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A Review of Biochar Production and Application in the Agroforestry Sector

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Abstract

Biochar is produced from the thermo-chemical treatment of biomass. Its quality and yield differ remarkably depending on the thermo-chemical technology and operational parameters deployed, which in turn influence its functionality in the agroforestry sector. In this review, different thermo-chemical technologies for biochar production such as pyrolysis (fast and slow), gasification, and torrefaction were analyzed and compared. It was discovered that biochar yield decreases with increase in heating rate and increase in oxygen amount. The benefits of applying biochar in agroforestry systems were examined. Enhancements in soil health, plant development, carbon sequestration, and mitigation of greenhouse gas emissions were observed in several instances, however, undesirable outcomes were equally discovered. This is an indication that the benefits from biochar application depend particularly on parameters such as the source of biochar, rate of biochar application, types of soil, climatic conditions, and species of plant. Limitations of available studies and recommendations for future investigations on biochar production and applications were also examined. Specifically, the influence of production technologies on biochar properties and its functionality in the agroforestry sector need to be further comprehended.
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1.0. Introduction

Biochar is predominantly obtained from diverse thermo-chemical treatment processes such as pyrolysis, gasification, and torrefaction, under varying operational parameters [1]. These treatments irrevocably alter the physicochemical composition of biomass and yield biochar, amongst other products, in an inert environment or a limited supply of oxygen at a specified temperature and pressure. During the treatments, biomass components are decomposed, depolymerized, and cross-linked to yield biochar (solid with high carbon content) and other products like bio-oil, tar, and synthesis gas depending on the treatment technology and parameters deployed [2].

Biochar has a huge prospect for carbon (C) sequestration, energy production, soil quality and productivity enhancement as well as conserving the environment [3-5]. These benefits indicate biochar's capacity to advance the economic sustainability of emerging bioenergy projects [6-8]. In addition, biochar application on land has the potential to store carbon in soils and reduce emissions of greenhouse gases [9, 10]. Such biochar application has the potential to enhance crop production by improving nutrient retention in the soil as well as soils' physicochemical and biological properties [11, 12], by reducing sediments and pollutants in soils [13-15]. Biochar application can also provide a sustainable avenue to return vital organics removed from the soil when biomass is harvested for energy generation. Thus, biochar has two potential economic benefits; firstly, improving the agricultural and environmental sustainance of the agroforestry sector, and secondly, enhancing the economic feasibility of bioenergy ventures by defraying operational costs with proceeds from the sales of biochar.

However, the effects of biochar on soils, the environment, and its agrarian attributes need to be studied comprehensively. Despite the capability of biochar to generate financial proceeds and improve agricultural and environmental sustainability, not much investment will be committed to its production until its impacts on soil health and crop yields have been fully ascertained. Commercialization of biochar production is hinged on the complete and lucid establishment of the copious advantages of biochar to the agroforestry sector and how these benefits are related to biochar properties, its propitious utilization, and the economic feasibility of the process. To achieve this, an in-depth understanding of biochar production processes and how these processes influence biochar performance is required. The gains of applying biochar for the improvement of soil, environment, and crop yield will be controvertible if they are not duplicatable and consistent.

Therefore, the goal of this paper was to overview the various technologies for biochar production. The objectives include comparing these technologies, evaluating the influence of these technologies on biochar yield and quality, and ascertaining how biochar characteristics influence agroforestry systems. Technologies compared in this work include slow pyrolysis, fast pyrolysis, gasification, and torrefaction. Biochar applications in agroforestry settings and their impacts on soil health, crop yield, carbon sequestration efforts, and reduction of greenhouse gas emissions were analyzed. Finally, the deficiencies of recent studies on biochar production and applications were equally examined.

2.0. Literature review methodology

The literature review focused on works related to biochar production and application, especially in agroforestry systems. A systematic literature search was carried out in Scopus, Elsevier and ScienceDirect scientific databases, covering most of the peer-reviewed interdisciplinary research papers. Obtained literature were examined using the PRISMA-P (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols) [16]. The PRISMA-P workflow contains a 17-item checklist intended to facilitate the preparation and reporting of a robust protocol for a systematic review. The search protocol was developed using the following steps. A search query was conducted in line with the objectives of the work as highlighted in Table 1. Several eligibility criteria were applied during the search protocol: (1) Coverage period: the publication period of articles was unlimited, (2) Search fields: title, abstract or keyword of articles, (3) Document types: all types of documents were considered, (4) Language: only literature published in English were considered. The search methodology was defined, and thereafter, the literature were identified, screened and assessed for eligibility to develop the most relevant literature.

Table 1: Outputs of literature search in scientific databases

Search strings	Number of publications found
Biochar production technologies	275
Biochar application in soil	75
Biochar application for plant growth	87
Properties and uses of biochar	67

3.0. Thermo-chemical technologies for biochar production

Biochar possesses varying physicochemical properties with respect to the operating parameters deployed during the thermo-chemical treatment and the innate nature of the biomass feedstock used. Thermo-chemical treatments are carried out in reactors. These reactors are akin in principles but differ in operating parameters (such as oxygen levels required, rate of heating, and temperature) which are crucial to the quality and yield of the produced biochar. Figure 1 highlights the different thermo-chemical treatments for obtaining biochar from biomass.

