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Review

Chemical and Physical Properties of Selected Biochar Types and a Few Application Methods in Agriculture

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Abstract: Biochar, a carbon-rich by-product of organic matter pyrolysis, has a variety of physiochemical properties beside a variety of applications. This review highlights some physical and chemical characteristics of herbaceous, woody, and sewage waste biochar under different pyrolysis conditions, as well as soil and foliar applications of biochar. The controlling role of pyrolysis temperature was the reason for selecting the discussed biochar types in the study. This review concludes that increasing pyrolysis temperature mainly raised the values of some chemical properties of the biochar, such as pH, electrical conductivity (EC), ash content, total phosphorus (TP), and a few values of physical properties like porosity and specific surface area (SSA). On the other hand, yield and total nitrogen (TN) decreased with rising pyrolysis temperature. Among biochar application methods to soil, mixing biochar with soil before planting is one of the best methods of application, and in most cases, biochar reapplication improved soil properties, while foliar application of biochar has positive effects on plant growth and yield parameters, ranging from low rates to the highest ones.

Keywords: biochar; chemical properties; physical properties; soil application; foliar application

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1. Introduction

Biochar is a sustainable economic solution that tackles food security and environmental problems. Its numerous uses include soil improvement, waste reduction, climate change mitigation, and energy generation [1–4]. It can be made from nearly any solid biomaterial, such as forest litter, herbaceous debris, agricultural residues, food processing waste, municipal organic refuse, animal manure, and biosolids [5,6].

Two types of biomasses could be identified: First, lignocellulosic biomass, which is woody and herbaceous. The cellulose, hemicellulose, and lignin content of woody biomasses can be 51.2%, 21.0%, and 26.1%, respectively [7]. The contents of these three primary components in herbaceous biomasses have been recorded to be 32.1%, 18.6%, and 16.3%, respectively [8]. Secondly, non-lignocellulosic biomass includes sludge, animals, and microorganisms, with the main components being proteins, lipids, chitin, and chitosan [9]. This review focused on two lignocellulosic biomass, which are herbaceous and woody biomasses, and one non-lignocellulosic biomass which is sewage waste biochar, as they are the most common types. Three preparation methods can be used to obtain biochar: pyrolysis, hydrothermal carbonization, and gasification [10]. In comparison to gasification, pyrolysis is a comparatively simple technique that requires no sophisticated process plant and is quite beneficial ecologically [11]. Particularly, pyrolysis consists of a series of complex reactions that can be divided into three stages according to the degradation temperatures for hemicelluloses (220–315 °C), cellulose (315–400 °C), and lignin (>400 °C) [12]. The physiochemical parameters of the resultant biochar product are strongly influenced by the feedstock type, pyrolysis temperature, residence duration, and reactor type [13–17].

Shinogi and Kanri [18] reported significant variations in the yield and density of biochar produced by pyrolysis of various biomass wastes (e.g., bagasse, rice bran, and activated sludge). On the same grounds, pyrolysis temperature affects the structural and physicochemical properties of biochar, such as surface area, pore structures, surface functional groups, and elemental compositions [19]. Numerous researchers have found that increasing the pyrolysis temperature increases the surface area of biochar [20,21], together with higher pH [22], electrical conductivity (EC) [23], carbon content (C), potassium content (K), and phosphorus (P) content [24] but decreases nitrogen (N) content [23]; and surface functional groups [25]. The O/C molar and the H/C atomic ratios help to measure the density of polar functional groups on biochar surfaces [26] and to represent the aromaticity of biochar, respectively. The H/C and O/C ratios decreased as the pyrolysis temperature increased [27,28]. On the other hand, it was revealed that there is a resistance to mass or heat transfer in rapeseed biomass at low heating rates, while increasing the heating rate resulted in greater conversion rates and lower yields [29].

Biochar application can improve soil fertility and plant productivity [14] by enhancing physical and chemical properties depending on soil type [30] and reducing the need for fertilizer as well as fertilizer leaching [31,32]. The application methods vary; however, the selection of biochar application methods depends largely on the availability of labor and farming systems [33]. The broadcast and incorporation modes of application have been chosen for most biochar field studies [34,35].

Similarly, the efficiency of biochar usage is greatly influenced by the method of application [36], combining biochar with other additives or activating biochar itself. The awareness of the chemical and physical properties of biochar and its application methods should be considered due to the high cost of obtaining and collecting feedstock, as well as the high capital, operating, and maintenance expenses of the pyrolysis plant [37]. In 2014, the average price of biochar in the United States (e.g., nurseries and garden centers) was USD 2840/t (or USD 1.29/lb), restricting its uses to small trials [6].

The purpose of this review is to describe the most current studies on the pyrolysis condition effect on the different physical and chemical features of herbaceous, woody, and sewage waste biochar, as well as a few biochar application methods, with a focus on the novel foliar biochar application trend affecting specific plant metrics. This overview will help to develop a guide to select and utilize special biochar types that help decision makers to overview and use different biochar varieties.

