soil systems

Review

Biochar Improves Soil Fertility and Crop Performance: A Case Study of Nigeria

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Abstract: Africa, specifically Nigeria, has witnessed a dramatic increase in population over the last century, prompting efforts to ensure sustainable food production and quality. Concerns for soil sustainability and food security have led to the exploration of cost-effective methods, such as biochar, to enhance soil quality. Researchers in Nigeria and Africa as a whole have investigated biochar's potential to improve soil fertility and crop performance across various agroecological zones. This paper aims to review recent biochar research priorities on soil fertility and crop performance with an emphasis on various sole biochar applications and combinations with fertilizers to determine the research gaps that need to be developed more in biochar research in Nigeria. From the papers reviewed, sole biochar applications and biochar + macronutrients and biochar + manure combinations were studied more dominantly, while biochar + micronutrients research projects were scanty despite their low content in the semi-arid soils of Nigeria. The studies were spread across the country with the majority taking place in derived savanna and humid forest, while Sudan savanna and Sahel savanna received less research attention despite being characterized by a low-fertile soil and vast area of land. Research involving BC in the context of Sahel savanna (SLS) and Sudan savanna (SS) soils is strongly encouraged in Nigeria. This research should encompass a wide range of investigations, including sole BC applications and combinations of BC with macronutrients, micronutrients, and manure, as well as exploring its potential as a slow-release fertilizer. Incorporating exclusive biochar in substantial amounts appears economically unfeasible within the context of local biochar production. However, it can be utilized in the synthesis of slow-release fertilizers, requiring smaller quantities and potentially offering cost-effectiveness. This approach enhances soil condition and crop productivity. Challenges are faced due to less commercial production as a result of inadequate power and structural facilities. Exploring the modification of local biochar for slow-release fertilizers through future research offers potential profitability.

Keywords: agroecological zones; biochar; feedstocks; pyrolysis; soil properties

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1. Introduction

Biochar is a solid material produced by the thermochemical conversion of biomass in an oxygen-limited environment [1]. Biochar (BC) is known to be a carbon rich by-product produced by the thermal degradation of organic materials through pyrolysis (reduced oxygen environment), which is gaining more relevance in the world of technology [2]. BC, derived from biomass, has gained significant attention in the scientific community due to its enormous potential to enhance long-period carbon sequestration, its recalcitrance in nature, and wide-ranging applications [3]. The utilization of BC enhances soil fertility by minimizing nitrogen leaching into groundwater, enhancing cation exchange, mitigating soil acidity, and improving water retention capacity [4]. Ensuring food security for an expanding global population is increasingly challenging due to declining soil fertility and reduced crop productivity worldwide [5]. Biomass energy is used by more than 2.7 billion people worldwide, and it has been used in Africa for a very long time [6]. Crop residues, forest and wood refuse, urban and livestock waste, and other wastes can all be used as feedstocks to make biochar. Africa produces more than 998 million tons of agricultural residues each year from crop, cattle, and aquaculture industries [6]. Most of these wastes are recycled as fuel, and the remainder is either allowed to decompose as organic manure on farms or used as feedstock for the anaerobic digestion process that produces biogas. However, the suitability of each biomass as a feedstock relies on its properties and chemical composition, as well as on logistical, economic, and environmental factors [7]. Omulo [8] suggests that the prevailing maize-production patterns in East Africa have the capacity to yield a substantial amount of biomass residues, with the potential to annually produce roughly 33.3 million tons of biochar.

Biomass as defined by Yaashikaa et al. [9] is regarded as a complex solid substance comprised of biological, organic, or inorganic elements originating from living organisms. This biomass can be categorized into two primary types: (i) woody biomass, which primarily includes tree residues and forestry residues, and (ii) non-woody biomass [10]. Yaashikaa et al. [9] also described the characteristics of woody and non-woody biomass. Woody biomass is characterized by its low moisture content, minimal debris, reduced voidage, high density, and substantial calorific value. In contrast, non-woody biomass includes materials such as animal waste, industrial residues, and agricultural solid wastes, which are distinguished by their high debris content, elevated moisture levels, increased voidage, low density, and lower calorific value. Higher moisture levels in biomass significantly impede the formation of char and necessitate a greater amount of energy to achieve the pyrolysis temperature [11].

Pyrolysis, a well-established thermochemical process, produces biochar from various agricultural wastes under high temperature and pressure. It operates within a temperature range of 350 to 650 °C, yielding solid (biochar), liquid (bio-oil), and gas (syngas) derivatives as its primary products [12]. Pyrolysis is categorized as slow, fast, and flash, with slow pyrolysis preferred for large-scale biochar production due to its gradual temperature increase and prolonged residence time, favoring biochar production over bio-oil and syngas [13].

The reaction mechanism involves three steps: dehydration, primary biochar formation, and secondary char formation, yielding a carbon-rich material [14]. Higher pyrolysis temperatures increase biochar surface area and porosity by breaking down organic-compound groups, removing pore-blocking substances [15]. Conversely, lower pyrolysis temperatures yield biochar with a structure resembling graphene, featuring fewer functional groups [16]. Fast pyrolysis is employed to obtain high-quality bio-oil from algae [12].

Predominantly, in sub-Saharan Africa (SSA), declining soil quality and nutrient losses are the main obstacles to improving agricultural productivity and food security [17]. Climate change, exponential population growth, and the need for climate-smart agriculture, which aims to provide valuable ecosystem services alongside food security, have further exacerbated the challenges faced by farmers in boosting crop productivity [18]. Nigerian soils face numerous challenges, such as inadequate agricultural practices, land degradation, soil erosion, and the impact of climate change [19] exacerbating the difficulties faced by farmers. Addressing these interconnected issues requires comprehensive strategies that consider both environmental and socioeconomic aspects to ensure the long-term viability of agriculture in the face of global challenges.

The predominant soil types in these areas are highly weathered and acidic, and have a poor nutrient and soil organic-matter status [18]. Consequently, without the use of organic materials and inorganic fertilizer, viable crop output is no longer possible [20]. Farmers are compelled to rely on alternative fertilizer sources, including organic manures, because the frequently used inorganic fertilizers are expensive and limited in supply [21]. However, due to quick disintegration and decreased stability, the impacts of organic manure amendment on soils in SSA are short [22]. Additionally, using mineral fertilizers has drawbacks such as soil acidity, nutrient leaching, priming impact on soil organic matter, deterioration of soil structure, eutrophication, and the enormous quantity of reserves of fossil fuels used during fertilizer manufacture [23]. To maximize and improve potential crop yield, it is crucial to look into sustainable methods of managing soils in SSA. To make this a reality, the soil will need to be amended with a biologically inert substance like BC, known for its nutrient retention properties and soil-structure stabilization [24]. In recent times, biochar has gained attention as a potential soil enhancer because of its distinctive physicochemical characteristics and its interactions with soil ecosystems [25].

Biochar (BC) exhibits recalcitrant properties, which are crucial for soil conditioning, determining nutrient availability and fertility, and reducing N_2O, CO_2, and CH_4 gas emissions, as well as sorbing inorganic and organic contaminants [26]. BC is made up of volatile and condensed aromatic organic substances [27] and elements of an inorganic source [28]. BC properties are highly dictated by the pyrolysis temperature. BC produced at high temperature usually has a higher cation exchange capacity (CEC) [29], porosity, inner surface area, adsorption capacity, organic C content, and pH [30]. The types of soil and BC determine the potential importance of BC application to soil [31]. BC application to soil enhances a soil's physical and chemical characteristics as reported by Omondi et al. [32] and enhances the bioavailability of nutrients [33]. Because of its high stability, BC has a high probability of increasing the sequestration of C in soil, which scales down atmospheric greenhouse gases (GHGs). According to studies by Bouqbis et al. [34], BC enhances soil chemical characteristics, reduces soil acidity, boosts CEC, enhances soil aggregates, maintains nutrients, and improves the water infiltration dynamics in various soil types.

Biochar (BC) application shows potential for enhancing agricultural output, particularly in degraded, low-fertility soils [35]. Notable outcomes reported include an 18–22% increase in sorghum dry weight with pine sawdust BC in barren, sandy, desert soil [36] and improved maize production with eucalyptus-derived BC in nutrient-depleted Kenyan soils [37]. The application of BC under the cultivation of maize and common beans in acidic soil over six years enhanced yields due to improved soil conditions [38]. However, BC's effectiveness varies, with inconsistent results in soil fertility [39]. For example, various levels of BC from eucalyptus charcoal residues had no significant impact on rice yield [37]. Yet, a notable 10.7% maize-grain-production increase occurred in a nutrient-deficient Inceptisol with BC and commercial fertilizers in the North China Plain [40]. Furthermore, a 5% BC application to sandy soil showed certain BC types resulted in leaf yields over 50% higher than BC-free sandy soil, benefiting barley growth [41].

Biochar is predominantly produced locally in Nigeria, with a focus on local methods due to the country's unreliable power supply, making power-independent production methods more acceptable [42]. This is particularly relevant for rural regions where agriculture is commonly practiced, as local thermal technology can be easily applied to BC production without incurring significant costs for farmers. Research on BC is still lacking in the areas of soil fertility and crop productivity, particularly in Nigeria's far-northeast Sahel savanna region, which has a semi-arid climate and requires special attention due to its less fertile soil characteristics and lower crop productivity despite rapid population growth. With a lot of residues after cultivation, farmers face a great challenge in disposing of these agricultural wastes. With the emergence of a new technology for converting this waste into a recalcitrant, carbon-rich substance known as BC produced by heating in an oxygen-depleted environment, much understanding is needed on how to use it properly. However, understanding BC's role in soil fertility and crop productivity should be first and foremost, as little or no environmental contaminants are present in the northern part of Nigeria. To achieve this goal, this review aims to present some recent works conducted between 2021 and 2023, which relate to BC soil fertility studies and crop productivity in different agroecological zones of Nigeria to find out the current state of studies and determine possible gaps in BC research in Nigeria, specifically in the low-fertile, semi-arid, Sahel savanna soil of Nigeria.