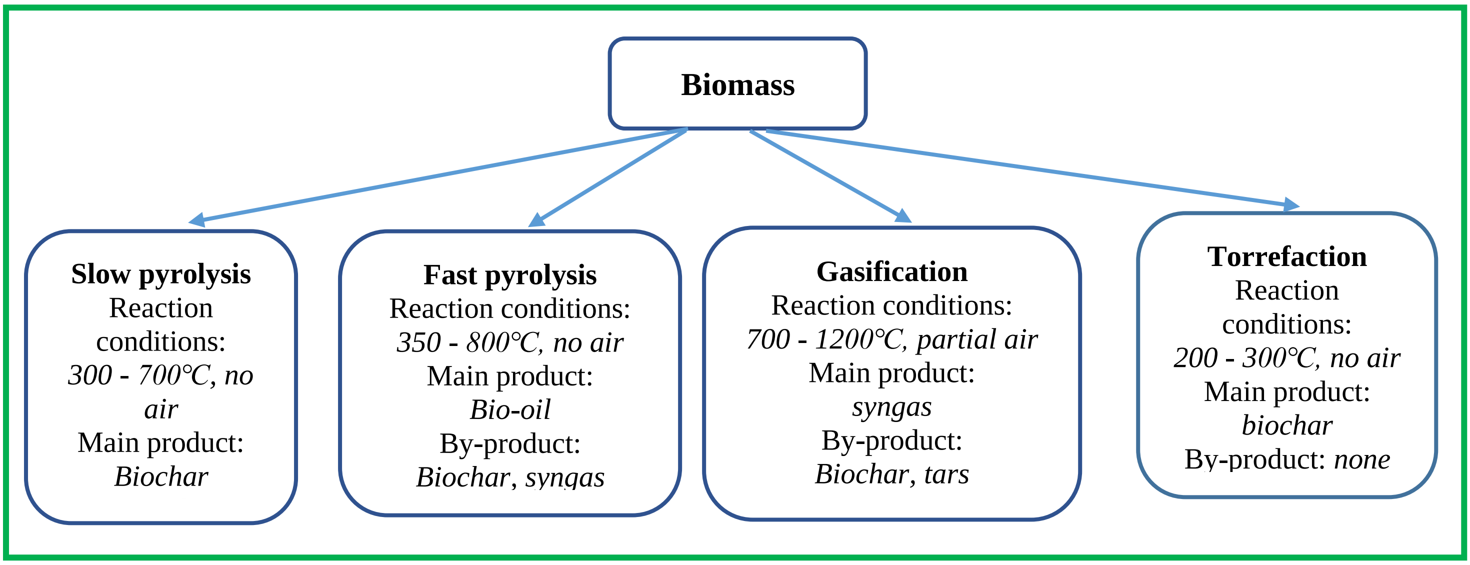

Figure 1: Thermo-chemical technologies for obtaining biochar from biomass

3.1. Slow pyrolysis

Slow pyrolysis involves the heating of biomass at a slow rate in an environment that is inert or has very limited amount of oxygen at about 300 - 700°C for a specific period of time. During slow pyrolysis, the biomass decomposes releasing vapours, known as pyrolysis vapours. The prolonged residence time of the process provides sufficient time for the secondary cracking of these vapours. However, these vapours can be condensed and collected as bio-oil, whose many organic constituents can be harnessed and utilized for various purposes [17 – 20]. The residue after the release of pyrolysis vapours is biochar, another important product from slow pyrolysis.

Heating rates and operating temperature are critical to the quality and yield of biochar during slow pyrolysis [21]. In general, the quality of biochar is connected largely to its carbon content, pH value, specific surface area, and porosity, with carbon content having a greater influence than the others [22 – 23]. As highlighted in Table 2, parameters like high temperature, prolonged residence time, and low heating rate are vital to obtaining biochar with high carbon content. For example, Mousa *et al.* [24] and Jahanshahi *et al.* [25] reported that biochar produced from wood pyrolysis at an elevated temperature (550 - 700°C) and long residence time (>30 min) performed better than coal and coke for steel-making. Yang *et al.* [26] reported that biochar produced from the slow pyrolysis of red cedar wood at 500°C and a heating rate of 6°C/min exhibited a carbon content of about 88.9% and a calorific value of about 33.0 MJ/kg. In slow pyrolysis, higher temperatures are vital for enhancing the quality of biochar, since more volatiles are released from the biochar as the temperature rises, thereby increasing their carbon levels. Additionally, a reduction in the rate of heating enhances heat conduction that is conducive to the deposition of carbon, leading to the production of high-quality biochar [27].

Other parameters that also directly influence the quality and yield of biochar are biomass type and particle sizes, as well as the use of catalysts. Biochar quality and yield can be enhanced by increasing the biomass/catalyst ratio, reducing biomass particle sizes, as well as increasing the residence time of biomass and pyrolysis vapours [27 – 28]. Generally, biomass type has been reported to largely affect the yield and quality of biochar. Solar *et al*. [29] obtained 30% biochar yield from slow pyrolysis of forestry plants at 500℃, 60 min residence time, and 10℃/min heating rate. In contrast, Farrokh *et al*. [30] reported a biochar yield of about 48% from the pyrolysis of lignin, indicating that lignin content is vital for biochar yield. Lee *et al*. [31] also observed that the levels of ash and carbon in biomass largely influence biochar yield.

Table 2: Yield and ultimate analysis of biochar obtained from slow pyrolysis

Biomass feedstock	**Operational parameters**			**Yield (%)**	**Elemental composition**				**References**
	T (℃)	**RT (min)**	**HR (℃/min)**		**C**	**H**	**N**	**S**	
Red cedar sapwood	500	30	6	30.90	85.80	2.40	0.35	0.35	[26]
Red cedar heartwood	500	30	6	21.00	88.90	2.60	0.35	0.40	[26]
Cow manure	300	120	10	58.00	51.30	4.52	1.70	-	[32]
Pinewood	300	60	17	43.70	71.30	4.70	-	-	[33]
Coffee husk	350	30	0.5	39.82	69.96	3.63	3.58	0.24	[17]
Wheat straw	475	180	8	-	69.90	2.50	-	-	[34]
Oil palm shell	500	60	10	35.50	60.12	9.21	0.42	0.92	[35]
Lignin	500	480	5	45.69	85.90	3.56	1.23	0.12	[30]
Algae	500	60	10	32.00	45.26	1.24	2.57	-	[36]
Walnut shell	500	60	15	30.00	77.97	3.22	1.13	-	[37]
Rubber wood	500	60	10	24.25	87.17	1.23	0.40	-	[38]

***T: temperature; RT: residence time; HR: heating rate**

Fixed-bed reactors are mostly used for slow pyrolysis. In these reactors, a pile of biomass is heated in the absence of air for a long duration (several hours or days) [39]. The disadvantages of fixed-bed reactors are that the biomass particles may not be uniformly heated, and the vapours-solid contact is poor. Another type of pyrolysis reactor is the auger reactor. This reactor is usually deployed for pyrolysis in the industry because it is simple to construct and operate [27, 40]. Garcia-Perez *et al*. [28] compared a fixed-bed reactor in batch mode and an auger reactor in continuous mode for the slow pyrolysis of pine. The observed biochar yield was very close for both reactors, with 30 wt% from the batch reactor and 31 wt% from the continuous reactor. Fluidized-bed reactors are other types of reactors utilized for the slow pyrolysis of biomass. It should be noted that despite the type of reactor deployed for slow pyrolysis, the released pyrolysis vapours are usually burnt to provide more heat for the process.

3.2. Fast pyrolysis

Fast pyrolysis is a thermo-chemical process whereby biomass is rapidly heated to high temperatures in an inert environment. It occurs in a high-temperature range of 350 - 800°C at a faster heating rate of 10 - 200°C/s, with a short solid resistance time of about 0.5 - 10 s and with fine feedstock particle size (< 1 mm) [41]. During fast pyrolysis, the biomass feedstock decomposes rapidly to generate pyrolysis vapours and biochar (15 - 25 wt%). The pyrolysis vapours are cooled to form a dark-brown liquid known as bio-oil.

