sustainability

Review

Biochar Role in the Sustainability of Agriculture and Environment

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Abstract: The exercise of biochar in agribusiness has increased proportionally in recent years. It has been indicated that biochar application could strengthen soil fertility benefits, such as improvement in soil microbial activity, abatement of bulk density, amelioration of nutrient and water-holding capacity and immutability of soil organic matter. Additionally, biochar amendment could also improve nutrient availability such as phosphorus and nitrogen in different types of soil. Most interestingly, the locally available wastes are pyrolyzed to biochar to improve the relationship among plants, soil and the environment. This can also be of higher importance to small-scale farming, and the biochar produced can be utilized in farms for the improvement of crop productivity. Thus, biochar could be a potential amendment to a soil that could help in achieving sustainable agriculture and environment. However, before mainstream formulation and renowned biochar use, several challenges must be taken into consideration, as the beneficial impacts and potential use of biochar seem highly appealing. This review is based on confined knowledge taken from different field-, laboratory- and greenhouse-based studies. It is well known that the properties of biochar vary with feedstock, pyrolysis temperature (300, 350, 400, 500, and 600 °C) and methodology of preparation. It is of high concern to further investigate the negative consequences: hydrophobicity; large scale application in farmland; production cost, primarily energy demand; and environmental threat, as well as affordability of feedstock. Nonetheless, the current literature reflects that biochar could be a significant amendment to the agroecosystem in order to tackle the challenges and threats observed in sustainable agriculture (crop production and soil fertility) and the environment (reducing greenhouse gas emission).

Keywords: biochar; food security; socio-economics benefits; sustainable agriculture; sustainable environment

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1. Introduction

The world's population is increasing day by day and is expected to reach 9.8 billion by 2050 (United Nations Department of Economics and Social Affairs, New York, NY, USA), which will put the world's agricultural system under an increasing threat. Thus, to feed the increasing population and fulfil the constantly growing demand for grains and organic food, the farming system has become dependent on technological and chemical inputs [1]. Some parts of the world have met the needs for food through improved farming system technologies. Such farming systems have been classified as agroforestry, agroecology, sustainable agriculture, organic agriculture, etc. [2]. The objective of all these improvements in the farming systems is to reduce hankering and enhance crop yield to obtain sustainable agriculture and the environment [3]. This concept has directed the attention of the scientific community and farmers towards natural residue and organic matters instead of commercially prepared products [4]. Biochar is one of the outcomes of scientific experiments, which has an important role in achieving sustainable agriculture and the environment [5]. Biochar, a type of charcoal obtained after the combustion of feedstock under no or very limited supply of oxygen, is considered as a potential soil conditioner [3]. It is also an efficient measure to sequestrate carbon to tackle climate change and global warming. It is highly durable when applied to the soil and can remain in soil for hundreds to thousands of years [5]. Biochar has become a public interest in the framework of bio-based industries, which depends on the alteration of feedstock into value-added chemicals and energy.

The term "sustainable agriculture" is defined as the consolidation of bioprocesses, chemical processes, physical activities, ecological processes, and socio-economic sciences in a holistic manner to design new agricultural practices that are safe and environmentally friendly [6]. Sustainable agriculture is a procedure by which agrofarming can nourish itself over an extended period by preserving and maintaining all its natural resources, e.g., maintaining the fertility of the soil, safeguarding surfaces and underground resources, developing renewable sources of energy, and seeking solutions to revamp farming methods to climate change [7,8]. Agrofarming must also consider the sustainability of the vast area and social groups.

Biochar is also being examined to rehabilitate environments, to diminish pollutant mobility in contaminated soils, and to reduce alteration of perilous elements to agronomic crops [7]. Mostly, biochar is produced from waste residues such as agricultural wastes, animal manures, and forest residues. The significance of these feedstocks is to produce biochar in a way that potentially transforms waste into a useful and valuable product [9]. Its impact on soil amendment includes increased soil quality and plant growth with enhancement in crop yield. The response and behavior of biochar can be substantially influenced by its manufacturing process, soil conditions and types where applied, and as well as the kind of crop to be grown [10,11]. In keeping with the importance of biochar, many researchers have studied the adaptability of biochar for the improvement of soil and environmental health. This review highlights the production processes of various feedstocks and pyrolysis temperatures at which biochar is produced and their impact on agriculture sustainability via improving soil ecosystem functions and services. This review is intended to help researchers globally in the selection of proper biochar produced at a certain temperature to improve agriculture and environment sustainability without compromising crop yield.

2. Brief Methodology

Data and literature were collected from Web of Science eBooks Freedom Collection (ScienceDirect) https://www.sciencedirect.com/; EBSCO Publishing (elFL.net duomenų bazių paketas) http://search.epnet.com/; Emerald Management e-Journals Collection https://www.emeraldinsight.com; Science Direct; Taylor & Francis https://www.tandfonline.com/; Springer LINK https://link.springer.com/. We collected and synthesized published literature from 1997 to 2020 using keywords "biochar", biochar and soil nutrients, "biochar and environment", etc., in the database. Though more than 1000 articles were downloaded, we focused on those indicating empirical outcomes. The cited literature was based on field studies as well as greenhouse pot or laboratory studies (Figure 1a,b). The online data search was irrespective of the region, biochar type, etc.

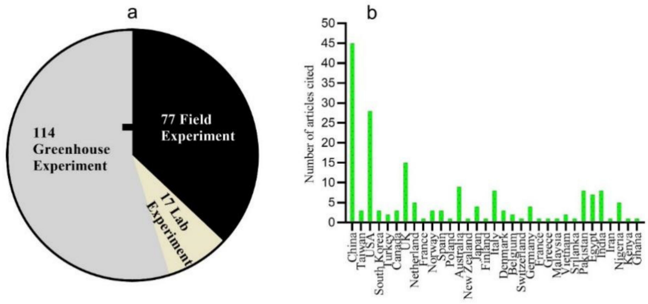

Figure 1. The details of cited information are (**a**) types of experiment and (**b**) countrywise published cited research.