2. Chemical and Physical Properties of the Biochar

2.1. Chemical Properties of Biochar

Biochar characteristics are influenced by several technical aspects, including pyrolysis temperature, feedstock type, residence duration, and heating rate, which can result in products with a broad range of pH, ash content, carbon content (C%), and macronutrients [38,39].

Overall, biochar yield among different feedstock types witnessed a downward trend with an increase in pyrolysis temperature. Dry sewage sludge had the highest yield under gradual pyrolysis temperatures [40], followed by date palm, wheat straw, rice straw, and eucalyptus wood at the lowest temperature range of 300–450 °C [41–43] (Table 1).

It is important to know that the highest mass reduction with temperature increments happened between 300 and 500 °C for the whole feedstock, while eucalyptus wood was highly resilient to yield losses (Table 1).

The ash content experienced an upward trend as the pyrolysis temperature increased. Starting at 300 °C, ash content for dry sewage sludge and rice straw were 37.42, and 31%, respectively, gaining the biggest values among all feedstock types [40,42], while at 700 °C, dry sewage sludge ash content peaked, reaching 66.66% [40]. On the other hand, the ash content of woody biochar (eucalyptus wood) was much lower compared to the former (dry sewage sludge) [41]. Changes in ash content were small for eucalyptus, whilst, for straw and dry sewage sludge, they were considerable (Table 1).

Regarding C%, there was an increasing trend with the increase in pyrolysis temperature for eucalyptus wood through the whole temperature range [41]. On the other hand, rice straw C% declined as the temperature increased [42]. The greatest values of C were reported for eucalyptus wood between 350 and 750 °C [41], while C content was the lowest for dry sewage sludge [40] (Table 1).

Table 1. Biochar chemical properties under different pyrolysis conditions.

Feedstock Type	PT °C	C%	Yield%	AC%	O/C	H/C	pH	EC (dS m^{-1})	TN%	TP%	TK%	RT min	HR °C min^{-1}	Location/ References
Rice straw	300	45.2	45	31			8.0	2.35	1.15	0.11	3.6			
	400	55.5	36	40	N/A	N/A	9.7	2.85	0.98	0.13	4.1	20	7–10	Faisalabad Pakistan [42]
	500	63.0	32	52			10.4	3.35	0.85	0.14	4.8			
Wheat straw	300	51.7	48	25			7.7	1.78	1.38	0.26	3.0			
	400	62.0	38	37	N/A	N/A	8.8	2.15	0.94	0.3	3.2			
	500	66.2	33	46			9.4	2.6	0.85	0.34	3.6			
Date palm	300	57.99	49.97	14.42	0.27	0.84	8.32	3.26	0.54	N/A	2.18	240	5	Riyadh, Saudi Arabia [43]
	400	66.87	36.54	16.34	0.13	0.63	9.25	3.28	0.45	N/A	2.17			
	500	72.30	32.38	19.68	0.05	0.35	9.59	3.50	0.42	N/A	2.23			
	600	72.89	30.88	20.71	0.03	0.28	9.57	3.59	0.39	N/A	2.58			
Dry sewage sludge	300	37.15	64.28	37.42	0.27	1.41	6.2	3.3	6.17	1.043	0.225			Shanghai, China [40]
	400	35.02	56.55	49.17	0.15	1.02	7.5	0.4	4.96	1.156	0.248			
	500	30.08	55.26	57.42	0.15	0.67	8.1	0.5	4.32	1.663	0.275			
	600	26.48	53.41	63.24	0.15	0.51	10.8	0.3	3.54	1.823	0.283			
	700	27.23	46.66	66.66	0.05	0.39	11.9	1.3	3.08	2.001	0.291			
Eucalyptus wood	450	74.96	42.76	0.60	0.25	0.050	N/A	0.12	1.25	0.016	0.182	60	1.7	São Paulo, Brazil [41]
	550	79.25	38.00	0.74	0.22	0.012	N/A	0.09	1.49	0.016	0.14			
	650	87.06	34.69	0.63	0.12	0.018	N/A	0.134	0.00	0.023	0.164			
	750	87.74	34.27	0.84	0.11	0.019	N/A	0.16	1.06	0.017	0.21			

PT: pyrolysis temperature; AC: ash content; RT: residence time (minutes); C%: carbon content; N/A: not available; HR: heating rate (°C minute).