It has been shown that rapid heating rates at higher temperatures reduce biochar yield due to the evaporation of more volatile matter [27]. Angin [42] reported that biochar yield from safflower seed decreased by 5% on average when the heating rate was increased from 10 to 50 °C/min. Chen *et al*. [43] observed a decrease in biochar yield from poplar wood from about 35 to about 32 wt% as the heating rate increases from 10 to 50°C/min at 400°C. Aguado *et al*. [44] observed that an increase in the heating rate from 5 to 40 °C/min decreased the biochar yield from about 39% to about 26%. However, an increase in pressure can improve biochar yield as vapour residence time within the biomass particles is prolonged, thereby promoting biochar-forming reactions [45]. Antal *et al*. [46] reported a biochar yield ranging from 41% - 62% from a high-pressure reactor. Wang *et al*. [47] reported a slight increase in biochar yield from pine sawdust from about 25wt% to about 28wt% in a closed fixed-bed reactor. Additionally, the effects of various parameters and reactor designs on the quality and yield of biochar obtained from fast pyrolysis are highlighted in Table 3. The effects are observed to differ remarkably, and also with respect to the biomass feedstock used.

Table 3: Yield and ultimate analysis of biochar obtained from fast pyrolysis.

Biomass feedstock	**Reactor type**	**Temperature (°C)**	**Yield (%)**	**Ultimate Analysis**					**References**
				C	**H**	**N**	**S**	**O**	
Wheat straw	Airtight twin-screw	500	26.00	56.00	2.30	1.00	-	-	[48]
Sweet sorghum	Fluidized-bed	500	23.80	69.03	2.78	0.59	-	2.76	[49]
Cornstalk	Fluidized-bed	550	-	72.28	3.14	1.09	0.90	22.47	[19]
Yellow poplar	Fluidized-bed	500	5.10	76.30	2.3	0.7	-	20.70	[50]
Corn cobs	Bubbling fluidized-bed	500	18.90	77.60	3.05	0.85	0.02	5.11	[51]
Pine sawdust	Fixed-bed	550	-	70.68	3.60	2.40	0.21	23.11	[52]
Rice husk	Conical spouted-bed	500	26.00	45.20	1.50	0.40	-	1.70	[53]
Pine sawdust	Fixed-bed	500	-	70.68	3.60	2.40	0.21	23.11	[54]
Douglas fir	Bubbling fluidized-bed	480	11.20	75.80	1.56	0.33	0.13	19.57	[55]
Ivory nut	lab-scale	500	15.82	69.59	2.93	-	-	18.31	[56]
bamboo	Horizontal screw conveyor	500	24.40	81.70	3.70	-	-	-	[57]
Rice husk	Fixed-bed	550	38.86	44.73	1.80	0.73	–	7.69	[58]
Brown algae	Bubbling fluidized-bed	375	56.08	30.67	2.72	2.09	-	64.53	[41]

Elevated pyrolysis temperatures have been proven to liberate volatiles from the biomass particles, and therefore increase the carbon content of biochar and its specific surface area. Zhao *et al.* [59] observed an increase in the specific surface area of biochar from rapeseed stem from 1 to about 45m^2/g as temperature rises from 300 to 700℃, while Peng *et al*. [52] reported that increasing the temperature from 550 to 750℃ increased the carbon content of biochar obtained from pine sawdust from about 71% to about 79%. However, during fast pyrolysis, the rate of heating is the main factor that influences the quality of biochar. Onay [60] observed that varying the heating rates led to different volatilization rates and structures of biochar, and therefore opined that biochar obtained using high heating rates possesses higher carbon percentage and better specific surface area compared to biochar obtained using low heating rates. Chen *et al*. [43] also discovered that raising the heating rates improved the carbon content of biochar; but, its surface area exhibited a sinusoidal trend in values. However, Mohan *et al*. [45] observed that rapid heating reduced biochar's specific surface area and porosity due to swift depolymerization at the biochar's surface. These studies revealed that although high heating rates positively influence biochar's carbon content, they have no direct impact on its specific surface area.

Several reactors have been developed and extensively used for fast pyrolysis to optimize bio-oil yield. These reactors include fluidized-bed reactor, ablative reactor, rotary cone reactor, and auger reactor [60]. How these reactors operate has been described in several literatures [62 – 63]. Generally, produced biochar should be isolated, as much as possible, from the pyrolysis vapour to reduce the cracking effects of the vapours on it. About 15 wt% of biochar can be obtained during fast pyrolysis in fluidized-bed reactors, rotary cone reactors or ablative reactors [63], while biochar yield can be as high as 25 wt% in an auger reactor [64].

3.3. Gasification

Gasification is a thermo-chemical process whereby biomass undergoes incomplete combustion at elevated temperatures (700 - 1200℃) in the presence of gasifying agents such as air, oxygen, and steam to produce a gaseous product (syngas). The main focus during biomass gasification is how to optimize the quality and yield of syngas, by reducing drastically or eliminating completely contaminants such as particulates and tars [65]. Despite being an undesirable by-product of biomass gasification, some researchers still carry out biochar evaluation at varying gasification conditions. Shackley *et al*. [22] observed that the quality of biochar obtained from biomass gasification is closely linked to its carbon content. The quality is affected majorly by parameters such as equivalence ratio (ER), temperature, biomass properties and particle sizes, gasifying agents, and pressure. However, ER is considered to have more influence on the gasification process than the other parameters, and its optimum value varies in correlation with the physicochemical properties of the biomass used [66]. Basically, an increase in ER increases the gasification temperature, which in turn affects biochar quality as highlighted in Table 4.

Table 4: Ultimate analysis of biochar obtained from gasification

Biomass Feedstock	**Reactor type**	**Temperature (℃)**	**Ultimate Analysis**					**References**
			C	**H**	**N**	**S**	**O**	
Rice straw	Dual fixed-bed	800	63.81	0.95	1.69	0.13	5.24	[67]
Grape	Pilot drop-tube	1200	52.97	3.92	1.65	0.47	40.97	[68]
Wood chips	Dual stage	900	78.97	0.68	0.20	-	-	[66]
Wood pellet	Co-current	700	83.39	0.98	0.23	-	1.86	[69]
Coconut shells	Fluidized-bed	750	87.70	1.30	0.30	–	6.8	[70]

Japanese cedar	Horizontal tube	900	94.60	0.60	0.30	-	-	[71]
Wood pellet	Nitrogen plasma torch	700	83.48	1.89	0.41	-	14.22	[72]
Pine sawdust	Fixed-bed	800	86.31	2.27	0.14	0.01	6.23	[73]
Beech bark	Batch fluidized-bed	850	75.49	0.56	-	-	6.06	[74]

The impacts of ER on the quality and yield of biochar have been widely studied in recent years. Yao *et al*. [23] observed that as the ER increased from 0.1 to 0.6, biochar yield decreased from about 0.22 to about 0.14 kg per kg of biomass, while its carbon content decreased from about 88.20% to 71.20%. Muvhiiwa *et al*. [72] observed a reduction in the carbon content of biochar from 89 percent to 80 percent at 700 degrees Celsius and from 93 percent to 86 percent at 900 degrees Celsius when the flow rate of oxygen was increased from 0.2 to 0.6kg/h. These studies revealed that increasing the ER during gasification decreases the yield of biochar and its carbon content. A higher ER implies the availability of more oxygen for gasification. This enhances the reactions that transform carbon from solid into the gaseous phase, thereby improving the porosity and specific surface area of biochar [75]. On the contrary, the presence of excess oxygen during gasification may lead to strong ablation of biochar; reducing its mechanical strength and yield, and increasing its ash content [75].