3. Formulation, Morphology and Biochemistry of Biochar

Biochar is the bioproduct of thermal decomposition of renewable feedstock (forest and agricultural residues, hard woods, bamboos, livestock manure, etc.) under zero or low oxygen (O) conditions [12,13]. Feedstocks lose their mass when pyrolyzed at a minimum of 200–250 °C, as the thermal deterioration of the pulp occurs and leaves behind a spongy structure. Slow pyrolysis at low to intermediate heating (around 300 °C) and outstretched reaction times have been used for a long time to transform wood feedstock into high yields of biochar (biocarbon) [14]. The slow pyrolysis process also produces lower yields of bio-oil and gaseous by-products. In the past three decades, fast pyrolysis accomplished at medium temperatures (≤500 °C) and very short processing times (couple of seconds) has received substantial interest as a method for generating higher yields with considerably higher energy density than the original feedstock, in conjunction with 20% of biochar and 15% of gas. Biochar yield and physiochemical properties considerably depend upon the pyrolysis process and feedstock used [15,16]. Biochar produced at a low temperature contains more aliphatic compounds in the pores that increase the hydrophobicity [17,18], while high temperature pyrolysis allows a much smaller number of aliphatic compounds to remain in the pores [17]. In a few studies, biochar had no significant influence on soil water repellency (SWR) and water holding capacity (WHC) of hydrophobic soil with high total organic carbon content [19]. In this study, to better understand the dynamics of biochar, thermogravimetric analysis (TGA) of swine manure (feedstock) was performed prior to its conversion to biochar for the ongoing field experiment. It was found that the digestate starts losing humidity in between 15 and 20 min at 200–300 °C of temperature followed by the loss of different volatiles, which leads to pure black carbon at 900 °C and evolution of porous structure.

The formulation of biochar was reported in [10–22] rice straw (RS), vinasse (VI), *Phyllostachys pubescens* (PP), *Arundo donax* (AD), chicken manure (CM) and sugarcane bagasse (SB) residues. The samples were cut into pieces (<5 cm) or crushed and dried for 24 h to achieve a constant weight before pyrolysis. Two kilograms (Kg) of each sample was put into the furnace and heated to the recommended temperature. The obtained biochar was passed through an 80 mm-mesh sieve to obtain finer biochar. Similarly, in [23], the same process of preparing biochar from Pine and Jarrah wood was indicated. The biochar obtained was alkaline in nature and had a large surface area, with tremendous porosity and molar ratio, e.g., C/N; H/C; and a large number of beneficial elements and organic matter, e.g., C, H, N, S, and O [20,22]. The aromaticity and the surface charge of the biochars decreased after coating with FA [15] and humic acid [12]. Antonangelo [24] reported that biochar obtained from witchgrass (*Panicum capillare*) and poultry manure (SGB and PLB, respectively) was thermally decomposed at various temperatures, e.g., 350 and 700 °C. The pH and elemental configuration of biochars were found to be alkaline and nutrient rich, and a strong correlation between accessible nutrients and ash contents was recorded [24,25]. The internal porosity of the biochar influences the surface chemistry and the bulk density of the biochar. Additionally, the source of feedstock controls the hydrophobicity and porosity of the material, along with production temperature.

4. Biochar and Nutrients

The nutrient composition of biocarbon always differs with the type of biomass and pyrolysis temperature (Table 1). The concentration of nutrients in animal-derived biochar would not necessarily be higher than in plant-derived biochar pyrolyzed at the same temperature [26]. Biochar produced from lantana camara at 300 °C was rich in available P (0.64 mg kg^{-1}), available Ca (5880 mg kg^{-1}), available Mg (1010 mg kg^{-1}) and available Na (1145 mg kg^{-1}) [24]. Dried swine manure waste-derived biochar under slow pyrolysis (300–750 °C) was found to be rich in soil micronutrients and macronutrients, such as Ca, Mg, Na, Fe, Mn, Cu, Zn, N, P and K [25]. Total N contents were significantly greater for poultry manure-derived biochar pyrolyzed at 400 and 600 °C treatments in silt loam and sandy soils; however, they were not affected by swine manure-derived biochar (400 and 600 °C) and wood chip biochar (1000 °C) in the same soils [26]. Similarly, freshly prepared biochar is a rich source of available nutrients and could discharge a significant amount of N ranging from 23 to 635 mg kg^{-1} and P ranging from 46 to 1664 mg kg^{-1} [27]. Jiang et al.

reported that old biochar was not as effective for soil organic carbon (SOC) protection as fresh biochar. The decline in SOC stability with old biochar might be associated with the attenuated sorption of SOC on aged biochar [28]. Compared with old biochar, the addition of fresh biochar in sandy loam soil increased the biomass production [29]. Major nutrients such as N, P and K could assume the role of fertilizer and be absorbed by plants and soil microbes. Therefore, these examples indicate that biochar can potentially influence soil nutrition. Several studies have assessed the availability of nutrients in biochar by carrying out transient and long-term leaching experiments in recent decades. Mallee wood-derived biochar was easily drainable with double distilled water after a day (24 h) (15–20% Ca, 10–60% of P and 2% of N) [30]. However, it is necessary to choose the suitable biochar for its long-term nutrient availability to plants.

Table 1. Nutrient composition of various biochars at different pyrolysis temperatures.