2. Feedstock for Biochar Production in Nigeria

Nigeria, with a large expanse of agroecological zones, produces various agricultural wastes after the harvest period. In the far north, maize, sorghum, and millet stovers, and rice straws and husks are abundant after the harvest with no proper disposal methods in place. Grasses, such as elephant grass (*Pennisetum purpureum* Schumach.), tree prunings, wood shavings, and sawdust, are also readily available. Also, there is a good quantity of manure such as cow dung and poultry manure, but its direct use as organic fertilizer by farmers may limit its use as biochar feedstock. In the southern part of Nigeria, palm kernel shells and plantain and banana peelings are abundant and can serve as a valuable feedstock for biochar production. Nigeria boasts a variety of tree species, including the shea butter tree (*Vitellaria paradoxa* C.F. Gaertn.) in the southern region, mahogany (*Khaya senegalensis* Desr. A. Juss.) in parts of the middle belt, neem trees (*Azadirachta indica*), and various *Acacia* species like the gum arabic tree (*Acacia senegal* L.) in the northern region, which can be excellent sources of feedstock for biochar production. However, tree cutting is often discouraged, rendering them unsuitable for biochar production. Ighalo and Adeniyi [43] reported that biochar made from elephant grass (*Pennisetum purpureum*) exhibited mesoporous characteristics with a specific surface area of 475.1 m^2/g and was rich in inorganic elements. They also reported similar results for plantain fibers (*Musa paradisiaca*). Solomon [44], produced biochar from maize cobs and rice husks and reported high-quality biochar characteristics. Therefore, biomass arising from harvest, such as palm kernel shells, rice straws, maize cobs and stovers, and sawdust/wood shavings from timber industries, represents the best-suited feedstock options in Nigeria.

3. Production and Properties of Biochar

3.1. Biochar Production Methods

The main feedstock to biochar conversion methods are given in Figure 1. Pyrolysis, as described by Osayi et al. [45], is the thermal decomposition of organic materials within an oxygen-deprived setting, leading to the production of biochar, syngas, and bio-oil. Slow pyrolysis, occurring at low temperatures (350–500 °C) and gradual heating rates, results in high-quality biochar with up to 88.9% carbon content and a heating value of 32.95 MJ/kg [46]. The yield of biochar is influenced by factors like heating rate, residence time, and lignin content in the feedstock. For instance, using forestry plants as feedstock, biochar yield was around 30% at 500 °C, 60 min residence time, and 10 °C/min heating rate [47]. Lignin content significantly affects biochar yield, with lignin pyrolysis producing a yield of up to 45.7% [48]. Slow pyrolysis can also produce bio-oil as a by-product, containing oxygenated organic molecules like acids, esters, ketones, and phenols [49]. It involves some production processes as described by [50–53].

In fast pyrolysis, biomass undergoes rapid decomposition at extremely high heating rates (around 1000 °C/min) and reaches a pyrolysis temperature of approximately 500 °C, with a vapor residence time of less than 2 s [54]. This process yields biochar (10–15 wt%) and pyrolysis gases (10–15 wt%) [53]. Higher pyrolysis temperatures lead to an increased carbon content and specific surface area of biochar as volatile substances are released from biomass particles. For example, rapeseed-stem biochar's specific surface area rose from 1 to 45 m^2/g when the pyrolysis temperature increased from 200 to 700 °C, and the carbon content of pine-sawdust biochar increased from 70.7 to 78.7% at temperatures between 550 and 750 °C [55,56]. Altering the heating rate changes the devolatilization rate and biochar structure [57], and high heating rates can cause quick depolymerization at the biochar surface [58].

Gasification, a thermochemical technique, breaks down carbonaceous materials into syngas, primarily composed of CO, CO_2, CH_4, H_2, and trace hydrocarbons, using gasification agents like oxygen, air, or steam at elevated temperatures [9]. Higher temperatures increase carbon monoxide and hydrogen production while decreasing methane, carbon dioxide, and hydrocarbons [59]. The primary output is syngas, with char considered a secondary by-product with relatively low yield. Biomass gasification occurs at temperatures between 700 and 1000 °C, utilizing various agents including air, oxygen, and steam [53]. The gasification process, influenced by factors such as pressure, the gasifying agent, feedstock qualities, and the equivalence ratio (ER), significantly impacts biochar quality [50,60–62].

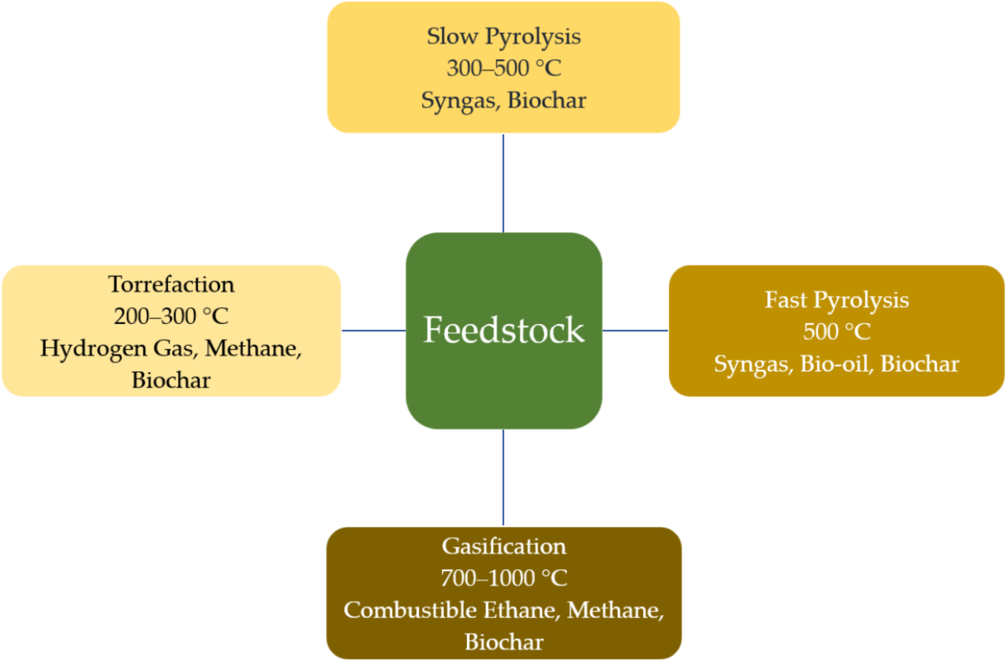

Figure 1. Feedstock to biochar conversion methods.

Torrefaction, a mild pyrolysis method, involves the removal of oxygen, moisture, and carbon dioxide from biomass using an inert atmosphere at temperatures around 300 °C [63]. The torrefaction process can be conducted through three main approaches [9]. The torrefaction process occurs in a temperature range of 200–300 °C, with a residence time of less than 30 min, a heating rate of under 50 °C per minute, and in the absence of oxygen. Torrefaction involves phases like heating, drying, torrefaction, and cooling [63]. Torrefied biochar has an energy density of approximately 1.3 and retains 90% of the original energy content [64]. It can be used as fuel and soil amendments and can have an energy density similar to coal used for electricity and heat generation [65]. The quality of torrefied biochar depends on factors like the moisture content, heating value, and ash content of the biomass [66]. Torrefaction temperature and residence time significantly influence lignin, hemicellulose, and cellulose content in torrefied biochar [67,68]. Dehydration and decarboxylation are key degradation events contributing to mass loss during torrefaction [69]. It is worth noting that torrefaction, similar to slow pyrolysis, fast pyrolysis, and gasification, yields products like syngas, bio-oil, and solid biochar, with torrefaction producing products like H_2, CH_4, and biochar [70,71] (Figure 1).

3.2. Biochar Kilns

Zanli et al. [70] highlighted the widespread use of kilns in developing nations like Zambia, Ghana, and Kenya for small-scale biochar and charcoal production. In Nigeria, particularly in the Borno state, Bababe et al. [72] developed and constructed a modified low-cost BC kiln for slow pyrolysis recommended by Wijitkosum and Jiwnok [73] in the Soil Science Department, University of Maiduguri, using an emptied oil drum container (200 L) (Figure 2). The patented design allows some control over pyrolysis conditions under limited oxygen availability inside the kiln, including air intakes and exhaust holes. The design is critical to produce high-quality biochar. The outer furnace is constructed with drilled holes (Figure 2F), which can vary in number and was 20 holes in this case. The drum is placed on a concrete block to allow air inflow from the outer kiln perforations. The inner kiln (Figure 2B) is loaded with the feedstock (Figure 2E), relatively uniform in size to minimize air pockets without restricting air flow. Fire is set in at the top of the open loaded drum (Figure 2H), until a good blaze begins to spread through the exposed material. Then, the cap piece is fitted over the fire to create a substantial draft through the chimney column (Figure 2I).

Figure 2. Local BC kiln designed by Bababe et al. [72] (unpublished): (**A**) drum kiln, (**B**) inner kiln, (**C**) chimney column, (**D**) drum kiln lid, (**E**) feedstock, (**F**) drilled holes, (**G**) digital electronic-probe thermometer, (**H**) ignited feedstock loaded in the drum kiln, (**I**) fixed chimney.

The unit is left to burn down from top to bottom, leaving charred feedstock above as the fire moves downward since all available oxygen is consumed at the burning line. While the fire burns downward, it is monitored by testing the temperature of the outside drum wall using a digital electronic-probe thermometer (Figure 2G). The drum kiln lid is removed together with the chimney and covered for about 10 min to complete the conversion. The drum is allowed to cool down after quenching the fire to terminate further combustion. The biochar obtained is usually 1/3 of the initial feedstock used but may vary with feedstock type. Figure 3 shows sample biochar obtained from the drum kiln.

Figure 3. BC obtained from the kiln developed by Bababe et al. [72] (unpublished).

The kiln is of low cost and can be built easily by farmers themselves locally with available materials and most importantly can use locally available biomass as feedstock. There remains a significant need for further efforts to comprehensively characterize the biochar produced from this specific unit.

3.3. Properties of Biochar

BC properties such as pH, surface area, water-holding capacity, electrical conductivity, and pore size distribution usually depend on the type of feedstock and pyrolysis temperature and condition [74]. The range of carbon in BC is 50–90%, with volatile substances about 40%, water 1–15%, and mineral substances about 5% when the biomass type and the parameters of thermal processing applied are considered [75]. The composition of feedstocks plays an important role in BC production and determines the final product characteristics and quality [16]. Crop residues contain high ash content compared to woody and organic feedstock like manure, which also has high calorific values and few voids [76]. Many feedstocks can be utilized, such as corn cob and corn stalk [77], rice straw, cotton stalk [78], wheat straw [79], sugar cane straw [80], and maize husk [81]. Proximate (volatile matter, ash, fixed carbon, and moisture), ultimate (carbon, oxygen, nitrogen, hydrogen, and sulfur), and lignocellulosic contents are categories employed for the compositional analysis of agricultural residues [82].