Biomass gasification is carried out in gasifiers. These gasifiers are of different types including fixed-bed gasifiers (such as the updraft, downdraft, and cross-draft gasifiers), and fluidized-bed gasifiers (such as the bubbling and circulating gasifiers). The development and advancement of these gasifiers was examined by [76]. Like the equivalence ratio, the type of gasifier deployed also influences the yield and properties of produced biochar, however, several experiments have shown that biochar's carbon content depends majorly on the equivalence ratio rather than on the gasifier type [66, 68, 74]. Nevertheless, using an updraft gasifier; a biochar yield of about 39wt% was obtained from the gasification of rice hulls [77 - 78], and a biochar yield of about 14.3wt% was obtained from the gasification of elephant grass, and the specific surface area of the biochar was about 475m^2/g [79].

3.4. Torrefaction

Torrefaction is a thermo-chemical process in which biomass is thermally degraded in an inert or nitrogenous atmosphere, at a pressure of one atmosphere, a temperature between 200 - 300℃, a low heating rate (< 40 ℃/min), and a residence time between 20 – 120 mins [80 - 81]. Torrefaction is majorly deployed for the production of a "charred" solid, which is fit for use as an energy source as well as for soil quality enhancement [80]. During torrefaction, about 30wt% of highly reactive volatiles are transformed into torrefied vapours [82], and torrefied biochar, a dark-brown solid, which possesses about 90% of the biomass' initial calorific value is obtained at the end of the process [83]. The calorific value of torrefied biochar can be enhanced for use as an energy source for purposes of heating and power generation [84 - 85]. To improve the calorific value of torrefied biochar, elevated temperature and long residence time are necessary, however, these factors lower the quality and energy yield of the torrefied biochar. Hence, Niu *et al*., [86] opined that the optimum torrefaction condition may be to sustain a solid yield of about 60 - 80%, so as to obtain biochar with high calorific value, mass density, and energy yield.

The quality of torrefied biochar is mainly affected by biomass physicochemical properties, such as moisture level, calorific value, and ash content [87]. Biomass moisture content has a more significant effect as it largely determines the energy input for the torrefaction process [83]. Biomass feedstocks are made up of cellulose, hemicellulose, and lignin, and torrefaction of these components has been investigated extensively to ascertain the main factors influencing torrefied biochar yield. According to [88], torrefaction of hemicellulose yields the lowest biochar quantity of the three components. Wang *et al.* [89] reported that increasing the temperature and residence time shrinks the levels of hemicellulose and cellulose in the obtained biochar, while the levels of lignin increase. Kai *et al.* [90] submitted that torrefaction temperature has more influence on the quality of torrefied biochar than biomass residence time. As highlighted in Table 5, irrespective of the biomass type, torrefaction yields biochar with enhanced carbon content, but with lower hydrogen content at elevated temperatures. Pala *et al.* [91] elucidated that dehydration and decarboxylation are the predominant degradation reactions responsible for significant losses in mass during torrefaction. Additionally, biomass torrefaction in the presence of various agents, such as air and nitrogen has also been studied. Brachi *et al.* [92] observed that the mass and energy yields of the torrefied biochar from oxidative torrefaction were lower than those from non-oxidative torrefaction.

Slow pyrolysis yields high-quality biochar as the biomass is subjected to “deep pyrolysis” at a relatively low temperature for a long time, releasing a high percentage of the biomass volatiles, leading to a significant increase in the biochar carbon content. In comparison, torrefied biochar has lower moisture and volatile contents because the biomass is only subjected to “light pyrolysis” even at 200°C for about a significant length of time. At such low temperatures, biomass only undergoes drying and does not experience several chemical reactions. Nevertheless, torrefied biochar still gets

Table 5: Yield and ultimate analysis of biochar obtained from torrefaction

Biomass feedstock	**Temperature (°C)**	**Mass yield (%)**	**Energy yield (%)**	**Elemental composition**		**Elemental composition**		**Refs**
				C	**H**	**C**	**H**	
Pine chips	225 - 300	89 - 52	94 - 71	47.21	6.64	49.47 – 63.67	6.07 – 5.58	[84]
Wood stem	260 - 310	97 - 46	99 - 63	50.30	6.20	51.40 – 69.20	5.90 – 5.00	[93]
olive pomace pellets	200 - 250	80 - 53	95 - 68	54.93	6.33	57.31 – 63.61	6.33 – 4.68	[92]
Wood pellets	200 - 250	80 - 53	94 - 50	50.91	6.25	52.22 – 66.65	6.06 – 3.34	[92]
Sugarcane bagasse	200 - 300	79 - 52	99 - 79	98 – 79	32.50	5.01	34.50 – 50.30	[94]
Corn stover	200 - 300	97 - 57	99 - 84	-	-	45.80 – 58.70	5.50 – 4.70	[87]
Peat	230 - 270	82 - 70	82 - 70	91.87	52.09	59.00 – 65.30	5.49 – 5.26	[95]

Rice straw	200 - 300	94 - 70	99 - 84	42.57	5.84	45.06 – 50.94	5.46 – 4.90	[90]
Bamboo	210 - 300	95 - 60	97 - 75	46.12	6.11	48.54 – 61.23	6.08 – 4.80	[82]
Empty fruit bunches	200 - 300	88 - 67	90 - 71	43.00	6.00	46.20 – 59.00	5.50 – 5.10	[96]
Spent coffee grounds	200 - 300	97 - 63	98 - 79	53.00	7.29	53.94 – 68.00	7.28 – 6.85	[97]
Micro algae residue	200 - 275	89 - 63	92 - 79	36.49	6.12	41.27 – 61.63	5.95 – 5.38	[97]

massive attention due to its advantages. For example, the biochar moisture content is reduced drastically, which reduces the cost of transportation and enhances the biochar storageability. The calorific value of the torrefied biochar can also be improved by decomposing the hemicellulosic fraction in the biomass [83].

4.0. Effects of biomass properties on biochar quality and yield

Lignocellulosic biomass comprises three main components viz; cellulose, hemicellulose, and lignin [99]. The pyrolysis of these components has been examined and it was reported that they decompose at varying temperatures; cellulose (240 - 310°C), hemicellulose (170 - 240°C), and lignin (300 - 550°C) [99 - 100], and they interact amongst themselves during pyrolysis [101], bringing to fore the complexity of biomass pyrolysis. Kan *et al*. [102] observed that during pyrolysis the reactions between cellulose and hemicellulose have no significant influence on biochar production. However, the reactions between cellulose and lignin hamper biochar production, as lignin inhibits the polymerization of levoglucosan from cellulose [103]. Hence, it is quite impracticable to foretell the quality and yield of biochar using just the thermal behaviour of these biomass components. Furthermore, it is worthy of note that other factors such as biomass types, pyrolysis conditions, and reactor types also influence, to a large extent, the quality and yield of biochar. This is an indication that prevalent studies on biomass pyrolysis are deficient to adequately estimate the properties of biochar. The effects of biomass on the quality and yield of biochar obtained from fast pyrolysis and gasification processes have not been significantly explored as their target products are bio-oil and synthesis gas respectively, and not biochar.