Biochar Feedstock	Pyrolysis Temp. (°C)	pH	C	N	C/N	P	K	CA	MG	References
						(%)				
Corn cob	600	10.1	79.1	4.25	19	-	-	-	-	[31]
Corn stover	600	9.95	69.8	1.01	70	0.181	2.461	0.938	0.858	[32]
Peanut hull	400	10.0	65.5	2.0	33	0.00162	0.0015	0.00044	-	[33]
Pearl millet	400	10.6	64	1.10	58	1.60	2.52	1.47	1.06	[34]
Corn stover	300	7.33	59.5	1.16	51	0.137	1.705	0.648	0.588	[32]
Dairy manure	700	9.9	56.7	1.51	38	1.69	2.31	4.48	2.06	[35]
Poultry litter	350	8.7	51.1	4.45	12	2.08	4.58	2.66	0.94	[35]
Turkey litter	700	9.9	44.8	1.94	23	3.63	5.59	5.61	1.24	[35]
Cow manure	500	9.20	33.6	0.15	22	0.814	0.005	0.042	0.034	[36]

5. Biochar and Chemical Properties

The additions of biochar with organic matter and humic substances are getting increasing attention regarding their influence on soil fertility and crop yield [37]. Cacao shell- and rice husk-derived biochar at 600 and 500 °C, respectively, increased the pH and released dissolved organic matter from the soil [38]. Straw-derived (500–600 °C) biochar enhanced the degradation of organic matter and maturity and increased soil nutrients [39]. Composting dynamics are influenced by biochar via increasing the speed of organic matter decomposition and enhancing soil porosity, therefore improving composting efficiency and humification processes [40,41]. Ten percent of poultry manure-derived biochar and cow manure-derived biochar application into a composting mixture increased carbon content in humic and fulvic acids [42]. Acacia saligna-derived biochar at 380 °C and sawdust-derived biochar at 450 °C were the potential sources of humic substances (17.7 and 16.2%, respectively) [43]. Adding biochar during the composting process to maize straw and sewage sludge increased the available water content in sandy soil [44]. Biochar with mushroom residues and with corn straw could accelerate biodegradation of polycyclic aromatic hydrocarbon [45]. The amendments of biochar help in carbon (C) abetment and improving soil quality [46–48]. However, there are several studies comparing the physicochemical and morphological characteristics of biochar obtained from various feedstock sources and at different temperatures (slow, medium and high), as their effect when used in soil acclimatization may vary, since thermal decomposition has a great impact on biochar characterization [49,50]. Biochar produced at low thermal decomposition is often rich in carbon biomass content [51,52]. Liard [53] reported that slow pyrolyzed biochar has a higher amount of available P content compared to fast pyrolyzed biochar. This could be attributed to the lower percentage of crystallized P-associated minerals in slow pyrolyzed biochar. Moreover, the total K and available K (water soluble) content increases with an increase in pyrolysis temperature [54]. C richness allied with high adsorption capacity, porous structure and high alkalinity makes biochar inclusion into soil a practicable and effectual way to enhance soil quality and fertility [55–58]. The alkaline nature of biochar and organic carbon richness also enhance cation exchange capacity (CEC), which leads to a greater heavy metal adsorption capacity [59], and thus improves soil quality [60]. Further, numerous studies have focused on the physicochemical properties of biochar and its influence on soil nutrients and crop yield (Tables 1 and 2).

Table 2. Outline of the primary literature cited about biochar dynamics and its effect on crop yields.

Biochar Types	Temperature	Country/Type of Experiment	Application Rate	Biochar Properties	Soil Type/Texture	Result	Reference
Wheat Straw	300–500 °C	China/Greenhouse	3% *w*/*w*	pH 10.60	Psammaquent and Plinthudult	Increased rice yields in both soils	[61]
Wheat Straw	300, 400 and 500 °C	China/Greenhouse	1% *w*/*w*	pH = 6.74, 7.8 and 8.0 C = 52, 62 and 66 g % *N* = 23.8, 19.4 and 18 g kg^{-1}	Sandy clay loam and Calcisols Yermi	Biochar prepared at 300 °C significantly increased Maize crop yield	[62]
Rice Straw and Corn Stalk	450 °C	China/Field	1, 2 and 4 ton/ha	C = 71.7 and 63.5%, H = 3.70% and 1.6, O = 16.50 and 9.2% *N* = 2.40 and 1.3%	Inceptisol	Increased Corn, peanut and sweet potato by 5%, 15% and 20%, respectively	[63]
Miscanthus Giganteous Straw	500–750 °C	Norway/Field	8 and 25 ton/ha	pH = 7.86 C = 80% H = 1.2% O = 0.6% *N* = 6.6%	Silty clay loam Albeluvisol	No effect on crop yield	[64]
Cow Manure	600 °C	Japan/Greenhouse	0, 10, 15 and 20 ton/ha	pH = 9.20 C = 33.61% *N* = 1.51%	Sandy soil	Significantly enhanced Maize crop yield	[65]
Rice Husks	450 °C	China/Greenhouse	0, 10, 25 and 50 tha^{-1}	pH = 9.21 C = 465.4 g kg^{-1} *N* = 6.2 g kg^{-1}	Upland soil and paddy soil	Increased rice and wheat yield by 12% and 17%, respectively	[66]
Maize Stover	600 °C	USA/Field	0, 1, 3, 12 and 30 tha^{-1}	pH = 10.02 C = 290 mg g^{-1} *N* = 3.02 mg g^{-1}	Kendaia silt loam	No significant effect on crop yield	[67]
Woodchips	290 °C	Taiwan/Greenhouse	2% *w*/*w*	pH 6.3 C = 59.1%, *N* = 0.35%, H = 5.73%, K = 0.78 g kg^{-1}	Clay texture and sandy loam texture	No significant effect on crop yield	[68]
Woodchips	700 °C	USA/Field	5% *w*/*w*	pH = 9.6 C = 83.0%, *N* = 0.34%, H = 2.57%, K = 3.90 g kg^{-1}	Clay texture and sandy loam texture	No significant effect on crop yield	[68]