The volatile matter, fixed carbon, ash, and moisture levels of biomass, respectively, range from 65 to 90, 3 to 26, 1 to 15, and 0 to 10% [83]. The pyrolysis temperature has the greatest impact on the volatile matter and yield of BC, while the feedstock has a greater influence on the ash content and fixed carbon than the pyrolysis temperature does [82]. For example, an increase in the pyrolysis temperature from 400 to 700 °C caused a 10% reduction in the biochar yield for hazelnut shell [10,84], while Aysu and Küçük [85] reported a 40.26–26.29% yield at 350–600 °C with *Ferula orientalis* L. as feedstock.

When considering BC as a soil amendment, volatile matter and ash content are more significant than the other proximate contents [86].

The production, transport, and storage of BC are greatly affected by the moisture content [87]. A lesser moisture content favors easy transport and storage as volume and weight is significantly reduced [83]. In terms of the ultimate composition, the highest proportion is the element carbon (40–65%) in almost all biomass with oxygen and hydrogen (25–50% and 5–10%, respectively) and negligible sulfur and nitrogen [83]. It is reported that BC carbon content is variable depending on the feedstock type, with higher BCs produced from crop residues with a higher carbon content compared to organic waste feedstocks like manure [76]. Leng and Huang [88] reported that higher carbon and oxygen contents in feedstocks results in higher calorific values and yields.

BC's polarity, aromaticity, and stability are dependent on the carbon-to-oxygen and hydrogen-to-carbon ratios [83]. Due to its high aromaticity and low polarity, BC is resistant to microbial degradation. This resistance is based on the ratios of hydrogen to carbon and oxygen to carbon [89]. The protein and macromolecular amino acid composition of the feedstock determines the nitrogen content of the BC, with organic waste having the highest nitrogen content followed by agricultural residues and woody biomass [90].

Cellulose, hemicellulose, and lignin determine the BC structural composition, properties, and yield as well [83]. The respective cellulose, hemicellulose, and lignin content of agricultural biomass ranges from 28 to 47%, 11 to 39%, and 9 to 27% [55]. Cellulose, hemicellulose, and lignin differ in their decomposition based on the temperature they are exposed to: 300 to 380 °C for cellulose, 200 to 300 °C for hemicellulose, and 200 to 500 °C for lignin [55]. With an increase in pyrolysis temperature, a greater gas yield of CO, CO_2, CH_4, and H_2 is obtained, as reported by Li et al. [83], which is proportional to the BC yield. With higher cellulose and hemicellulose contents than lignin contents, the pyrolysis rate increases together with a higher bio-oil and lower BC yield [91]. There is an increase in BC porosity and specific surface area with a higher lignin content [92].

4. Biochar and Soil Fertility

The capacity of the soil to provide water and nutrients in a nontoxic form to boost crop productivity is known as soil fertility. According to Igalavithana et al. [93], the physical, chemical, and biological characteristics of soil affect its fertility. The most problematic soil fertility problems are found in tropical, dry, and semi-arid locations, which makes it challenging to grow crops there. Due to the high temperatures and frequent rainfall in these areas, vital plant nutrients readily leach from the topsoil, and the abundance of decomposers swiftly break down organic materials in the soil [94].

Soils in arid and semi-arid regions have a low capacity to retain water and a low supply of vital nutrients [95]. This is due to the soil's poor ability to retain nutrients and water due to its low organic-matter level. Degraded soil has low fertility, which limits the amount of food that can be produced [96]. Land abandonment and desertification may arise due to a continuous decrease in soil productivity [97]. The primary threat to soil fertility, sustained agricultural yield, and overall biodiversity is soil erosion, as it leads to the depletion of organic matter and essential nutrients [98]. To preserve food security, low-fertility soils must be rehabilitated, and to achieve this, inorganic fertilizers have frequently been used to boost crop output [99]. According to Carlson et al. [100], intensive agriculture techniques that heavily rely on inorganic fertilizers endanger soil quality and sustainability. Given this, a more practical, sustainable, and ecologically friendly method for preserving soil quality and productivity needs to be developed [2]. This method should be readily available, biodegradable, and renewable [101].

Adding BC to soil can increase the soil's fertility [102,103] through certain mechanisms (Table 1), and therefore, BC is an excellent choice for this use, enhancing many fertility factors of soils (Figure 4).

Table 1. Biochar and its mechanism in enhancing soil fertility and crop performance.

Soil Fertility Factors	Improvement Mechanism	Reference
Nutrient supply	Supplies the soil with nutrients from the feedstocks and enhances nutrient use efficiency	[104]
Soil pH	Provides liming effect	[105]
Soil CEC	High surface functional group	[36]
Nitrogen use efficiency	Decreases N leaching	[106]
Soil C storage	More stable and recalcitrant in soil	[107]
Soil microbial activity	The presence of pore spaces in biochar offers a conducive environment for microorganisms	[108]

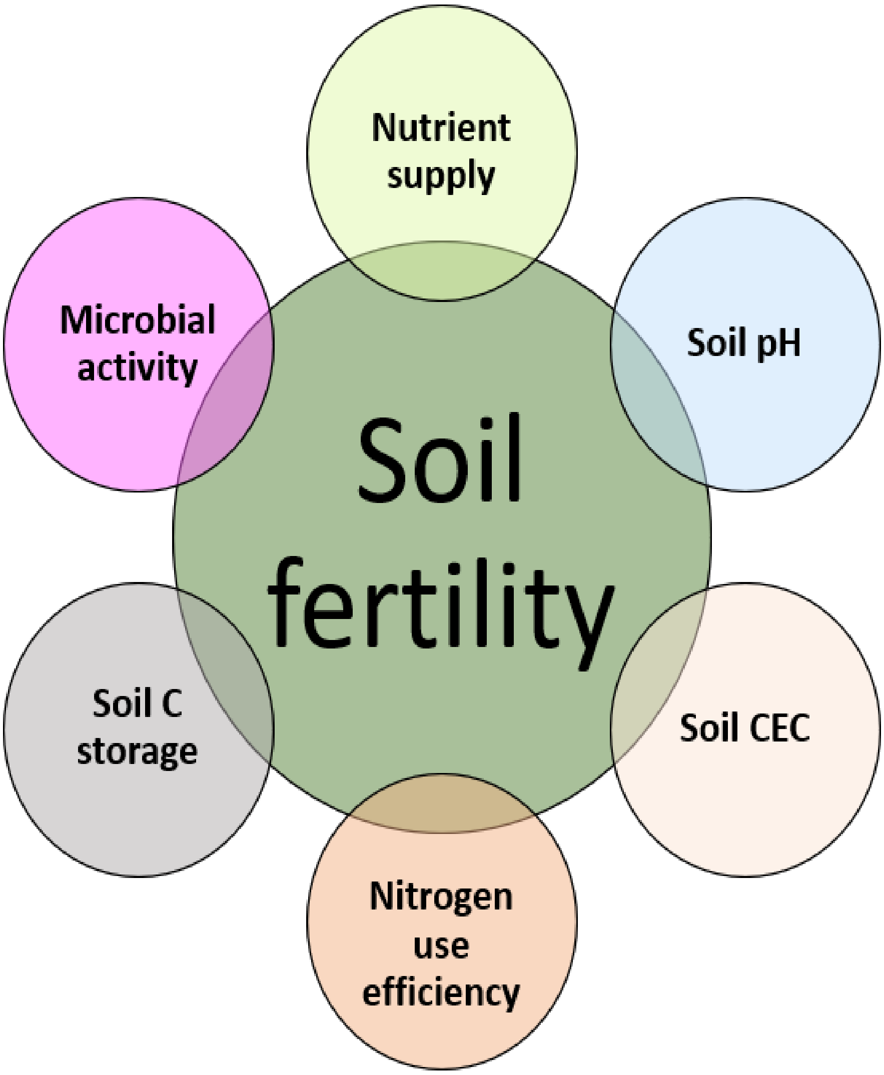

Figure 4. Soil fertility factors enhanced by biochar.

4.1. Biochar and Nutrient Supply

When applied to soil, BC acts as an organic fertilizer and provides the soil with nutrients from the feedstocks [104]. Biochar (BC) application provides various benefits, including nutrient retention, improved nutrient usage, reduced nutrient leaching in the soil [103], an inherent richness of nutrients [41], and is specifically noted for its ability to directly retain macronutrients such as nitrogen (N) [103]. In the study conducted by Laghari et al. [36], it was observed that the introduction of biochar (BC) to low-fertility sandy soils resulted in notable improvements in various nutrient levels. Specifically, the addition of BC led to an increase of 7–11% in total carbon (C), 37–42% in potassium (K), 68–70% in phosphorus (P), and 69–75% in calcium (Ca) levels compared to the control group.

Furthermore, research carried out by Zhang et al. [35] demonstrated that applying biochar derived from wheat straw and pyrolyzed at a low temperature had a significant positive impact on the availability of nitrogen, phosphorus, and potassium in a low-fertility acidic soil. However, it is important to note that the effects of BC applications can vary depending on the soil's characteristics. For instance, according to the findings of Gunes et al. [109], the introduction of BC to an alkaline soil could potentially lead to decreased concentrations of plant-available iron, zinc, copper, and manganese.

Drawing from the inherent attributes of biochar (BC), including factors like pH, cation exchange capacity (CEC), porosity, and specific surface area, it can be inferred that BC plays an indirect role in enhancing the preservation of soil nutrients, as discussed by Yuan et al. [110].

It was discovered that BC pyrolyzed at relatively high temperatures was effective at reducing soil acidity and encouraging the retention of nutrients [33]. Conversely, it was determined that BC generated under lower temperature conditions predominantly augmented soil CEC, as observed by Mukherjee et al. [111].