Lignocellulosic biomass differs in chemical composition depending on the type and origin of the crop [104]. The type of lignocellulosic biomass utilized affects the physicochemical properties of the resulting biochar [105]. For example, biochar obtained from forest residues usually possesses more carbon than those obtained from agro-residues and animal residues [105]. The authors also reported that biochar obtained from algae contained more nitrogen than biochar produced from forest biomass, due to the high nitrogen content of algae. The intended use for biochar determines the type of feedstock to be utilized for their production [105]. Forest biomass is recommended when the biochar is to be utilized for barbecue, metallurgy, and activated carbon. While agro-residues are better if the biochar is intended for soil amendment [105]. The commercial viability of biochar production should be accentuated. It depends on several factors, including the cost of transportation, biomass cost, biochar quality, its utilization, and the cost of other necessary chemicals [106 - 107].

5.0. Applications of biochar in agroforestry settings

5.1. Soil quality enhancement

5.1.1. Enhancing soil physical and chemical properties

The benefits of biochar application on the physical properties of soil have been widely reported. Biochar has been found to increase the net surface area of soils and improve the aeration, bulk density, porosity, as well as packing of soils [108 - 109]. Furthermore, the application of biochar in soils has been reported to enhance soils' aggregate stability, water penetration, and water retention capability [110 - 111]. Improved porosity contributes hugely to better circulation of water, heat, and gases in soils, thereby improving the soil's quality [112 - 113]. The improvement in the physical properties of soil can be adduced to large surface area and low bulk density of biochar due to its porosity [114].

Besides improving soil physical properties, biochar application in soil also affects soil chemical properties. Biochar application can modify soils' pH value, a benefit that is prominent distinctly for acidic soils [109, 115]. The reduction of soil acidity has been adduced to several factors including; (1) the alkalinity of several biochars, (2) the ability of biochar to buffer high pH values due to its high cation (such as potassium, calcium, magnesium and sodium) exchange capacities (CECs), (3) the presence of functional groups (such as –COO– and \\O\\ ) in biochar, which is instrumental to its alkalinity, and (4) formation of carbonates or oxides by mineral elements (like calcium, potassium, magnesium, sodium and silicon) in the feedstocks during the biochar formation, which then react with hydrogen ions and monomeric aluminum species in acidic soils thereby reducing their acidity and improving their pH [116 – 118]. Altering the pH of soils enables more nutrients (like potassium, phosphorus, calcium and magnesium) to dissolve into them, thereby making more nutrients available in the soils [12, 119], and reducing the toxicity of aluminum in acidic soils [111].

The ability of soils to exchange cations (CECs) is crucial to their fertility, and applying biochar to soils helps to improve this ability [120 - 121]. The enhanced CECs ability of these soils may be adduced to; (1) the development of carboxyl groups and oxidation of aromatic carbon in the biochar, (2) the presence of dominant negatively charged surface functional groups, and (3) an increase in biochar surface area [109, 120 - 122]. Increasing soils' CECs ability enhances their ability to retain more nutrients, thereby making more nutrients available to plants' roots [123]. In view of these benefits of biochar application to soils' physicochemical characteristics, it can be stated that biochar is vital for improving the quality and performance of soils. For instance, the presence of biochar can upgrade the physical qualities of clay and sandy soils by facilitating; better water retention, better aeration, more nutrient solubility and retention, more microbial interactions, and stimulating chemical reactions in the rhizosphere [124].

However, studies have also revealed conflicting influences of biochar applications on soil's physical, chemical, and biological properties. Busscher *et al*. [125] observed that the application of pecan shell biochar to loamy soil lowered the soil penetration resistance, but didn't impact the stability of soil aggregate and water diffusion.

5.1.2. Enhancing soil nutrition and fertility

Biochar contains nutrients originally in the biomass feedstock [109], hence when applied to soils, it serves as a source or sink for nutrients [108, 126]. Adding biochar to soils has proven to be an effective method of improving nutrient cycling, as well as interactions between biochar and plant roots, thereby enhancing root development and the entire plant functionality [111, 124]. Biochar can also indirectly influence the levels and types of nutrients in the soil, as it can serve as a long-acting fertilizer for the supply of exogenous nutrients to the soil [127]. In addition to the nutrients (nitrogen (N_2), phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, copper, zinc, and silicon) derived from the biomass feedstock, both macro- and micro-nutrients (e.g., copper ion (Cu^{2+}), iron ion ($Fe^{2/3+}$), manganese ion (Mn^{2+}) and zinc ion (Zn^{2+})) can be absorbed and released slowly by biochar due to its large surface area and porous microstructure [128 - 129]. Specifically, biochar's porous networks initiate some barriers or chemical sorption that facilitate slow desorbing nutrients for plant uptake [130 – 132]. Generally, applying biochar as a sustained-releasing fertilizer could limit nutrient leaching and run-off, boost nutrient availability, and therefore improve the efficiency of nutrient utilization and crop yield [133 - 134].

Adding biochar to soil can help to circulate vital nutrients through physicochemical and microbial interactions [135 – 137]. The distinctive porosity of biochar coupled with its sundry functional groups can facilitate sustained adsorption of elements, surface conglomeration, and ligand exchange reactions, which basically controls the mobility of nutrients in soils [138 - 139]. Biochar application abates the leaching of soil nitrogen and boosts the recovery of nitrogen-based fertilizers, as the adsorption of some inorganic forms of nitrogen onto biochar mitigates the loss of ammonia and nitrate from soil [140]. Biochar application in soils also enables better nitrogen utilization and prevents nitrogen accumulation by regulating nitrogen mineralization, ammonia volatilization, and nitrification/denitrification in soils [141 - 142]. The improved capacity of soils to exchange positive and negative ions, due to the presence of biochar, further aid nitrogen retention in soils [129, 143 - 144]. Biochar being a carbon (C) rich substrate with a high carbon-to-nitrogen (C/N) ratio, can boost microorganisms' population in soils and trigger them to rapidly decompose organic matter in soils [145]. Other nutrients biochar addition can help to boost and retain in soils include phosphorus, and potassium [111, 121, 137].

Generally, applying biochar to soils can assist in boosting soil nutrition, by aiding better nutrient retention and utilization, lowering nutrient run-off, and consequently enhancing soil fertility [122, 146, 147]. However, the impact of application varies with respect to soil type. Van Zwieten *et al.* [148] observed a more significant response to biochar in acidic soils than in calcareous soils. Several other studies concentrated on the impact of biochar application on nutrient-deficient acidic soils, and the observed improvement in crop yields has been attributed to increased levels of nitrogen and phosphorus, better fertilizer usage, increased concentration of cations, and reduced pH, with a proportionate reduction in substitutable aluminum [112, 149 – 151], however, negligible impacts were observed in soils with high nutrient levels.