Table 2. *Cont.*

Biochar Types	Temperature	Country/Type of Experiment	Application Rate	Biochar Properties	Soil Type/Texture	Result	Reference
Rice straw	300,400 and 500 °C	Taiwan/Greenhouse	1% *w*/*w*	pH = 6.74, 7.8 and 8.0 C = 52, 62 and 66 g kg^{-1} *N* = 23.8, 19.4, 18 g kg^{-1}	Sandy clay loam, Calcisols Yermi	No effect on Maize crop yield	[62]
Sorghum	500 °C	USA/Laboratory	200 bushels ha^{-1}	C = 750.5 g kg^{-1} *N* = 13.5 g kg^{-1}	Norfolk soil and Dunbar soil (fine, kaolinitic, thermic, Aeric Paleaquults)	Wheat yield increased by 31%	[69]
Maize Cobs	300–550 °C	Ghana/Field	0, 2 and 6 t ha^{-1}	pH = 7.6–9.7 C = 69–81g kg^{-1} *N* = 0.6–0.7%	Sand and loamy sandy soil	Has positive effect on crop yield	[70]
Wheat Straw	370 °C	Spain/Greenhouse	0, 0.5, 1 and 2.5% *w*/*w*	pH = 9.8–11 Total C = 483–894 g kg^{-1} Total *N* = 3.7–8.3 g kg^{-1}	Haplic Luvisol	20–30% increase in wheat grain yield	[71]
Hard Wood	500 °C	Nigeria/Field	0,10, 20 and 30 t ha^{-1}	pH = 7.5 Total *N* = 0.65% Organic carbon = 52%	Sandy loam	30 t ha^{-1} of biochar significantly enhanced Cocoyam crop yield	[72]
Eucalyptus Polybractea	550 °C	UK/Greenhouse	10 t ha^{-1}	pH = 9.5 Total *N* = 1.1% Total C = 42	Ferrosol Soil	No effect on Cauliflower, peas or broccoli crops	[73]

6. Biochar and Physical Properties

Biochar amendment reduces soil bulk density and enhances water holding capacity (WHC) and nutrient holding capacity (NHC) as a result of its large surface area which increases water and nutrient use efficiency (Figure 2) [74–77]. Biochar could decrease soil bulk density by 3 to 31% and increase porosity by 14 to 64%. It shows a promising behavior of WHC and NHC in sandy soil due to its macropores and lower surface area [78]. Biochar could have a positive impact on WHC (Figure 2) and NHC, thus increasing water and nutrient availability to plants in sandy soil [79]. Barrow [80] proposed that biochar amendment could be an effective strategy to combat desertification and promote plant growth. Straw-derived biochar at 525 and 400 °C has a long-term effect on soil physiochemical properties, as it is most efficient in enhancing plant available water and soil aggregate stability in a coarse-textured Planosol [81]. The information on the physical and chemical properties of biochar is also presented in Table 1.

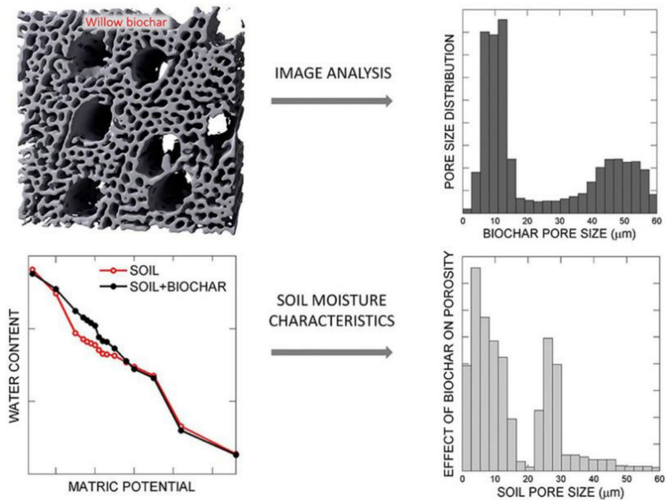

Figure 2. Determination of pore size distribution by 3D image analysis of X-ray tomography image (top panel) and the change in the pore size distribution due to biochar addition and determination of soil water content [82].

7. Effect of Biochar on Microbiota

The effect of biochar on the activity of soil microbes is dependent on types of soil and crop [83]. Wood-derived biochar application at a rate of 30 and 60 t ha^{-1} has a very short-lived positive effect on the microbial community [84]. In a recent study, Lu [85] reported that the porous structure of biochar substantially enhanced soil microbiota, due to the niche environment favorable to microbes. Otsuka [86] reported that multifariousness of the soil bacterial community expanded by 25% following biochar amendment compared to untreated soils. However, microbial biomass carbon and N mineralization were lowered with biochar amendment, thus reflecting that any boon from the liming effect of biochar is counterbalanced by a decrease in mass and community of soil microbes [87,88]. The application of biochar may increase soil pH. An increase in alkaline microsites may also alter the ammonia oxidizer population, particularly in acidic soil [89,90]. Similarly, rice straw biochar application significantly decreased Actinobacteria and Ascomycota fungi communities; however, soil microbial species diversification and copiousness may vary after biochar application [91]. Further, biochar amendment alters the soil nutrient cycling and nutrient supply, which in turn may affect the microbial community [92].

8. Biochar and Abatement of Greenhouse Gases

Climate change is usually attributed to the enhancing atmospheric abundance of greenhouse gases (GHGs) due to anthropogenic activities. Ninety percent of the anthropogenic climate warming is caused by three major GHGs, i.e., CO_2, CH_4 and N_2O [93].