4.2. Biochar and Soil pH

Modifying the pH of soil through BC amendment is contingent upon the specific soil type or biochar (BC) used. The introduction of alkaline biochars to acidic soils, for example, can result in an elevation of soil pH. This alteration in pH can subsequently influence the availability of nutrients within the soil matrix, as outlined in a study by Zhang et al. [35]. Therefore, by increasing the availability of essential soil nutrients, BC can act as a soil amendment to provide a liming effect, reduce soil acidity, and improve soil quality [105]. However, adding acidic or neutral BC to alkaline soils could lower soil pH, which would alter the solubility of soil nutrients including phosphorus and trace elements [36]. However, the pH is typically only slightly lowered by BC application, therefore this slight drop in the pH of alkaline soil has little impact on the availability of nutrients [112]. However, it was reported that a great decrease of 0.92–0.95 pH units was observed when BC was applied to alkaline sandy soils at a rate of 45 $t \cdot ha^{-1}$ [36].

4.3. Biochar and Soil CEC

BC can increase soil CEC due to the functional groups on its surface composition, especially in sandy-textured soils [36]. A significant advantage of low-fertility soils is the significant contribution of BC in raising soil CEC. The increase in soil CEC increases the availability of nutrients to plant roots and decreases nutrient leaching from the soil profile [113]. According to Liang et al. [114], the CEC rose from 88.4 mmolc kg^{-1} in BC-unamended soil to 211.3 mmolc kg^{-1} in BC-amended soil. They hypothesized that this rise in CEC was caused by the presence of negatively charged BC functional groups (i.e., –COOH). Additionally, adding hardwood-derived BC to low-fertility sandy soil at a rate of 450 g kg^{-1} resulted in an increase in CEC from 3.4 cmolc kg^{-1} in the control to 5.9 cmolc kg^{-1} in the amended soil [22]. Other investigations have confirmed that the addition of BCs causes CEC to rise [115]. According to research by Mukherjee et al. [111], pyrolyzed wood- and grass-derived BCs aged for 15 months had an average rise in CEC from 26.2 cmolc kg^{-1} (fresh BC) to 173 cmolc kg^{-1} (aged BC). The modification was thought to have been brought about by the oxidation of its surfaces, which produced more O-containing functional groups which increase CEC. However, a variety of variables, including the type of soil, BC-production conditions, and application rate, may influence how BC affects soil CEC. For instance, in a 90-day incubation study, the addition of three distinct BCs derived from amur silver grass residue, paddy straw, and umbrella tree wood, produced at temperatures ranging from 500 to 600 °C, was implemented in two dissimilar low-fertility soil types (sandy and sandy loam) [116]. Within the sandy soil, treatment with umbrella tree wood, amur silver grass, and paddy straw BCs resulted in a significant elevation in CEC from the control value of 0.3 cmolc kg^{-1} to 0.7, 0.9, and 3.1 cmolc kg^{-1}, respectively. However, in the sandy-loam soil, only the paddy straw BC led to a CEC increase, from 10.2 cmolc kg^{-1} to 11.5 cmolc kg^{-1}. In a separate incubation study, biochars derived from pinecones (produced at 200 and 500 °C) exhibited no impact on soil CEC for both soil types. In contrast, biochars derived from vegetable waste (produced at 200 and 500 °C) significantly heightened CEC in both paddy and upland contaminated soils [117]. El-Naggar et al. [118] and Igalavithana et al. [117] suggested that the favorable influence of certain BCs on soil CEC might be attributed to their elevated ash content. Another critical aspect is the BC application rate. For example, Uzoma et al. [119] observed a favorable correlation between the BC addition rate and the rise in soil CEC.

4.4. Biochar and Nitrogen Use Efficiency

The impact of biochar (BC) on soil nitrogen (N) dynamics, retention, and usage efficiency has been extensively studied [115]. The application of BC has been shown to enhance soil N content [120]. Notably, Güereña et al. [106] demonstrated that the addition of BC led to an increase in N fertilizer recovery and a reduction in N leaching from the soil profile. This effect is likely mediated by changes in soil microbial populations, which in turn influence nitrogen levels. Microorganisms in the soil play a pivotal role in the conversion of nitrate (NO_3^-) to ammonium (NH_4^+), effectively minimizing N losses via leaching or gaseous fluxes [113]. Fundamentally, the impact of BC on soil N cycling depends on two primary factors: the type of feedstock used and the pyrolysis temperature applied [121].

The gradual nutrient release to plant roots can be facilitated by the adsorption of specific inorganic nitrogen (N) forms onto biochar (BC), effectively mitigating ammonia and nitrate losses from the soil [115]. Field investigations have consistently highlighted the observed retention of ammonium and nitrate after BC application [115], a trend also mirrored in laboratory and greenhouse studies [122]. The influence of BC on soil nitrogen cycling is contingent upon factors such as feedstock selection and pyrolysis temperature [121]. The potential to curb nutrient release to plant roots by means of inorganic N adsorption onto BC, thereby reducing soil ammonia and nitrate losses, is supported by existing research [115]. This phenomenon has been substantiated by experiments conducted in both laboratory and greenhouse settings [123], as well as through field investigations [94,115] and other relevant studies, e.g., adsorption [42,124].

4.5. Biochar and Soil Carbon Storage

In the global effort to mitigate the escalation of atmospheric CO_2 concentrations, biochar (BC) has emerged as a focal point of attention [125]. Particularly, low-fertility soils could benefit most from BC application [126], as it has the potential to amplify plant productivity, leading to increased soil carbon (C) inputs [127]. As highlighted by Zimmerman et al. [107], the carbon component of BC demonstrates a heightened level of stability and resistance to degradation within soil compared to other organic soil amendments, such as compost and manure, which degrade at a relatively faster rate. This resilience is attributed to the extended carbon half-lives spanning from 102 to 107 years for lower- and higher-temperature BC, respectively [107]. Jeffery et al. [128] further support this notion, asserting that BC exhibits 10–100 times greater stability in comparison to most other types of soil organic matter (SOM). The augmented chemical stability of BC, owing to its condensed aromatics, is detailed by Purakayastha et al. [129]. Wang et al. [130] demonstrated that the introduction of BC to soil leads to a sustained inhibition of long-term native soil organic carbon (SOC) mineralization.

Furthermore, the introduction of biochar (BC) containing readily available organic carbon and other nutrients can potentially stimulate soil microbial activity, thereby accelerating the rate of soil organic carbon (SOC) mineralization [126]. It is important to note that this effect is typically transient, predominantly manifesting during the initial months following BC incorporation [107]. Consequently, employing BC as an amendment in low-fertility soil presents a notably effective strategy for augmenting SOC levels [131].

For instance, infertile sandy and sandy-loam soils exhibited a substantial SOC increase of up to 72% in sandy soil and up to 48% in sandy-loam soil when treated with BC derived from amur silver grass, paddy straw, and umbrella tree wood at a rate of 30 $t \cdot ha^{-1}$. However, this notable increase was observed only after a 90-day incubation period. In a separate two-year field experiment, a silty loam soil characterized by low SOC content (1%) witnessed a 51% overall enhancement in SOC when supplemented with BC produced from a mixture of crop residues at a rate of 6.0 g kg^{-1}. This increase extended up to 76% in the coarse-sand-size fraction over the two-year period [118].

4.6. Biochar and Soil Microorganisms

By leveraging its unique attributes that contribute to soil's physical and chemical properties—including its porous structure, CEC, and significant sorption capability—biochar displays the capacity to heighten the richness and activity of soil microbial populations. This phenomenon has been extensively explored by researchers such as Zheng et al. [132] and Diatta et al. [108]. As posited by Lehmann et al. [133], the inherent characteristics of biochar have the potential to enhance the retention and accessibility of nutrients for microorganisms, concurrently influencing the intricate interplay among soil constituents, plants, and microorganisms, as highlighted by Quilliam et al. [134]. Notably, the microstructure of biochar, especially those forms rich in microporosity, significantly enhances its utility as a microorganism habitat, providing optimal pore spaces that support their proliferation, as emphasized by Diatta et al. [108].

Beyond its role in providing easily degradable carbon (C) sources and essential mineral nutrients that foster microbial growth, biochar plays an additional role in safeguarding microorganisms from challenges such as exploitation and desiccation, an aspect brought to light by Warnock et al. [135]. The application of substantial quantities of biochar, according to findings by Gomez et al. [136] and Li et al. [137], can bring about shifts in the composition of soil microbial communities, favoring the prevalence of bacterial-dominated populations. Furthermore, a comprehensive review by Zhang et al. [138] has established that the inclusion of biochar correlates with heightened microbial biomass and activity, along with the augmentation of Gram-positive-to-Gram-negative bacteria ratios ($G+/G-$). This transformative effect on the microbial community is closely tied to both the potential of biochar to elevate pH levels, as demonstrated by Rousk et al. [139], and the infusion of easily degradable organic carbon into the soil matrix, as outlined by Farrell et al. [140], leading to wider carbon-to-nitrogen (C/N) ratios, a phenomenon elucidated by Thies and Rilling [141].

By altering the activities of enzymes like peroxidase, cellulase, and protease, biochar additions can also have an impact on the activity of the microbial population [142]. Additionally, because harmful chemicals bind to biochar, modified soils can have increased microbial diversity and growth [143]. According to Kuzyakov et al. [144] and Ding et al. [145], biochar can alter the makeup or activity of microbial communities, which can have an impact on plant development, nutrient cycles, and soil organic-matter cycling (Figure 4).

4.7. Biochar and Micronutrients

Biochar is rich in trace elements, including Fe, Cu, B, Zn, Mn, and Mo. While many studies primarily focus on Fe, Zn, and Cu levels in biochar, fewer address Mn content, and only a limited number report Mo and B contents [146]. Research indicates that biochar produced from animal manure exhibits a higher Fe content (ranging from 311 to 7480 mg kg^{-1}) compared to biochar derived from crop residues and woody materials, as demonstrated by Enders et al. [147]. The Fe content observed in biochars originating from waste materials ranged from 0.009 to 380 mg kg^{-1} [148]. Similarly, for Zn and Cu, animal manure biochar exhibited higher levels, with Zn ranging from 131 to 4981 mg kg^{-1} and Cu from 99 to 2446 mg kg^{-1}, in comparison to biochars derived from waste and crop residues [147]. It is worth noting that the micronutrient compositions of biochars are influenced by factors such as feedstock type and biochar-production temperature. Nevertheless, the impact of these factors on the micronutrient content in biochar products is not consistently predictable, primarily due to the inherently low micronutrient levels in the feedstock materials. For example, eucalyptus green-waste biochar when produced within the temperature range of 650–750 °C exhibited a substantial Fe content of 7000 mg kg^{-1} [149]. In contrast, willow-wood-waste biochar produced at 550 °C contained a significantly lower Fe concentration, measuring only 0.05 mg kg^{-1} [150]. Moreover, Li and Shangguan [151] have also noted that biochar contains significant amounts of micronutrients, although these are present in relatively small quantities.