5.1.3. Enhancing plant development

Biochar addition to soils influences their physical properties, which may subsequently have a direct impact on plant development. Application of biochar to degenerated and nutrient-deficient soils has been found to be more effective than application to healthy fertile soils [152 - 153]. Biochar contributes to the amendment of nutrient-deficient soils, resulting in better plant development by; (1) enhancing nutrient availability and circulation, (2) boosting efficient use of fertilizers [131 - 132], (3) improving soil CECs, pH, as well as retention of water and nutrients, (4) lowering the tensile strength of soils and improving their structure [133 – 134, 154], and (5) instigating a rhizosphere environment conducive for earthworms' growth and microbial interactions [110, 155, 150]. Generally, a major challenge for plants growing in degenerated soils is root development. Improving the soil quality essentially improves the rhizosphere conditions and enables the root to develop easily, which is beneficial for more nutrient retention and better plant development [156].

Plant stress is a major predicament experienced in agroforestry environments. Biochar has been reported to display great potential to alleviate both biotic and abiotic stresses in plants [157]. According to Thomas *et al.* [158] and Ramzani *et al.* [159], treating soils with biochar increased the growth-promoting hormones in quinoa, thereby enhancing its antioxidant response to drought and salt accumulation. Treating saline and sodic soils with biochar ameliorates the adverse effects of salts, as more cations on the surface of biochar can replace sodium ions in the soils, consequently reducing the percentage of exchangeable sodium [160 – 161]. Besides alleviating biotic stresses, biochar addition can instigate microbial activities capable of mitigating plant pathogenicity that poses threats to plant development, or encourage the release of microbial inhibitors that can dissuade soil pathogens thereby, enhancing plant development [162].

Field studies have yielded mixed results of biochar application on crop cultivation. Biochar application may [11 - 12] or may not [163] improve crop yields, depending on the type of soil and efficiency of fertilizer usage. Asai *et al.* [12] reported that biochar application to soils with low phosphorus (P) content improved rice yield, but recorded no improvement in rice yield in soils with high phosphorus amount. Yamato *et al.* [11] also observed that biochar promotes crop yield when added to low-phosphorus soils. Several authors also reported enhanced crop yields when biochar was applied to soils due to more nutrient availability, but however, didn’t provide any explanation of the mechanisms responsible for the yield improvement [8, 163 – 164]. Gaskin *et al.* [165] revealed that the application of biochar both increased and decreased crop yield with respect to application rate, soil type, source of biochar, and season. Hence, a distinct relationship between biochar application and crop yields has not been fully established.

5.2. Soil remediation and wastewater treatment

Besides improving soil fertility, biochar can also be deployed to remediate polluted soils. The structure of biochar enables it to interact with inorganic and organic pollutants in the soil in such a manner that affects the movement and availability of the pollutants thereby instigating remediation of contaminated soils [166].

Microorganisms in soils cannot degrade heavy metals, making soils contaminated with heavy metals a major cause of health and environmental concerns through food crop consumption and direct exposure [155]. Several studies have revealed that biochar’s ability to remediate contaminated soils is not only due to their surface adsorption but also to the presence of several functional groups and inorganic ions in the biochar that probably contribute hugely to stabilizing heavy metals in the soils [164 – 170]. Basically, biochar influences the aggregate and migration of heavy metals in soils according to the mechanisms shown in Figure 2. These mechanisms include; (1) Electrostatic attraction between the negative charges in biochar and the positively charged metals [157, 171 – 172], (2) exchange of ions between the biochar and the heavy metals in the soils [173],

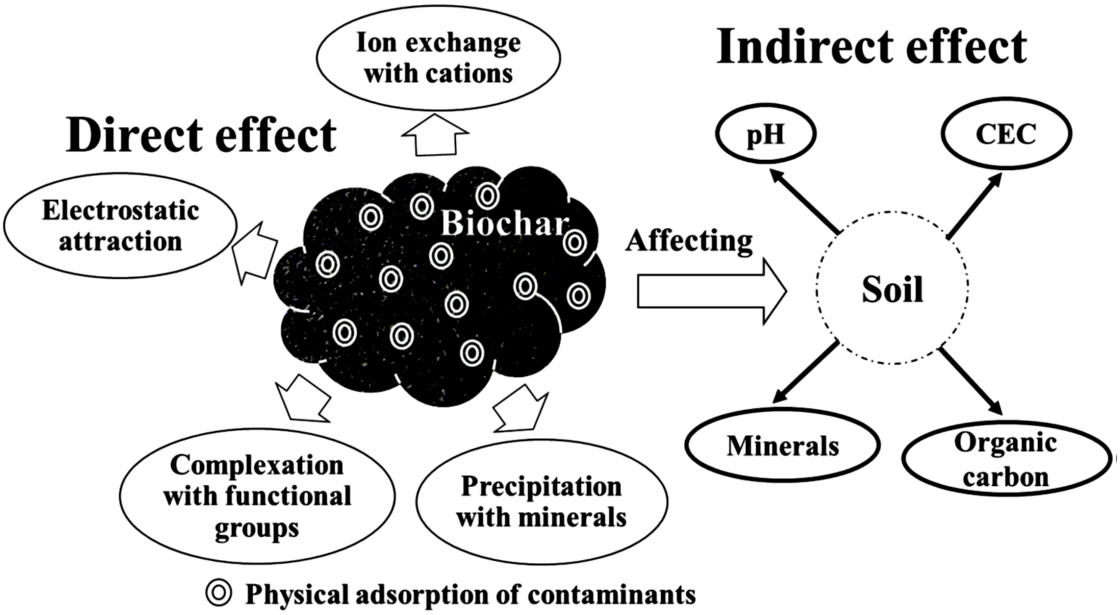

Figure 2. The mechanisms of biochar influence on the availability and mobility of heavy metals in soils (adapted from [172])

(3) Complexation with functional groups in the biochar [174 – 175], (4) Precipitation: the mineral elements in biochar may combine with heavy metals in the soils to form insoluble precipitates. Furthermore, the alkalinity of some biochar can instigate liming effects in soils thereby inducing precipitation of heavy metals [131 - 132, 174]. In addition, biochar also immobilizes heavy metals in soils through soil pH modification, CECs enhancement, reordering the redox state of heavy metals, and increasing contents of carbon and minerals in soil [109, 176].

Generally, several mechanisms can be involved in the adsorption process for a specific metal, while in a multi-contaminant system, metals can compete with each other for the same sites and functional groups to initiate corresponding inhibition [170, 177]. In addition, the methods through which biochar stabilizes heavy metals differ according to the type of metals. For example, the adsorption of lead and cadmium may be influenced by biochar’s porosity and prominently controlled by the exchange of ions, while the removal of copper may be linked to surface functional groups, which could promote complexation with the metals [169].