Biochar has been suggested as an idle matter and beneficial soil amendment for carbon (C) sequestration to reduce CO_2 emission and its abundance from the environment [94,95]. Biochar offers a multitude of benefits for ensuring environmental safety. In view of their importance and diverse dynamics, a new terminology, "biochar culture", has been introduced to encircle the implementational and environmental gains of biochar [96]. It is an extremely valuable soil conditioner, as it changes a number of soil physicochemical characteristics (enhances soil moisture retention and increases air permeability) and impacts the soil microbial activity [97]. Biochar amendment also helps in the mitigation of greenhouse gases or setback by efficient management of agrofarming. Consequently, the "carbon foot-printing" of a specific land management has to be distinguished earlier than the targeted use for reducing emission by increasing "carbon sequestration" [96,97]. As "carbon sequestration" aims to reduce global warming by capturing the GHGs for a longer period, it can be proficient, because biochar overwhelmingly contains cyclic carbon with high aromaticity and exhausted H and O, which confer defiance to microbial strike on amendment in soil [98]. This increased obstinacy aspect, which helped in mitigating the emission of GHGs by reducing microbial decay and carbon digestion of organic biomass. Therefore, manufacturing of biochar and its amendment principally exploits the natural process of photosynthesis for crop biomass generation with the exception of removing atmospheric CO_2 by autotrophic microbes, that is, plants, mitigation of CO_2 to carbohydrate and other materials. Rondon [99] was the first scientist who reported N_2O emissions from a greenhouse experiment amended with biochar. Biochar pyrolysis at high temperatures and low N content might be more suitable to mitigate CO_2 and N_2O emission. A study from Terra Preta soil of the Amazonian region [100] reported that biochar can mitigate CO_2 emission for hundreds to thousands of years. Further, Wang [101] demonstrated from his dimensional analysis studies of the putrefaction and dressing effects on biochar stability in soil that only 3% of biochar C is bioavailable, and the rest is rendered into long-term stability. We expect a 4.0 °C rise in temperature by the end of the 21st century. Such environmental changes are the result of an increase in the atmospheric denseness of GHGs [102]. Biochar is anticipated to possess the desirable conditions for combating global warming and climate change. Biochar helps in atmospheric expulsion of CO_2, and due to its intractable nature, it captures the carbon to facilitate a huge carbon-negative economy [103]. Biochar amendment to soil curbs the emission of not only CO_2 but also about a hundred other potent GHGs, particularly nitrous oxide and methane [104]. Numerous studies advocate a substantial reduction in emissions of CO_2, N_2O and CH_4 gasses due to biochar application in land use under vegetable cultivation [105,106], but more long-term studies are needed.

9. Biochar and Soil Fertility

9.1. Effect of Biochar on Soil Nutrients

The effects of biochar on soil physicochemical properties are shown in Table 3. Biochar application is an effective practice for restoration of the functionality of degraded soils, and maintenance of long-term soil functions and fertility [107]. The addition of biochar improves degraded and low fertility soils, and thus improves crop production [108,109]. A. El-Naggar reported that biochar has the potential to be the best management practice for low fertility soils [110]. Major nutrients in biochar might not be necessarily available to plants in the desired amount [111]; the available NH^{4+}, $NO3^-$, $PO4^{-3}$ and K^+ might be associated with the amount of total N, P and K. For instance, the total N loss leads to a reduction in available N in highly thermally decomposed biochar [112]. The absorptivity of different nutrient ions on the surface of biochar and release occur due to variation in the CEC and pH of soil amended with biochar [113]. Yao [114] reported that the uptake of N and P as ammonium/nitrate and phosphate ions is significantly decreased by biochar application, decreasing their frequency in soil leachates by a high proportion. The properties of soil, e.g., texture, SOC, clay-to-sand contents and pH can change the biochar nutrient-sorption characteristics [114]. Additionally, the nutrient movement also changes biochar adsorption and succeeding release properties. The nutrient use efficiency of added organic fertilizer also increases with biochar amendment. The dynamism of nitrogen, principally engaging a decrease in nitrate transformation for subsequent reduced N loss, happens in response to biochar amendment, which can be deemed significant for optimal nitrogen use efficiency [78]. Thus, nutrient dynamics of biochar also assist in temperature and pH- reliant slow release of adsorbed nutrients by capturing nutrients from draining, runoff, leaching, microbial digestion and physical volatility processes. Therefore, plants and crops can potentially uptake nutrients, as these will be in plant-available forms in the root zone [112,113]. A sustained improvement of the physical characteristics of soil with biochar amendment involves better aggregate stability and formation, and alteration in the soil microbial community and activities imposes an indirect effect on retaining highly and reasonably mobile nutrients such as N and P [114].

Table 3. Different feedstock of biochar alters soil physicochemical properties.

Biochar Feedstock	Type of Soil	Sand	Silt	Clay	pH	TN	TC	References
			%					
Wheat straw	Sandy loam	-	-	16	5.6	0.18%	2.01%	[115]
Charcoal biochar	sandy	90.9	4.6	4.5	6.8	0.1 g kg^{-1}	1.0 g kg^{-1}	[116]
Charcoal biochar	Sandy loam	67.3	25.9	6.8	6.1	1.7 g kg^{-1}	31.0 g kg^{-1}	[116]
Oak and wood Bamboo	Clay loam	22	40	38	4.57	0.94 g kg^{-1}	5.50 g kg^{-1}	[117]
Poultry litter	Silt loam	26.6	33.7	39.7	7.99	0.13%	0.70%	[118]
Fruit tree and stem branches	Sandy loam	61.7	32.1	6.17	7.33	0.71	12.6 g kg^{-1}	[119]
Poultry litter	Sandy clay loam	52	17	31	3.95	0.25%	3.5%	[120]
Sewage sludge	Loam	71	25	4	6.50	0.04	5.48%	[121]
Wheat straw	Silt clay loam	16	52	32	8.3	1.0 g kg^{-1}	8.1 g kg^{-1}	[122]
Maize straw	Silty loam	13	72	15	7.9	0.99 g kg^{-1}	15.1 g kg^{-1}	[123]
Commercial biochar	Silt loam	16.1	64.1	19.8	6.90	0.13%	1.96%	[123]
Bamboo biochar	Sandy loam	49.2	39.2	11.6	4.72	0.17%	1.83%	[124]
Pine sawdust	Silt loam	30	56	14	5.7	2.2 g kg^{-1}	21.3 g kg^{-1}	[125]
Apple branches	Silty clay	10.7	73.0	16.8	6.23	0.47 g kg^{-1}	3.32 g kg^{-1}	[126]
Wheat straw (WSB) and miscanthus straw (MSB)	Sandy loam	73	15	12	6.46	1.28 g kg^{-1}	9.84 g kg^{-1}	[127]
Corncob	Silty loam	12.0	85.1	2.94	7.94	0.95 g kg^{-1}	8.23 g kg^{-1}	[128]
Sugarcane bagasse	Sandy loam	77.3	20.3	14.5	7.54	13.40 g kg^{-1}	4.20 g kg^{-1}	[129]
Pine sawdust	Clay loam	29	36	35	6.3	9.0 g kg^{-1}	97.2 g kg^{-1}	[125]