Research on biochar reveals its remarkable ability to adsorb substantial quantities of metal cations like copper (Cu) and zinc (Zn), as evidenced by Rodríguez-Vila et al. [152]. This property positions biochar as a potentially valuable tool for mitigating metal contamination in soils. Furthermore, studies such as that of Sizmur et al. [153] have elucidated how biochar can effectively reduce the availability and uptake of these metals by plants, a critical aspect of soil remediation and plant health. The mechanism underlying this reduction in metal availability is primarily linked to biochar's impact on soil pH, a factor that can be modulated by the pyrolysis temperature of the biochar, as elucidated by Gomez-Eyles et al. [154]. Biochar often acts as an alkaline amendment, raising soil pH levels, which, in turn, limits the solubility and accessibility of certain metal cations for plant roots.

In scenarios where biochar is introduced into uncontaminated temperate soils, its influence on micronutrient uptake, including copper (Cu), iron (Fe), and zinc (Zn), appears to be negligible, as indicated by Schimmelpfennig et al. [155]. This finding is particularly reassuring for agricultural practices aimed at enhancing soil quality without disturbing the delicate balance of essential nutrient uptake by plants. However, it is essential to tread cautiously when working with biochar, as Kookana et al. [105] have raised concerns about specific biochar types potentially releasing heavy metals, such as zinc (Zn), to levels that could lead to toxicity. This highlights the necessity of the rigorous screening and selection of biochar products to ensure they meet the intended goals without inadvertently harming the environment or plant health. The complexity of biochar's impact on soil chemistry is further observed by Ch'ng et al. [156], who noted a decrease in exchangeable iron (Fe) following biochar application, alongside an increase in pH. Such intricate chemical interactions emphasize the need for a comprehensive understanding of biochar's effects in various soil contexts to harness its benefits effectively while minimizing potential risks.

5. Biochar and Crop Performance

Increased agricultural output may result from applying BC to low-fertility soils [35]. As stated by Laghari et al. [36] in their study, this phenomenon is commonly noted in soil with a low nutrient content and degradation, contributing to enhanced agricultural yield. Nonetheless, its efficacy is sporadically evident in fertile or robust soils [39]. The introduction of biochar (BC) derived from eucalyptus led to an increase in maize (*Zea mays* L.) production in the nutrient-depleted soils of Kenya [37]. In an experimental setup, the influence of a pine-sawdust BC treatment on sorghum (*Sorghum bicolor* (L.) Moench) was explored by Laghari et al. [36] using a barren, sandy, desert soil from China. Results indicated a significant upsurge of 18–22% in sorghum dry weight compared to a BC-free control soil. Over a six-year timeframe, Raboin et al. [38] cultivated maize (*Zea mays* L.) and common beans (*Phaseolus vulgaris* L.) in an acidic soil employing a two-crop rotation strategy. The altered soil conditions, characterized by a higher pH and diminished exchangeable aluminum, led to substantial yield increments for both maize and common beans compared to the control. Nevertheless, the application of various levels of BC derived from eucalyptus charcoal residues (ranging from 10 to 50 $t \cdot ha^{-1}$) did not yield significant alterations in rice (*Oryza sativa* L.) yield. In a study by Zheng et al. [40], a noteworthy 10.7% enhancement in maize-grain production was observed in a nutrient-deficient Inceptisol in the North China Plain, following treatment with BC and commercial fertilizers, in contrast to the control soil receiving only fertilizer. In sandy soil with an application of 5% BC, Shepherd et al. [41] evaluated the effects of 17 BCs on the growth of barley (*Hordeum vulgare* L.). They discovered that some BCs produced leaf yields greater than 50% higher than the sandy soil without any BC.

6. Studies on Biochar in Africa

On whether results of biochar application are also tenable in other African countries, several research studies like that of Steiner et al. [157], Akoto-Danso et al. [158], and Faye et al. [159] have reported that applying biochar increased agricultural yields. The yield increases are typically linked to biochar's capacity to hold onto nutrients and moisture beneath the soil [160]. Accordingly, the findings of Steiner et al. [157] demonstrate that Tamale farmers in Ghana were able to enhance lettuce yields by 93% via incorporating biochar (ranging from 0.9 to 10.7 $t \cdot ha^{-1}$ rice husk) into their regular agricultural operations. Local farmers in Tamale devised a practical method for producing biochar directly in the field, utilizing a simple top-lit updraft gasifier combined with a distinctive chimney design to carbonize rice husks, achieving an efficiency range of 15–33%. Akoto-Danso et al. [158] conducted a comprehensive study in Tamale, assessing the effects of mineral fertilizer application and biochar amendment on soil moisture, plant nutrition, and biomass production over two years, under varying levels of water quality and quantity, in a Petrolinthic Cambisol. Notably, when rice-husk biochar was applied at a rate of 20 $t \cdot ha^{-1}$, fresh-matter yields during the initial five crop cycles witnessed a remarkable 15% enhancement, which extended to a 9% increase after a span of two years.

On the other hand, while continuing to focus on Ghana's circumstances, a study by Yeboah et al. [161] found that applying biochar to maize farms in sandy soil resulted in an up-to-5% increase in nitrate recovery (demonstrating the potency of biochar's nutrient retention). Similar to this, a two-year research that included eleven crop cycles with a single application of maize-cob biochar at a rate of 20 $t \cdot ha^{-1}$ successfully showed a nutrient-retention increase.

The findings reported in Ouagadougou/Burkina Faso indicated that the utilization of biochar led to a significant increase in overall fresh yield for two cycles of amaranth (39% and 17%), lettuce (7%), and carrot (11%) [162]. Häring et al. [163] examined the dynamic interplay between soil, biochar, wastewater, and fertilization across a span of two years in Tamale, Ghana, and Ouagadougou, Burkina Faso, using two distinct types of sandy soils characterized by depleted soil organic carbon (SOC) and nutrient content. On the other hand, biochar's impact on increasing yields gradually diminished; the application of biochar to 2 kg m^{-2} of rice-husk and corn-cob material initially led to a twofold increase in SOC storage, subsequently followed by a 35% decline in SOC. Despite these changes, the pH of the soil, phosphorus availability, and effective cation CEC remained unaffected for both forms of biochar, with the rice-husk biochar demonstrating nitrogen (N) retention. Studies conducted by Koné and Galiegue [164] in Senegal, Cornelissen et al. [165] in Zambia, Kimetu et al. [37], and Mahmoud et al. [166] in Kenya also documented positive outcomes associated with biochar application on crops, mirroring the findings observed in Nigeria.

In summary, utilizing BC as a soil amendment in the African context has shown promising results in many countries including Ghana, Burkina Faso, Senegal, Zambia, Kenya, and Nigeria. This demonstrates that applying biochar to different agricultural soils in Africa is a highly effective strategy to improve soil fertility and, consequently, crop performance. This could convince more farmers to adopt it use as a soil amendment and researchers to advance its studies in more diverse and feasible ways to arrive at more convincing results.

6.1. A Case Study of Recent Studies of Biochar in Nigeria

Nigeria's expansive tropical rainforest offers abundant biomass resources [167]. Due to distinct weather patterns, diverse crops can be cultivated across both the northern and southern regions of the country. This diversity enhances the availability of residue suitable for biochar (BC) production. Recent studies have been conducted in Nigeria, aiming to enhance the understanding of BC's role in soil fertility and agricultural performance. Table 2 provides a summary of these efforts across various agroecological zones in Nigeria.

Adekiya et al. [168] utilized BC derived from *Prosopis africana* trees, pyrolyzed at 580 °C, to examine the impacts of BC and potassium fertilizer on soil properties, growth, and the yield of sweet potatoes (*Ipomoea batatas* (L.) Lam) in Kwara State, Nigeria, on Alfisol. Their findings revealed that the combined application of BC and potassium fertilizer enhanced sweet-potato performance, while also increasing soil pH and organic C, N, P, K, Ca, and Mg compared to singular applications. In Ekiti State, Ilori et al. [124] investigated the effects of maize-stover BC pyrolyzed at 463.4 °C on phosphorus adsorption in soils derived from charnockite. They observed reduced phosphorus adsorption, indicating a potential increase in phosphorus availability. In Owo, Ondo State, Nigeria, Agbede and Oyewumi [169] observed that the sole application of poultry manure, combined with hardwood BC derived from *Parkia biglobosa* (Jacq.), *Khaya senegalensis* (Desr.) A. Juss., *Prosopis africana* (Guill. & Perr.) Taub., and *Terminalia glaucescens* Planch. at an average temperature of 580 °C, improved the quality of degraded acidic soil and sweet-potato-tuber yield. Comparable outcomes were also achieved on sandy and loam soils [170].

In Awka, Anambra State, Anozie et al. [171] examined the influence of different growth media on the initial growth of *Annona muricata* L. seedlings. The study's findings indicated that goat dung, sawdust, and chicken droppings were followed by topsoil amended with biochar (BC) derived from *Tectona grandis* L.f., *Irvingia gabonensis* (Aubry-LeComte er O'Rorke) Bail, and *Gmelina arborea* Roxb. with a restricted air supply. BC exhibited the highest growth performance in terms of plant height, collar diameter, and leaf count.

In the humid, tropical, sandy-loam-textured, acidic Ultisol of Enugu State, Okebalama et al. [172] explored the effects of bambara-seed (*Vigna subterranea* (L.) Verdc.) residue, BC, and NPK on soil fertility, aggregate carbon and nitrogen concentrations, and cucumber (*Cucumis sativus* L.) yield. The study observed that the application of sole BC, in conjunction with NPK, enhanced soil characteristics and resulted in an increased cucumber yield. Adekanmbi et al. [173], in their investigation of the effects of inorganic phosphate fertilizer and BC produced from agricultural-waste (sawdust and maize cob) and animal-manure (swine dung and poultry manure) feedstocks, produced at 400 °C on soybean (*Glycine max* (L.) Moench) growth and nodulation in Niger, the Southern Guinea savanna zone of Nigeria, reported a positive influence of BC application on soybean growth and nodulation.