Unlike for inorganic contaminants, reports on the utilization of biochar for remediation of soils polluted with organic contaminants are quite limited, even though biochar possesses the necessary carbon required to absorb organic compounds such as polyaromatic hydrocarbons (PAHs) [178]. Furthermore, biochar can stimulate the decomposition and redox reactions of organic compounds due to its graphite and semi-quinone structures that are capable of accepting or donating electrons and producing free radicals [131 – 132]. However, biochar’s effectiveness to remediate organic pollutants in agroforestry soils depends on the type of biomass feedstock and reactor temperature [179]. For instance, only biochar containing high carbon and sulphur contents can be used for remediating soils polluted with compounds like sulfamethazine [180].

Unique features such as large surface area, porosity, surface functional groups, and enriched mineral components have positioned biochar as a potential adsorbent to eradicate pollutants from aqueous solutions [181 – 182]. Biochar has already demonstrated impressive ability as an adsorbent to eliminate several heavy metals and toxic organic pollutants (e.g. dyes, pesticides, herbicides, antibiotics) from water [181 – 182]. Studies by Kostas *et al*. [183] and Inyang *et al*. [184] revealed that both the Langmuir and Freundlich isotherm models demonstrated a perfect fit of the adsorption data when utilized to model how these pollutants interact with biochar, and the pseudo-second-order kinetic model concurs with experimental data. The possible methods of adsorption usually involve the integration of several mechanisms as depicted in Figure 2.

5.3. Carbon sequestration

Carbon sequestration is a process whereby carbon is captured and stored, probably in soil, consequently increasing soil carbon sink [185]. Biochar has been globally endorsed as a potential carbon sequestration medium for building carbon sinks in soils. This is because biochar can highly resist soil chemical and biological decomposition due to the recalcitrance and stability of its carbon acquired during its production processes [186]. In addition, the improved chemical stability of biochar is accredited to its dense aromatic contents [187 – 188]. According to Wang *et al.* [189], the labile fraction of biochar has an average chemical half-life of about 556 days, while Graber and Hadas [190] and Gwenzi *et al*. [134] reported that about 63 percent of the carbon in biochar is sustained on an anhydrous basis. Therefore, the application of biochar can potentially sequester carbon in the soil for centuries, probably because; (1) biochar application in soil may inhibit the mineralization of endemic soil organic carbon (SOC) indelibly [189 - 191], and reduces significantly the amount of dissolved organic carbon (DOC) in soil due to its adsorption onto the surface of biochar [124, 192], (2) Biochar application in soil can boost microbial carbon and decrease their metabolic quotient due to its influence on availability of carbon and nitrogen [192 – 193].

Biochar application for the amendment of poor fertile soils has been deemed as a potent method to sustain SOC [8 – 9]. Sustaining or improving SOC has beneficial effects on the health and performance of agroforestry soils, such as improving aggregate stability, eliminating pollutants, enhancing water penetration, and lowering water run-off [194]. These effects incidentally mitigate climate change by reducing the demand for fertilizers for crop production [195]. Generally, biochar transmutes labile carbon from the active carbon pool to the passive pool, and its application could advance carbon sequestration and soil management practices [134].

5.4. Mitigation of greenhouse gas emissions

The agroforestry sector is a major contributor to greenhouse gas (GHG) emissions [157]. Biochar application in soil does not only assist in carbon sequestration but also in lowering emissions of GHG. During biochar production, irrespective of the biomass type used, more GHG is consumed than discharged leading to a net negative GHG emission, an indication that biochar application to soil supports climate change mitigation efforts [196 – 197].

Biochar potentially assists in reducing the emission of greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), and carbon dioxide (CO_2) [198]. During respiration, soil emits CO_2 amount that is about ten times higher than CO_2 emitted during the burning of fossil fuels, hence, it is quite pertinent to decrease the amount of CO_2 emitted from soil to mitigate climate change [199]. During photosynthesis, plants absorb CO_2 from the atmosphere and more than 90% of this carbon is passed on to the resulting biomass [200], and when the biomass is decomposed by microorganisms in the soil, CO_2 is released into the atmosphere [110]. However, if the biomass is converted to biochar, and the biochar is added to the soil, its features enable it to capture carbon from the soil and store it for long durations [134, 155]. The application of biochar in soil also indirectly reduces GHG emissions through savings in energy meant for irrigation by enhancing soil quality [8].

Methane (CH_4) has more capacity to trap radiation in the earth's troposphere than CO_2, making it a huge contributor to global warming [201]. Methane is emitted through methanogenesis under conducive anaerobic conditions, such as neutral pH and sufficient nutrients. Applying biochar to soil improves its aeration, thereby enhancing methanotrophic activities and hampering methanogenic activities resulting in a reduction in CH_4 emissions [202 – 203]. Similarly, biochar supports the biological immobilization of inorganic nitrogen, which aids its retention and minimizes ammonia volatilization [204]. Also, adding biochar to soil has been observed to significantly reduce denitrification by lowering the nitrous oxide-to-nitrogen + nitrous oxide ($N_2O/(N_2 + N_2O)$) ratio, leading to a reduction of N_2O by up to about 90 percent [205]. Reduction of nitrous oxide emission can be adduced to; (1) biochar playing the role of "electron shuttle" by transmitting electrons to denitrifying microorganisms in the soil, which fosters the reduction of nitrous oxide to nitrogen, (2) nitrification by the amended soil, (3) nitrifier inhibitors in biochar, which are capable of reducing nitrous oxide emissions and producing nitrous oxide ions [206 – 207].

Influence of biochar application on GHG emissions has also been reported with varying outcomes. The scope of application ranged from soybeans, grass ecosystems [208], common beans [209], rice production [210] or wheat parcels [211] to diverse agro-soils [207]. Rondon *et al.* [210] reported a decrease in nitrous oxide emissions of about 50% for soybeans and about 80% for grasses growing in low-fertile soil from the Colombian savanna. Castaldi *et al.* [211] cultivated wheat in biochar-amended soil and discovered that the fluxes of N_2O were from 76% to 26% lower than the N_2O fluxes observed in the control parcel. Similar results were observed by Zhang *et al.* [210], who studied the impacts of biochar application on N_2O emission in rice paddy. They reported a consistent reduction in nitrous oxide emission in a single crop cycle after biochar amendment. On the contrary, capacious variations in CO_2 emissions rates from biochar-amended soils have equally been highlighted by researchers. Spokas *et al.* [212] observed a reduction of more than 20% in CO_2 emissions from loamy soil treated with biochar compared to untreated loamy soil. Liu *et al.* [213] observed a reduction in CO_2 emission when paddy soil was treated with biochar obtained from the pyrolysis of bamboo and rice straw. In contrast, Bell and Worrall [214] reported a significant increase in CO_2 emissions from uncultivated soils treated with wood biochar, but observed no increase in cultivated plots. Similarly, another study conducted by Spokas *et al.* [215] observed that when three different soil types were treated with sixteen different biochars, three different effects were observed including reduction, no change and increase in CO_2 emissions. Reduction in methane emissions has been observed in most soils treated with biochar. Liu *et al*. [213] also reported a decrease of about 91% in methane emission from paddy soil treated with biochar compared with untreated paddy soil. Karhu *et al*. [216] observed a reduction in methane emission from southern Finland soil treated with biochar obtained from birch. A contrary result was reported by Castaldi *et al.* [211] who concluded that there was no significant reduction in methane emissions on applying biochar for Mediterranean wheat cultivation.