9.2. Effect of Biochar on Soil Organic Matter

The anticipation of enhanced soil fertility assigned to biochar amendment originates from the investigation of the terra preta that comprises a large percentage of black carbon [130]. Terra preta soil was found to be rich in organic matter content, which reflects the earlier evidence of biochar existence in the soil. Wang [131] reported that biochar enhanced C storage in macroaggregates of the fine-coarse soil and thereby increased the physical security of soil organic matter (SOM); C storage in stable microaggregates can promote the stabilization of SOM for a long period of time [132]. Biochar-stimulated physical fixation of C may be related to the existence of partially carbonized, highly degradable organic residues, often a characteristic of low thermally decomposed biochars [133]. Though SOM is usually more vulnerable to digestion in coarser rather than finer textured soils because of the lower surface area of mineral binding sites that can brace organic particles, Fang [134] indicated that Eucalyptus saligna wood biochars enhanced the mineralization of indigenous organic C in sandy soil, but not in a clayey textured soil. Moreover, biochar amendment to a grassland soil results in the arousal of mineralization of indigenous soil organic C because of the positive short-term priming effects [135].

10. Affinity of Biochar and Soil Characteristics

Biochar increases water and nutrient holding capacity (Table 2, Figure 3); however, these characteristics depend not only on biochar types but also on retention capability of soil [136]. Jien [136] reported that due to the physical structure of biochar, it improves soil porosity and structure, aggregate stabilization [137], nutrient cycle [138], penetration resistance [139] and tensile strength [140]. Asai [141] added that biochar enhances soil infiltration and lowers water runoff, thus decreasing erosion due to its bulkiness and spongy structure. Biochar amendment alters the physiochemical properties of soil, which highly influences P retention in soil. [142]. Thus, the effect could be different depending on soil properties when biochar produced from the same feedstock is added to various soil types. The release of phosphorus in sandy soil is quicker compared with that in clay soil. Therefore, biochar acts as a holding agent of P and prevents the leaching or runoff loss of P from sandy soil [143,144]. The P release characteristic of biochar-amended soil is even independent of the pyrolysis temperature at which biochar is produced [145].

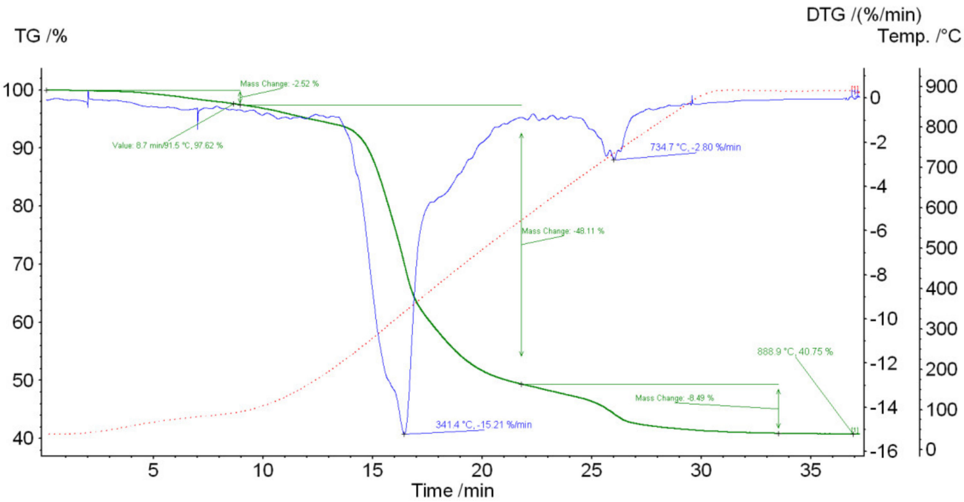

Figure 3. Thermogravity of swine digestate performed by author.

With the evolution of pore structure, the morphology of biochar also undergoes tremendous fluctuation under pyrolysis. Biochar gains the parental features of feedstock irrespective of the rate of temperature [146]. The permeable configuration in corncob [147], "beehive-like" pore structures in sugarcane [148], the symmetrical structure in wood [149] and the origin of surface morphological structure in rice husk and sawdust [150] were all retained after pyrolysis at 400–900 °C. At higher pyrolysis temperature (>1000 °C), melting with substantial deformation of biochar structure could be observed [150]. Under pyrolysis at 2000 °C, the macropores of biochar surface disappeared due to melting, while small grains emerged as the accumulation of beads on the surface of biochar [151].