In a study conducted on a degraded tropical Alfisol located in Ondo State, Agbede and Oyewumi [174] investigated the impacts of hardwood BC (pyrolyzed at 580 °C), poultry manure, and their mixtures on the essential nutrient content of sweet-potato leaves and storage roots. The outcome observed indicated that the application of either biochar alone, poultry manure, or their combined treatments at different levels resulted in heightened nutrient concentrations within the leaves and enhanced mineral composition in sweet potatoes. These favorable effects were attributed to the improvements in soil conditions. For the evaluation of carbon sequestration and maize growth on sandy-clay soil in Gombe, Sudan savanna zone of Nigeria, Mustapha et al. [175] utilized maize-stalk biochar generated at 400 °C. The application of biochar was reported to enhance soil organic carbon, total nitrogen, and accessible phosphorus, along with improvements in the soil's bulk density and water-holding capacity. However, maize production and growth were not significantly impacted. To investigate nitrate leaching from soils with various textural classes in Adawama State, located in the Nigerian savanna, Solomon [44] employed biochar derived from maize cob, rice husk, cow dung, and chicken litter pyrolyzed at 600 °C. The application of 2.5, 5, and 7.5 t ha^{-1} rice-husk biochar and cow-dung biochar on sandy-loam soil significantly reduced nitrate leaching. Moreover, 2.5 and 5 t ha^{-1} rice-husk biochar and 2.5, 5, and 7.5 t ha^{-1} cow-dung biochar decreased nitrate leaching from loamy soils.

Sanni et al. [176] used rice-husk biochar (BC) produced at temperatures exceeding 700 °C to investigate its impact on the physicochemical composition of the soil and the performance of cowpea (*Vigna unguiculata* (L.) Walp.) in Lagos State. Among different application rates, 1.25 t·ha^{-1} of BC yielded the best results in terms of enhancing soil pH, CEC, and promoting cowpea growth and yield. Eifediyi et al. [177] examined the effects of a sawdust-biochar application on the growth, morphological characteristics, and yield of four varieties of sesame (*Sesamum indicum* L.). The study revealed that sawdust biochar had positive effects on low-fertility soil during sesame cultivation in Kwara State, within the Guinea savannah zone of Nigeria. These effects contributed to the improved growth and yield characteristics of the crop.

Tate et al. [178] conducted research in Bayelsa State, focusing on the effects of locally pyrolyzed wood and cattle-dung biochar on macronutrient distribution and the toxicity of heavy metals in diesel-contaminated soils. The findings indicated that additions of biochar at all levels significantly increased soil pH, organic-matter content, accessible phosphorus, and exchangeable bases. These effects were particularly prominent in biochar derived primarily from cattle-dung feedstock, as well as from a combination of cattle dung and wood sources. Furthermore, the study demonstrated that the substantial surface area of the biochar attracted cation bases, leading to the reduction of cadmium and nickel concentrations at colloidal exchange sites. This process contributed to the removal of heavy metals and increased their mobility and bioavailability within the soil solution.

In Nasarawa State, located in the Southern Guinea savanna zone of Nigeria, Sodah et al. [179] assessed the impact of a combined BC and micronutrient application on the growth and yield of soybean (*Glycine max*. L. Merril). The most favorable soybean-production results in the study region were observed when combining micronutrients at a rate of 0.5 l·ha^{-1} with BC at a rate of 8 t·ha^{-1}. Ibrahim [180] investigated the effects of a rice-husk-derived BC and NPK fertilizer application on sandy-loam soil characteristics and okra (*Abelmoschus esculentus* L.) yield in Nigeria's Plateau State. The application of BC was found to enhance soil qualities, nutritional status, and the growth and yield of the okra plant. The highest okra yield was achieved through the combination of 20 t·ha^{-1} BC and 150 kg·ha^{-1} NPK fertilizer.

Remigius et al. [181] evaluated the influence of different fertilizer types (solid, liquid NPK, and poultry manure) and rice-straw BC produced at 400 °C on drip-irrigated upland rice performance in Ondo State, Nigeria. The results indicated that the combinations of fertilizer and BC treatments effectively increased rice yields. In Ogun State, Adebajo et al. [182] reported the effects of rice-husk biochar pyrolyzed at 350 °C on the soil microbial biomass and agronomic performance of tomato plants (*Solanum lycopersicum* L.). The study revealed improvements in soil properties including Ca, Mg, K, Na, H^+, S, P, B, and CEC, leading to enhanced tomato plant growth. Furthermore, the application of 7.5 t·ha^{-1} of biochar to the soil resulted in the highest yield and microbial biomass levels.

According to Amin et al. [42] in Kano State, the substantial results of rice-husk-biochar (BC) amendment indicated a general increase in the number of tomato leaves and fruits over the observation period. The best results were recorded with the application of 15 t·ha^{-1} BC under 50% irrigation, particularly in terms of leaf numbers. Abdu et al. [183] conducted a study on the kinetics and thermodynamics of nitrate adsorption using Freundlich, Langmuir, and Dubinin–Radushkevich models. They employed two agricultural wastes (maize cob and rice husk) and two animal wastes (cow dung and poultry litter), all produced at 600 °C in Kaduna State, Nigeria. The Langmuir adsorption isotherm analysis revealed that only maize-cob biochar and poultry-litter biochar had the ability to adsorb nitrate. The Freundlich and Dubinin–Radushkevich models were found to fit well for NO_3^- adsorption onto poultry litter, whereas the Freundlich model provided the best description for NO_3^- adsorption onto maize-cob biochar.

Iren and Ediene [184] investigated the combined effects of wood biochar (BC), poultry manure, and urea on strongly acidic loamy sand soil in Calabar, Cross River State, Nigeria, and their influence on soil pH and microbiological characteristics. As per the findings, soil amended with complete BC (20 $t \cdot ha^{-1}$) and half the amount of poultry manure (10 $t \cdot ha^{-1}$) raised the pH value from 5.4 to 6.8. This combination yielded more favorable results than BC alone or combined with urea, particularly in relation to the amaranth crop (*Amaranthus cruentus* L.). In a study by Agbede [185], the effects of tillage, hardwood biochar (produced at 580 °C), poultry manure, NPK 15-15-15 fertilizer, and their combinations were investigated on soil characteristics, growth, and carrot (*Daucus carota* L.) yield in the tropical sandy-loam soil of Ondo State, Nigeria. In contrast to using NPK fertilizer, BC, or poultry manure separately at their recommended rates and their combinations, lower-than-optimal levels along with various tillage methods yielded more substantial enhancements in soil physical properties, the increased availability of key nutrients in the soil, and promoted the greater growth and yield of carrot roots. Moreover, when compared to the control group, the application of BC, poultry manure, or NPK fertilizer individually resulted in heightened soil fertility, improved growth, and increased production of carrot roots. However, in terms of soil characteristics, especially physical attributes, the combination of BC and poultry manure demonstrated superior performance compared to NPK fertilizer.

In Enugu State, Nigeria, Ebido et al. [186] conducted a study investigating the impacts of rice-husk BC pyrolyzed at 550–600 °C on organic carbon, aggregate stability, and the nitrogen fertility of coarse-textured Ultisols. They observed that as the rate of rice-husk BC increased, soil organic carbon and aggregate stability also increased. The best total nitrogen content was achieved at the highest application rate of 40 g per pot. Nwangwu and Anedo [187] explored the effects of mixed biochar and poultry manure on specific soil chemical characteristics and ginger yield in an Ultisol located in Umudike, Abia State, Nigeria. According to their findings, the simultaneous use of both biochar and poultry manure led to a notable enhancement in soil chemical properties and a substantial increase in the fresh-rhizome yield of ginger. The highest yield, reaching 13.2 $t \cdot ha^{-1}$, was achieved through the joint application of 8 $t \cdot ha^{-1}$ of biochar and 8 $t \cdot ha^{-1}$ of poultry manure.

Adamu and Junaidu [188] conducted a study in Nasarawa State, Nigeria, examining the effects of softwood-pruning-branch BC and additional micronutrient applications on soil and okra growth. Their findings indicated that both biochar and micronutrients contributed to enhanced vegetative-growth indices in okra, although there were no significant differences. Notably, the application of 16 tons of biochar per hectare significantly increased the proportion of organic carbon, organic matter, nitrogen with high cation exchange capacity, and soil pH.

Table 2. Summary of published research on BC–soil fertility–crop performance in the various agroecological zones of Nigeria.

Feedstock	Temperature (°C)	State	Agroecological Zone * (Figure 5)	Scope	Effect	Author (s)
Prosopis africana tree	580	Kwara	DS	BC + K fertilizer	Improved sweet-potato performance and elevated soil pH, organic carbon content, nitrogen, phosphorus, potassium, calcium, and magnesium concentrations	[168]
Maize stover	463.36	Ekiti	DS	Sole BC application	Decreased P adsorption	[124]
Hardwood BC	580	Ondo	DS/HF	Poultry manure + hardwood BC	Enhanced the condition of impoverished acidic soil and bolstered the yield of sweet-potato tubers	[169]
Tectona grandis, *Irvingia gabonensis*, and *Gmelina arborea*	-	Anambra	HF	Sole BC and goat dung, sawdust, and chicken droppings	BC gave the highest growth performance in terms of plant height, collar diameter, and number of leaves	[171]
Bambara-seed-residue BC	-	Enugu	DS	BC + NPK	Enhanced soil characteristics and increased cucumber yield	[172]
Sawdust, maize cob, swine dung, and poultry manure	400	Niger	NGS/SGS	BC + inorganic phosphate fertilizer	Favorable impact on soybean growth and nodulation	[173]
Hardwood BC	580	Ondo	HF	BC + poultry manure	Increased leaf nutrient concentrations and mineral composition of sweet potato	[174]
Maize-stalk BC	400	Gombe	SS/NGS/SGS	Sole BC	Improved soil organic carbon, total nitrogen, and accessible phosphorus but maize production and growth were not said to be significantly affected	[175]
Maize cob, rice husk, cow dung, and chicken litter	600	Adamawa	NGS/SGS	BC + cow dung + chicken litter	Reduced nitrate leaching	[44]
Rice-husk BC	>700	Lagos	HF	Sole BC	Increased soil pH, CEC, and cowpea growth and yield	[176]
Sawdust	-	Kwara	DS	Sole BC	Enhanced growth and yield characteristics of sesame	[177]
Wood and cattle-dung BC	-	Bayelsa	HF	Sole BC application	Increased soil pH and elevated levels of organic material, accessible phosphorus, and exchangeable cations, decreased cadmium and nickel at the colloidal exchange sites of soil	[178]
-	-	Nasarawa	DS	BC + micronutrients	Enhanced the growth and yield of soybean	[179]
Rice-husk BC	-	Plateau	MA/DS/NGS	BC + NPK fertilizer	Improved nutritional status, soil qualities, and the development and yield of okra	[180]
Rice straw	400	Ondo	HF	BC + fertilizer types (solid, liquid NPK and poultry manure)	Effective in rice-yield increase	[181]

