence of specific apple illnesses. According to studies, apple trees treated with biochar have fewer cases of illnesses like root rot and crown rot [40]. This can contribute to healthier trees and improved fruit production. Its application has been associated with improved fruit quality attributes in apple orchards. It can enhance fruit size, color development, firmness, and sugar content [48]. These improvements contribute to marketable and visually appealing apples, potentially increasing their value and market competitiveness.

PEACH (*Prunus persica*)

Numerous research investigations have shed light on the impacts of biochar and examined its possible impact on peach fruit production. It has been discovered that biochar increases the nutrients' availability and uptake by peach trees. The study showed that the concentrations of vital nutrients like nitrogen, phosphate, and potassium in the plant tissue increased when biochar was added to peach orchard soil. This increased nutrient accessibility may have a positive impact on fruit yield and quality [22]. The ability of peach orchard soil to retain water can be improved by adding biochar. The addition of biochar boosted the sandy soil's ability to store water, avoiding water stress and enhancing the effectiveness of irrigation for peach trees. For the best fruit development and quality, the soil must have sufficient moisture levels. Peach plants may benefit from improved soil aeration and structure as a result [28]. Adding biochar to soil increased porosity, decreased compaction, and improved soil aggregation. These enhancements encourage root development, nitrogen absorption, and general plant vigour. In peach orchard soil, it may encourage advantageous microbial activity [37]. Biochar to soil improved soil fertility by increasing microbial biomass and enzymatic activity. The health and fruit quality of peach trees can both benefit from active and diverse soil bacteria. With the use of biochar, increased fruit quality attributes have been found in several investigations.

These elements contribute to the fruit's flavour, nutritive content, and antioxidant qualities, making biochar a viable tool for improving the quality of peach fruit [52].

FUTURE PROSPECTS

The impact of biochar on fruit farming has bright future potential. The potential of biochar to benefit the fruit business is becoming more and more clear as knowledge of its advantages and methods of application grows. Nutrient runoff can be reduced by adding biochar to the soil, ensuring that vital components are still accessible to the plants. Increased harvests, better fruit quality, and higher overall plant health can all result from this. Second, biochar can lessen the negative impacts of chemical restrictions on the production of fruit. Its special mechanisms for adsorption and desorption can control the pH, salinity, and sodicity of the soil, resulting in a more hospitable environment for fruit crops. Incorporating biochar can also change the texture of the soil, increasing its capacity to retain water and boosting its general structure. Fruit trees may more effectively absorb water and nutrients thanks to these enhancements, which will further foster their growth and output. A sustainable substitute for synthetic fertilizers in the production of fruit is provided by biochar potential as an organic fertiliser. Its nutrient content and slow-release characteristics assist the soil and plants over the long run. The application of biochar can support environmentally friendly and sustainable fruit-producing practises by reducing the dependency on chemical fertilisers. Research must go on in order to fully comprehend the precise impacts of biochar on various fruit varieties, soil types, and climatic circumstances. Each fruit crop may respond differently to biochar application, and optimizing the dosage, timing, and application methods will be essential for maximizing its benefits.

CONFLICT OF INTEREST

To ensure the integrity of the results, I declare that I have no conflicts of interest with regard to this review study on using biochar to improve fruit quality.

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