The process of pyrolysis of organic feedstock into biochar brings stability to oxidized carbon fractions existing in the organic debris [152] that can persist in soils for years [153]. Therefore, biochar amendment substantially reduces greenhouses gases [154] and can be deemed as a climate change mitigation strategy. Due to these facts, biochar, the black diamond, acts as an optimistic soil conditioner of high economic and environmental value [155]. Several studies demonstrated the positive effect of biochar application on crop yield enhancement via different mechanisms. For instance, biochar amendment to soil significantly improves soil micro and macronutrients [156], despite the fact that biochar bears a higher pH value [155–158]. Nonetheless, biochar serves as a slow-release fertilizer due the strong adsorption of soil nutrients [159]. So, it is considered that biochar could be a perfect utility to acidic soil rather than alkaline or calcareous soil. Additionally, biochar, due to its high surface area and large porous structure [160], causes indirect impacts on soil physical characteristics, for instance, it significantly enhances water retention [158–162] and hydraulic conductivity [163] while decreasing soil bulk density in sandy soil [164]. However, the efficiency of biochar application to soil is not always the same. Rather, it depends on properties of applied biochar and soil conditions. Due to large surface area porosity, biochar has a significant adsorbing ability in increasing the water holding capacity (WHC) [165] and plant-available water capacity of soil (AWC) [166]. In the case of coarse sandy soil, the water and nutrient storage is generally lower under a drought condition, and thus large proportions of hydrophilic micropores (0.2–30 mm) are found in biochar, potentially retaining plant-available water and benefiting coarse sandy soils [167]. Further, gasification of biochar (GB) improves root development and thus enhances soil water retention, hence improving crop productivity [168].

11. Immutability of Soil Organic Matter and Soil Configuration

The influence of biochar on aggregate formation and organic matter stability is of high importance. Pituello [169] stated that biochar is a potential amendment for the stabilization of aggregates, especially if soil has a coarse texture and a low organic content [169]. These recommendations were further supported by Ma [170], who reported a significant increase in aggregate stability and soil organic carbon. However, Fungo [171] reported from his two year experiment that biochar had no effect on soil aggregates in tropical Ultisol. Moreover, increasing biochar amendment to fine sand and sandy loam textured soil may decrease aggregate strength [172]. Thus, the effect of biochar is multifarious and could vary with soil types and textures.

Biochar improves the structure and fertility of soil [117,118]. Glaser [173] reported that a substantial amount of biochar in terra preta was present in vulnerable fractions. However, in [174], it was indicated that biochar was associated primarily with the ultrafine, sub-50 µm soil chunk, and in [175], it was found that biochar, rather than as a free organic matter, was preponderantly available in small clumps of soil particles or soil aggregates. Brodowski [176] also found large macro-aggregate fractions with a small amount of practical biochar (>2 mm); thus, biochar might act as a binding agent for organic matter in aggregate formation and soil against degradation. Due to the interaction of biochar with soil organic matter and microorganisms and minerals, it may influence soil aggregates and its stability [177,178]. The slow oxidation properties of biochar determine the long-term effect on soil aggregation [179].

12. Biochar and Sustainability

The key obstacles with the current agrofarming systems are to enhance crop yield in a more sustainable and environmentally friendly manner [180,181]. Post-green revolution, agricultural practices enhanced their dependency on organic fertilizer for securing higher crop yield. Chemical fertilizers do increase crop yield, but they also risk the sustainability of the environment by provoking key ecological disparities, such as biodiversity loss, global warming and inclusion of heavy metals in living organisms [182,183]. Thus, adopting a more natural way of farming will reduce the reliance on organic fertilizers and sustain agricultural production and productivity.

More recently, biochar is thought to be an auspicious soil conditioner to sustain carbon and nutrients in soil, and thereby reflects the environmental problems regarding sustainable agricultural nutrient management [184,185]. Contemporary research on biochar is predominantly focused on customizing biochar properties to enhance their elimination capability for organic and inorganic pollutants [89]. Biochar has comprehensive environmental use due to its idiosyncratic properties, e.g., large surface area, microporosity, higher adsorption capacity and ion exchange capacity [99,100]. These properties have substantial consequences to its competency and potency in sustainability of the environment. The transformation of feedstock into biochar is a carbon-negative technique and has been indicated to sequestrate around 87% of carbon [186]. This not only reduces the problems of waste disposal of agricultural residues but also provides a viable and frugal method of waste transformation into value-added products. Due to its exceptional surface characteristics, biochar shows remarkable efficacy in reducing contaminants such as antibiotics, herbicides, dyes, pesticides and heavy metals and plays a key role in alleviating global climate change [187]. Biochar is thus a promising way to return lost C into the soil [188].

Many investigators have suggested biochar as an efficient soil supplement to encourage C storage [189], to augment value to agricultural products and to foster plant growth for sustainable agriculture [190]. Biochar has an exceptional function to immobilize rhizospheric heavy metals and farm chemicals on its large surface and inhibits their movement into the plants/crops, thus improving crop productivity [191]. Biochar substantially increased crop grain yield and biomass, and such favorable impacts of biochar were greater under rational P fertilization where half (50%) of P is from a natural source and the remaining 50% is from an inorganic fertilizer. The synergetic effect on nutrient accessibility and plant uptake is necessary for better crop yield and soil fertility, which can be gained by combinative use of organic and inorganic fertilizers with biochar [192]. In addition, biochar amendment increase in grain yield could signal the instrumental role of biochar in the conservation of soil nutrients and moisture, increasing nutrient uptake for potential crop yield and development [193]. Biochar can strengthen crop biomass and growth by enhancing nutrient availability [194]. Biochar application has been shown to decrease the saturated hydraulic conductivity of the soil, especially in light textured soils [195,196]. For example, Ajayi and Horn reported a decrease between 23 and 82% in the saturated hydraulic conductivity of a fine-sand soil when amended with a large application rate (2–5%, *w*/*w*) of biochar [197]. Several field trials have been conducted side by side to greenhouse pot experiments on biochar effects on soil nutrients (Table 2). While soil amendment with biochar resulted in an increase in crop production and improved soil fertility under different natural and agricultural environments [198], the immediate impact of biochar addition on soil fertility and nutrition is incoherent and weakly understood. Biochar has a consistent effect on some parameters of soil but not in all conditions [199]. While the beneficial effects and usage of biochar are widely discussed, more research is warranted to understand its perks and magnitudes, as well as the constraints of biochar amendment, in agroecosystems (Figure 4). Farming systems mostly depend upon the locally produced waste materials, e.g., crop residues and animal manures, as farmers have very limited resources to buy commercially prepared organic fertilizers [200]. The Oxisol class of soil by its very nature is poor in nutrients and organic matter content [201], which further limits microbial activities, thus leading to low crop yield. Smallholder farmers have access to bundles of local waste, so mutually rewarding benefits of crop yield and waste management can be gained, if policies associated with biochar are made for its governance in developing countries.