Among all feedstock types, the higher the pyrolysis temperatures, the greater the pH values were. The initial pH values at 300 °C (reported as high) were date palm 8.32 and rice straw 8 [42,43]. The initial pH values at 300 °C (reported as low to moderate) were dry sewage sludge at 6.2 and wheat straw at 7.7. At 500 °C, date palm attained the highest pH value, 9.59, followed by wheat straw, 9.4, and dry sewage sludge, 8.1 [40,42,43]. At 700 °C, dry sewage sludge sustained a pH value of more than 11 [40]. In terms of electrical conductivity (EC), it increased under pyrolysis temperature increments for all feedstock types apart from dry sewage sludge, which experienced an opposite trend. Date palm owned the highest EC regardless of pyrolysis temperature, followed by rice and wheat straw, with an exception for dry sewage sludge at 300 °C [40,42,43]. It seems that woody biochar had the lowest EC values (eucalyptus) [41] (Table 1).

Total nitrogen (TN%) dropped gradually as a response to temperature increments. However, these reductions were noteworthy for straw biochar compared to woody biochar. Dry sewage sludge biochar had the greatest TN% across all pyrolysis temperatures [40]. Different behavior for total phosphorous (TP%) could be noticed; as the pyrolysis temperature increased, the TP% also increased. Dry sewage biochar unearthed the greatest contents of P during every pyrolysis temperature [40]. Eucalyptus wood < rice straw biochar had the poorest content of TP% [41]. The figure for total potassium (TK%) generally fluctuated among feedstock types under temperature changes. However, TK for rice straw, date palm, and wheat straw, among the entire range of pyrolysis temperatures, was the highest [42,43]. On the other hand, eucalyptus wood and dry sewage sludge biochar possessed the least TK% [40,41] (Table 1).

The lowest heating rates of 1.7–10 min °C reported the highest C% proportion for eucalyptus wood [41], while the highest mass was recorded for dry sewage sludge [40]. The long residence time of 240 min revealed high pH values with pyrolysis temperature increments.

O/C and H/C ratios decreased in all biochar types with increasing temperature. The highest values of the H/C ratio were for dry sewage sludge, followed by date palm and eucalyptus wood biochar [40,41,43]. Regarding the O/C ratio, all biochar reported in Table 1 were close to each other in values.

Due to the elimination of water and the degradation of complex components (such as cellulose and hemicellulose), the largest weight decreases in straw biochar were observed between 300 and 400 °C [44,45]. The yield decreased steadily as the temperature rose above 400 °C. This variation might be attributable to a decrease in volatile matter emissions and lignin degradation below 400 °C [45,46]. On the other hand, during pyrolysis, dehydration, cleavage, and polymerase reactions cause easily degradable C compounds to be restructured, while other elements may be lost to volatilization, and thus overall biochar total C content increased with increasing pyrolysis temperature [47,48]. Low temperatures (300–400 °C) are ideal for N enrichment in biochar, but higher temperatures (about 700 °C) are favorable for P and K enrichment [49]. Biochar C% decreases slightly as the heating rate increases, but its hydrogen and oxygen content increases. Furthermore, the heating rate impact tends to fade at high temperatures [50].

The rise in ash content was caused by a gradual accumulation of inorganic components and organic matter combustion residues [51]. Zama et al. [52] described the increases in Mg (magnesium), Ca (calcium), K, and P on high-temperature pyrolyzed biochar as a result of increased ash amounts ranging from 4 to 33.1%. On the contrary, higher biochar N concentrations are most likely due to greater levels of amino acids and proteins in these materials [53]. With rising pyrolysis temperature, considerable N quantities emerge as gaseous forms (e.g., NO, N_2O, NO_2, NH_3, N_2 > 60%) [54].

The higher the pyrolysis temperature, the more minerals begin to separate from the organic matrix, and separation of the organic (C) and inorganic compounds, such as alkali metal salts (ash), has been observed [52–54], causing pH to increase. Similarly, the EC increase was attributed to the loss of volatile matter, resulting in a higher concentration of elements in the ash fraction [55]. Furthermore, elevated mineral ash in biochar likely has higher electrical conductivity, particularly those that have high K^+ concentrations, due to the motion of the K^+ [56].

Regarding biochar with O/C ratios, (a) <0.2 is highly stable (half-life > 1000 years), (b) between 0.2 and 0.6 is moderately stable (half-life between 100 and 1000 years), and (c) >0.6 is relatively unstable (half-life less than 100 years) [57], which means increasing the pyrolysis temperature increased biochar stability. On the other hand, the higher the pyrolysis temperature, the greater the losses in H and O by volatilization [58], explaining the lower H/C values.

According to Zhao et al. [59], physical characteristics are greatly affected by the chemical characteristics of biochar. Sawdust had the largest surface area of 203 $m^2\ g^{-1}$ with the lowest ash output (9.94 wt%) among the 12 feedstocks, while the surface area of the waterweeds and cow manure with the greatest ash of 63.5–67.5% was 3–22 $m^2\ g^{-1}$.