Table 2. *Cont.*

Feedstock	Temperature (°C)	State	Agroecological Zone * (Figure 5)	Scope	Effect	Author (s)
Rice husk	350	Ogun	DS	Sole BC	Improved soil Ca, Mg, K, Na, S, P, B, and CEC, which enhanced tomato agronomic performance and microbial biomass	[182]
Rice husk	-	Kano	NGS/SS	BC + irrigation intervals	Increased number of tomato leaves and fruits	[42]
Maize cob, rice husk, cow dung, and poultry litter	600	Kaduna	NGS	Sole BC	Maize-cob and poultry-litter BC have the ability to adsorb nitrate (Langmuir adsorption isotherm) NO_3^- adsorption on to poultry litter (Freundlich and Dubunin–Radushkevich, while Freundlich best described NO_3^- adsorption onto maize-cob BC)	[183]
Wood	-	Cross River	HF	BC + poultry manure + urea	Whole BC and half poultry manure increased the pH value with a more beneficial result than BC alone or in combination with urea on an amaranth crop	[184]
Hardwood	580	Ondo	HF	BC + poultry manure + NPK fertilizer	Utilizing NPK fertilizer, BC, and poultry manure at less-than-optimal levels led to enhanced soil physical characteristics across various tillage methods. This approach also resulted in an increased accessibility of essential nutrients in the soil, fostering greater growth and yield of carrot crops	[185]
Rice husk	550–600	Enugu	DS	Sole BC	As the rate of rice-husk-biochar (BC) application rose, there was a corresponding increase in soil organic carbon content and improvement in aggregate stability	[186]
--	-	Abia	HF	BC + poultry manure	Significant improvement in soil chemical characteristics and the yield of fresh ginger rhizomes	[187]
Softwood prune branches	-	Nasarawa	DS	BC + supplemental micronutrient	Okra vegetative-growth parameters increased with the application of both BC and micronutrients with no significant difference. Increased soil percentage of organic carbon, organic material, cation exchange capacity, nitrogen content, and pH levels	[188]

* SLS Sahel savanna, SS Sudan savanna, NGS Northern Guinea savanna, SGS Southern Guinea savanna, MA mid-altitude, DS derived savanna, HF humid forest.

Studies on various crops such as *Annona muricata* [171], cowpea [176], sesame [177], okra [180], tomato [42], and ginger [187] demonstrated the positive effects of BC on growth and yield. These findings suggest that BC application benefits a wide range of crops, making it a versatile soil-amendment option. Studies like Remigius et al. [181] and Ebido et al. [186] highlighted the importance of optimized BC application rates. Higher application rates of BC led to increased soil organic carbon, aggregate stability, and nitrogen fertility, emphasizing the need for the careful consideration of BC dosage for optimal results. The combination of BC with micronutrients, as studied by Sodah et al. [179] and Adamu and Junaidu [188], demonstrated enhanced crop growth. These findings suggest that integrating BC with micronutrient supplements can lead to improved agricultural outcomes. Nigeria's agricultural landscape, comprising seven distinct agroecological zones, has seen limited research on biochar (BC) applications. These zones (Figure 5) encompass a diverse range of environments, including Sahel savanna (SLS), Sudan savanna (SS), Northern Guinea savanna (NGS), Southern Guinea savanna (SGS), mid-altitude (MA), derived Savanna (DS), and humid forest (HF) [189]. Despite the agricultural significance of these regions, research on BC has predominantly been conducted in DS and HF, each constituting 31% of the documented studies (Figure 6). NGS and SGS followed with 17% and 10% contributions, while SS, MA, and, surprisingly, SLS accounted for merely 7%, 4%, and 0%, respectively. This alarming lack of research focus on SLS is particularly concerning, given that this region predominantly features low-fertility sandy soils with meager yields for arable crops.

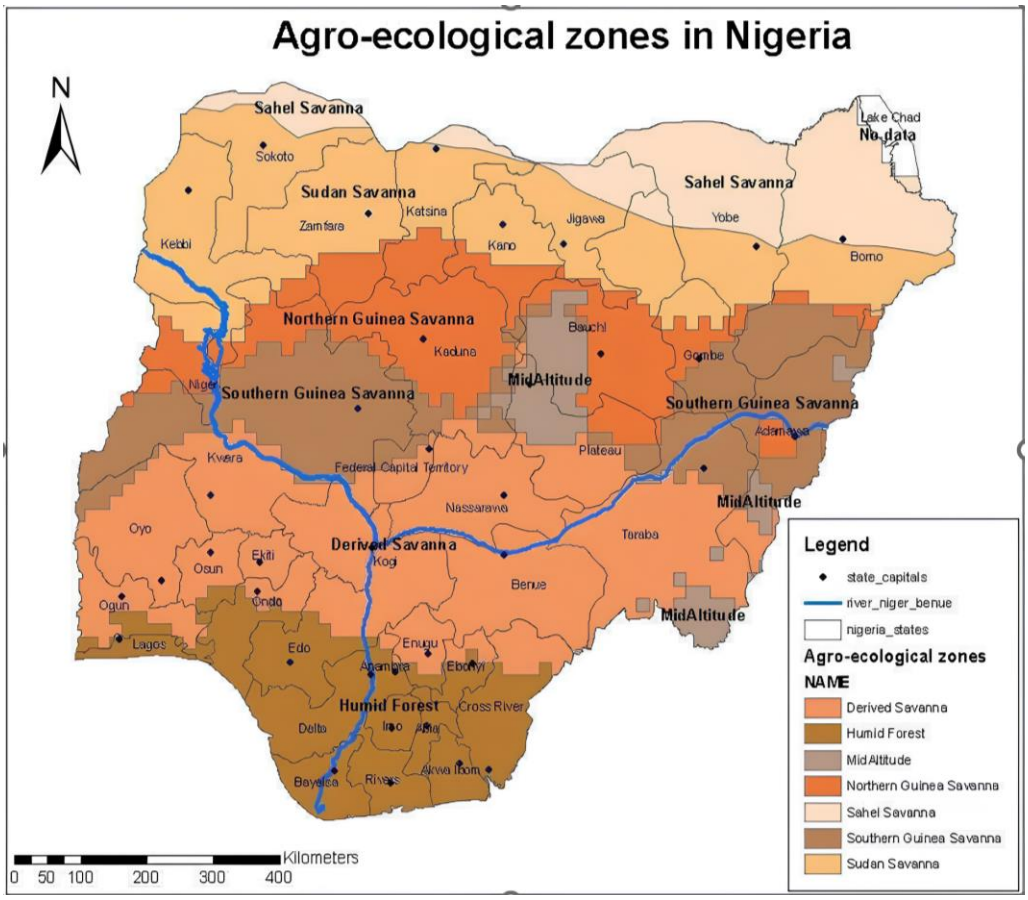

Figure 5. Agroecological zones of Nigeria, adapted with permission from Oniosun [189].

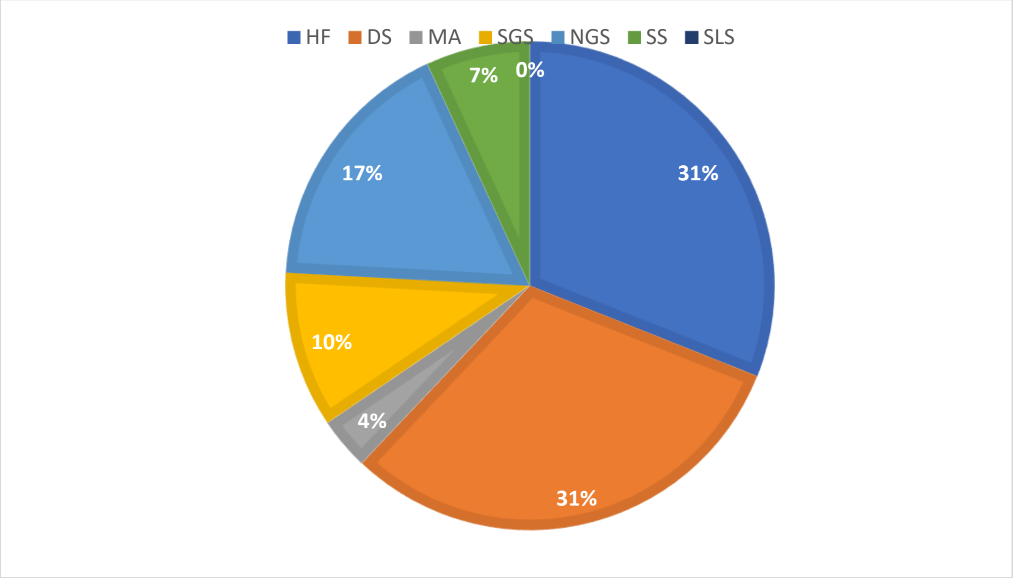

Figure 6. Recent BC–soil fertility–crop performance research distribution in the various agroecological zones of Nigeria. SLS Sahel savanna; SS, Sudan savanna; NGS; Northern Guinea savanna; SGS Southern Guinea savanna; MA mid-altitude; DS derived savanna; HF humid forest.