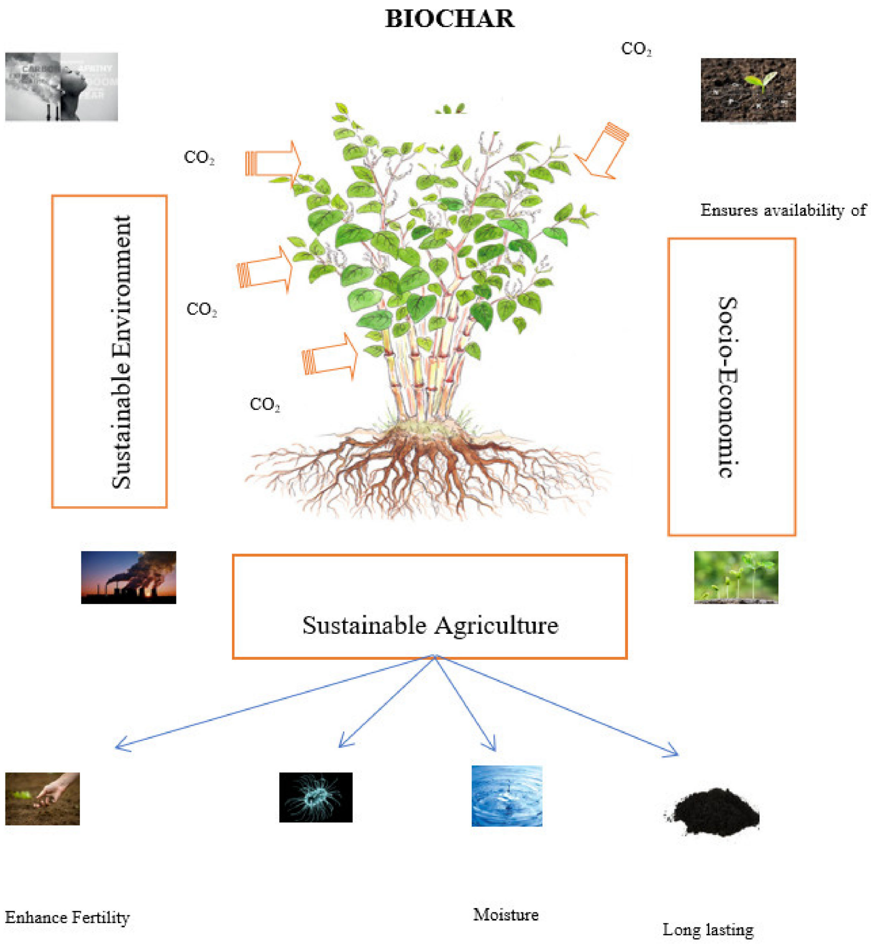

Figure 4. A diagrammatic representation of biochar dynamics and its role in agroecosystem and environmental sustainability.

13. Constraints of Biochar Application

Even though, overwhelmingly, the literature outcomes reflect the valuable prospect of biochar application, there are some constraints of biochar application which deserve attention. It is documented that weed yield increased by 200% with an increase in wheat straw-derived biochar (300–1100 °C) application rate from 15 t ha^{-1}, thus becoming a big competitor for soil nutrients to the main crop [202]. Biochar has a repressive effect on soil aging, and sporadic amendment of fresh biochar might be needed for the maximum nutrient cycling and aqua environment in soil [203]. For example, Anyanwu [204] reported that aged biochar derived from rice husk in soil has a substantially negative effect on the growth of soil earthworms and fungi. Biochar application may cause a delay in flowering in plants [205]. Additionally, Zhao [206] reported that aged biochar led to a significant reduction in the root biomass of Oryza sativa and Solanum lycopersicum in the soil. Biochar application at 14 t ha^{-1} enhanced vegetative growth but not tomato crop fruit yield, thus indicating the impact of biocarbon and crop yield dependency on plant species or the targeted part of the plant [207]. Furthermore, biochar is characterized by a selective capability to assimilate pollutants. For example, dichlorodiphenyltrichloroethane (DDT) chemical pesticide absorption was not limited by biochar application in a soil [208]. Thus, Table 2 presents the current research cited on the effect of biochar amendment on crop yield and fertility dynamics. The results fluctuate, both positively and negatively, depending on the biochar type, amount, soil type, crop type, etc.

14. Conclusions

Agroecosystems are extremely important to ensure food security and abate GHG emissions. Measures to reduce chemical fertilizer inputs and alleviate GHGs emissions include increasing soil C sequestration by addition of biochar, and thus increased crop-use efficiency of fertilizer-N. Smart choice of biochar type, rate, and affinity with agrofarming systems should not be ignored before its application. Biochar is an approach to slow the release of nutrients, and thus protect the environment without compromising crop yield. The beneficial capacity of biochar to amend agroecosystems and achieve a sustainable environment needs rational research knowledge as well as economic and social research. The practice of biochar application could enhance soil quality, increase the resilience of agroecosystems and agroforestry and support their adaptation capacity to the fluctuating climatic conditions. Nevertheless, the effects of biochar would be site dependent. Of course, biochar is not a solution to all agroecosystem problems; however, it could be a substantial strategy that deserves cognizance to achieve a sustainable agroecosystem in the future. This review has indicated many benefits, complexities and effects of biochar; however, more research is needed to provide a better understanding of biochar mechanisms and their interactive effects on plants, soil and the environment.

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