6.0. knowledge gaps and future perspectives

The potential benefits of biochar to the agroforestry sector have been examined in this review, and illustrated pictorially in Figure 3. Apparently, the correlations between production technologies and vital properties of biochar are non-existence in literatures. The diverse parameters at play during biochar production result in biochar obtained from distinct technologies that are extremely dissimilar, making it difficult to contrast the produced biochar. Furthermore, most researchers have typically focused on carbon content as the measure of quality for biochar, whereas, properties like pH, surface area, porosity, water retention capability, cation/anion exchange capability, and surface functional groups are equally crucial to how biochar application can impact soils. Consequently, it is virtually impracticable to predict or standardize the properties of biochar produced from distinct technologies. The most appropriate properties of biochar would invariably equally be reliant on the desired usage for them.

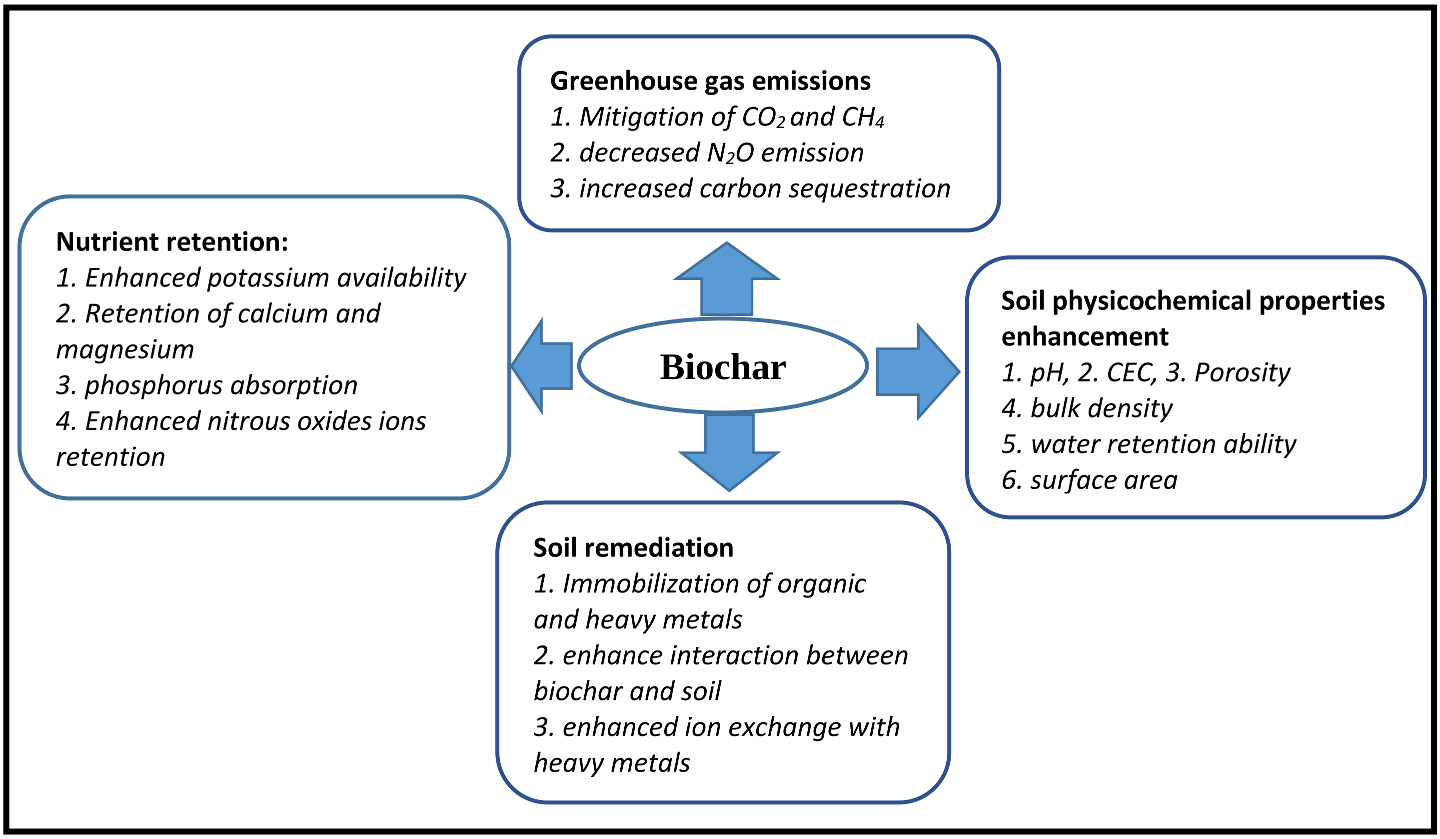

Figure. 3. Benefits of biochar to agroforestry systems

Particularly, biochar meant for energy generation would be distinct from biochar meant for wastewater treatment. The former needs a high calorific value, whereas the latter requires a high adsorption capacity. Therefore, future studies on explicating the influence of biochar production technologies on their properties are essential.

Similarly, the correlations between biochar properties and their functionality in the agroforestry sector have not been extensively examined according to the available literature. Conflicting impacts of biochar on plant development, crop yield, and emissions of greenhouse gas from soils have been reported, due to differences in biochar properties, rate and methods of application, type of soil, crop species, and even climatic conditions. Evidently, the process of biochar interactions with soils and plants is essential but the systematic processes of how these interactions occur are still largely unknown. Considering the diverse properties of biochar, it is virtually difficult, if not impracticable to estimate how biochar would perform in specific systems. Therefore, concerted efforts would be required to correlate the properties of biochar to crop and soil responses in both controlled and uncontrolled environments.

7.0. Conclusions

Biochar production and its application in the agroforestry sector have been explicated in this paper. It was discovered that the quality and yield of biochar obtained from biomass using distinct thermo-chemical technologies are quite different, attributable to the differences in operating parameters, which include oxidant requirement, rate of heating, residence time, and temperature. Basically, biochar yield decreases with rapid heating and increasing amounts of oxygen. Although biochar applications in agroforestry sectors have huge benefits, like enhancing soil health, improving plant development, carbon sequestration, and lowering emissions of greenhouse gas, the mechanisms of biochar interactions in such systems are yet to be fully delineated. Furthermore, conflicting results from such applications have also been duly reported, hence, the benefits from biochar application are oftentimes restricted to specific parameters like the source of biochar, biochar application rates, types of soil, and species of plants. Therefore, systematic analyses are essential to explicate the correlations amongst biochar production technologies, biochar properties, and their performance in the agroforestry sector.

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