The absence of documented BC research in SLS, an area plagued by soil fertility challenges, underscores the critical need to redirect research efforts toward this neglected agroecological zone. SLS, characterized by its low-fertility sandy soils and poor crop productivity, represents a pressing concern for agricultural sustainability in Nigeria. Addressing the soil fertility issues in SLS through innovative BC applications can potentially transform this region into a productive agricultural hub, improving food security and economic stability for the communities residing there. Examining the existing research combinations in other agroecological zones where BC studies were conducted, three predominant approaches emerge: sole BC application (SB), BC–macronutrient combination (B + Ma), and BC–manure combination (B + MN), each accounting for 29% of the documented studies (Figure 7). These combinations signify the diverse strategies employed to enhance soil fertility and agricultural productivity. Given the success observed in other regions, it is imperative to prioritize SLS soils as the focal point for future research endeavors. By exploring the efficacy of these common BC applications in the context of SLS, researchers can develop tailored solutions to address the specific challenges posed by low-fertility sandy soils, thereby unlocking the agricultural potential of this region. The disproportionate distribution of BC research across Nigeria's agroecological zones highlights the urgency of directing research efforts toward the neglected SLS region. By focusing on innovative BC applications, particularly utilizing the proven approaches of sole BC application, BC–macronutrient combination, and BC–manure combination, researchers can pioneer solutions to the pressing soil fertility issues in SLS. This strategic shift in research focus has the potential to revolutionize agricultural practices, improve crop yields, and uplift the livelihoods of communities in this vulnerable region, ultimately contributing to the overall agricultural resilience and sustainability of Nigeria.

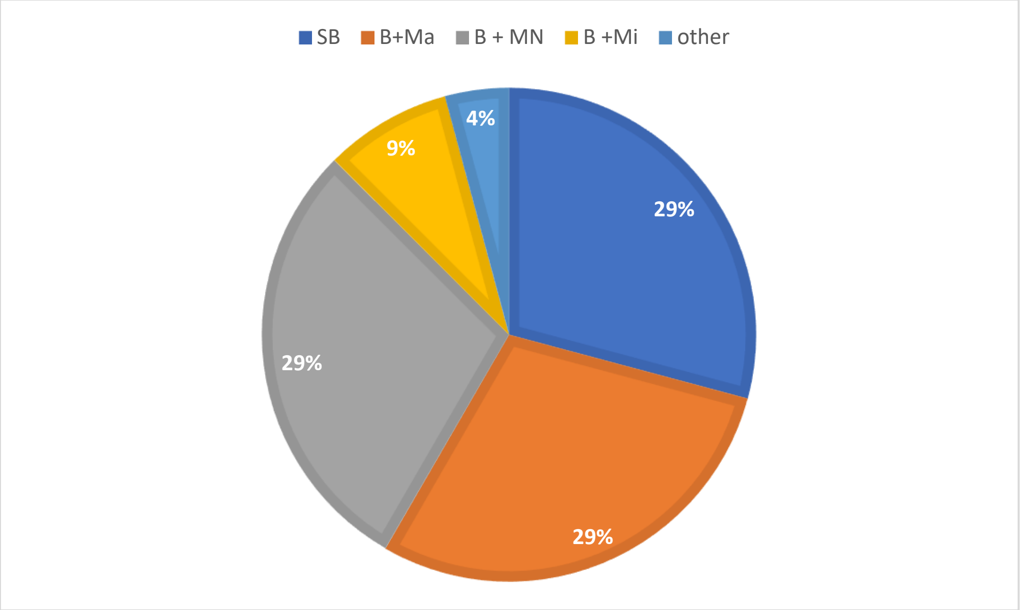

Figure 7. BC–soil fertility–crop performance research scope in Nigeria. SB = sole BC, B + Ma = BC + macronutrient, B + MN = BC + manure, B + Mi = BC + micronutrient.

6.2. Challenges and Opportunities for Biochar Implementation in Africa

The selection and accessibility of substantial quantities of suitable biomass, possession of pyrolysis equipment, pyrolysis parameters, and workforce availability represent notable limitations when utilizing biochar [190]. Cutting down trees or removing biomass from the earth will only worsen the soils and ecosystems we are seeking to recover. In addition, several unsolved questions cast doubt on biochar's usefulness, benefits, and significance. As stated by the African Biodiversity Network, Biofuel Watch, and The Gaia Foundation [191], the utilization of biochar, particularly on a significant scale, has the potential to impact various aspects including the climate, soil water quality and retention, agricultural productivity, soil erosion and depletion, pollution, and human health.

There are certain difficulties with biochar that need to be resolved. When biochar is mixed into soils or later eroded, tiny particles of biochar that are discharged into the air can potentially cause considerable regional and global warming [164]. Black carbon, present in charcoal, is one of the biggest contributors to global warming. Adding biochar to soil makes it darker, introducing a significant concentration result in soil darkening, influencing both soil color and surface reflectance, consequently impacting soil temperature and heat distribution [192]. Additionally, due to the fact that poisons have a tendency to adhere to charcoal, an increase in the amount of toxins in food is also a challenge [193]. Due to the alkaline nature of biochar, the application of very high doses causes certain plants to grow more slowly, resulting in reduced yields [194]. Ash and nutrients in fresh biochar are quickly reduced after a short time. Because of this, yield performance frequently increases at first before declining [157].

The soils of Africa are dry for weeks or even months within the dry season, making many regions vulnerable to erosion. Crop residues that are used to make biochar rather than compost or are left in the soil may cause a considerable increase in soil erosion and depletion. The production of biochar is not industrialized or closed in the majority of African nations. The local production of biochar using kilns can result in excessive smoke and CO_2 emissions that contaminate the air. These stand to be a major problem during pyrolysis, particularly if the biomass has undergone chemical treatment, includes other pollutants, or is combined with municipal solid waste, used tires, and other garbage. Additionally, a study found that when applied, 30% of the biochar escaped into the atmosphere [164]. The dust produced by the ashes of rice husks has been linked to silicosis, a lung condition that often proves fatal and has irreversible and increasing effects [195].

According to Adeniyi et al. [43], unusual obstacles to biochar production in Nigeria include an epileptic power supply, which means thermal processes that do not require any power will unintentionally become more popular in the nation. Since agriculture is typically practiced in rural locations in Nigeria, such technologies that do not require an electrical source would be pertinent. Considering that most agricultural activities are still conducted manually within rural villages, modern agricultural practices including mechanization and the use of agrochemicals are still not very common in distant areas. This implies that to help alleviate these conditions, biochar technologies appropriate for such places would need to be created. It is the responsibility of agricultural extension agents to assist in providing local farmers with appropriate training on the usage of biochar in agriculture/farming. Only agricultural extension specialists can bridge the gap between research discoveries and their practical implementation by farmers [43]. Nigeria in particular, as well as the rest of Africa, has a promising future to produce biochar from biomass. The country has access to a range of various biomass types due to its possession of a tropical rainforest, a Southern Guinea savanna, a Northern Guinea savanna, a Sudan savanna, and a Sahel savanna. Additionally, agriculture still plays a significant role in Nigerian society, so any advancements in technology there will have a long-term effect.

According to prior research conducted by Rogers et al. [196] in Tanzania, the acceptance of biochar in developing countries is influenced by variables such as age, gender, educational level, income, occupation, beliefs, farm size, and the availability of feedstocks. As reported by Fru et al. [197], a minority of smallholder farmers (20%) in the Nkolbisson Forest region of central Cameroon have received limited formal education spanning only a few years. Furthermore, it was revealed that 55% of farmers concurred that both the pyrolysis procedure and the cost of gathering, storing, and transporting feedstocks were high. Due to their access to resources, including land, manpower, and money, farmers over 40 years of age were more willing to use biochar than those under 40 years of age. These factors collectively reduced the levels of biochar application and the anticipated benefits of biochar investments, making them seem unclear. However, after receiving biochar education and the establishment of demonstration plots, smallholder farmers observed an improvement in soil quality and an increase in yields. According to Rogers et al. [196], farmers' lack of financial resources and education hampered the adoption of the technology. For instance, instead of being used as a soil amendment, the created biochar was left to be used as fuel for cooking [198]. Rogers [196] also stated that local conceptions and attitudes can affect smallholder farmers' adoption of biochar technology. Farmers were shown to prefer purchasing prepackaged biochar over producing their own since the manufacturing of biochar matches that of charcoal, a lower-class profession. Therefore, it was recognized that producing biochar could lower the social status of the farmers.

However, since minimal feedstock is required, biochar can be easily applied to small farms. In addition, compared to large farms, the application process is quicker. This is in line with research by Uaiene et al. [199], who discovered that small farms are more suited to innovation that requires less input than large farms, which may not have the resources.

7. Summary and Conclusions

Biochar is a promising soil amendment having the potential to raise soil fertility and thus crop performance through various processes in the soil, as well as ensure sustainability and mitigate climate change through carbon sequestration. From this BC–soil fertility–crop performance review, the conclusions are as follows:

i. With seven agroecological zones in Nigeria, each vary in available biomass, with the dominating agricultural waste being mostly from grass species across the northern part and shrubs and trees in the southern part. Straw/husk/stover from rice, corn, and sorghum can be the best option as feedstock for biochar production, as well tree prunings and timber/wood by-products like sawdust being likely suitable.

ii. Knowledge Gaps and Potential Research Directions: This review suggests that although some studies have examined the impact of biochar on soil fertility and crop performance in specific Nigerian regions, knowledge gaps still exist, especially in low-fertility, semi-arid regions like the SLS. Future research should focus on addressing these gaps and exploring the optimal utilization of biochar in various agroecological zones across the country.

iii. BC research with SLS and SS soils are highly recommended in Nigeria at any scope or magnitude comprising sole BC application and BC macronutrient, micronutrient, and manure combinations and as a slow-release fertilizer,

iv. More micronutrient or more advanced BC research can be recommended in the other agroecological zones of Nigeria as the majority of the soils in these areas are rich in soil organic matter.

Though feedstock for biochar production in Nigeria is available, power supply problems make it necessary to employ local methods for its production. In this case, with local production, obtaining the quantity needed for soil amendment can become much more challenging, as local kilns may only produce a small quantity at a time. Developing an alternative approach for using biochar in lower quantities would be a significant innovation. Little to no effort was spared to test both local unmodified biochar and modified biochar as slow-release fertilizers. These fertilizers require a minimal amount of biochar to achieve their intended effects. Furthermore, they have the potential to contribute to efficient nutrient utilization by crops, while also enhancing soil carbon over time and reducing year-to-year fertilizer costs. Future research should focus on these aspects before achieving a more stable power supply and establishing a standard, commercial-level biochar-production infrastructure. Both macro- and micronutrients can be subjected to trials using modified and unmodified biochar for slow-release fertilizer production. Given the nutrient-deficient and poor soils found in the SLS and SS regions of Nigeria, adopting slow-release fertilizers can be a highly beneficial soil-nutrient management strategy. This approach has the potential to substantially improve soil fertility, thereby ensuring food security and facilitating carbon sequestration.

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