2.2. Physical Properties of Biochar

Biochar's physical properties are crucial to soil processes. Surface area, pore volume, and pore size distribution are among the most critical, possibly having a significant influence on biochar performance in the majority of its uses [60].

With growing pyrolysis temperatures, both porosity and specific surface area (SSA) increased. However, SSA increments were much higher for woody biochar compared to other feedstocks [61–63]. In the detailed picture, the Douglas fir wood (*Pseudotsuga menziesii*) intra-porosity comes to the fore, reaching 83%, followed by miscanthus at 79% and hazelnut shells at 62.5% at the lowest pyrolysis temperatures of 370–400 °C, and still more than hazelnut shells at three different temperatures for both [61,62] (Table 2).

Table 2. Biochar physical properties under feedstock type and pyrolysis conditions.

Biochar Feedstock	Pyrolysis Temperature °C	Bulk Density g cm^{-3}	Particle Density g cm^{-3}	Porosity	Type of Porosity%	SSA BET m^2 g	Heating Rate °C min^{-1}	Residence Time h	Location/ References
Douglas Fir	370 500 620	0.262 0.236 0.254	1.55 1.57 1.71	83 84.9 85.1	Intra porosity [1-bulk density/particle density) × 100]	153 229 280	NA	1	Western Oregon, USA [61]
Hazelnut shells	370 500 620	0.554 0.557 0.505	1.48 1.57 1.64	62.5 64.5 69.2	Intra porosity [1-bulk density/particle density) × 100]	58.7 161 211	NA	1	Western Oregon, USA [61]
Maize stalk	400 500 600	0.12 0.12 0.13	0.35 0.37 0.46	60.20 62.70 65.90	Intra porosity [1-bulk density/particle density) × 100]	12.90 23.20 43.90	10	4	Sikkim, India [63]
Lantana camara	400 500 600	0.15 0.15 0.16	0.40 0.42 0.51	53.18 55.68 58.88	Intra porosity [1-bulk density/particle density) × 100]	12.70 22.10 41.40	10	4	Sikkim, India [63]
Pine needles	400 500 600	0.14 0.14 0.15	0.43 0.45 0.54	46.96 49.46 52.66	Intra porosity [1-bulk density/particle density) × 100]	12.50 21.80 40.20	10	4	Sikkim, India [63]
Black gram crop	400 500 600	0.13 0.13 0.14	0.37 0.39 0.48	48.87 51.37 54.57	Intra porosity [1-bulk density/particle density) × 100]	12.10 20.40 38.90	10	4	Sikkim, India [63]
Sewage waste	400	1.220	1.760	31	Intra porosity [1-bulk density/particle density) × 100]	N/A	5	4	Texas, USA [62]
Pine	400	0.410	1.450	72		N/A	5	4	
Mesquite	400	0.520	1.450	64		N/A			
Miscanthus	400	0.320	1.510	79		N/A	5	4	

SSA: specific surface area (SSA) m^2 g^{-1}. NA: not available.

Douglas fir wood biochar has the largest SSA, regardless of the pyrolysis temperature. It hits a peak of 280 m^2 g^{-1} at 620 °C, followed by hazelnut shells with 211 m^2 g^{-1} and maize stalk with 43.9 m^2 g^{-1}, but black gram biochar was the lowest of all with only 38.9 m^2 g^{-1} [61,63]. At 500 °C, Douglas fir with SSA of 229 m^2 g^{-1} remained in the highest place, followed by > hazelnut shells 161 m^2 g^{-1} >, maize stalk 23.20 m^2 g^{-1} >, and *Lantana camara* 22.10 m^2 g^{-1}, whilst black gram had only SSA of 20.40 m^2 g^{-1} [61,63] (Table 2).

Internal pore volume (the sum of pyrogenic nanoporosity and residual macroporosity) very marginally increases as production temperature rises [61]. The difference in porosity between feedstocks could be attributed to differences in cell shape and size distribution in woody and herbaceous plants, given that much of the original plant structure is maintained in biochar after pyrolysis [64,65]. According to the IUPAC classification, hemicellulose and cellulose decompose at temperatures ranging from 200 to 400 °C, but lignin has a more complicated structure and more intricate breakdown mechanisms [60].

The degradation of lignin occurs mostly between 350 and 500 °C and continues until 900 °C [66]. The formation of pores in the nm range during pyrolysis has been linked to the chemical structure and lignin quantity in raw biomasses [66].

Although there is a growing tendency for SSA with pyrolysis temperatures for wood biochar, this trend does not exist for manure and crop waste biochar [67]. The higher the lignin content in the biomass feedstock, the greater the biochar surface area and pore volume in the nm range should be when produced via slow pyrolysis in the mild temperature range of 350–600 °C [68]. Because pore-blocking compounds are pushed off or thermally broken as the pyrolysis temperature rises, the externally exposed surface area increases [69].

Bulk density generally decreased for Douglas fir and hazelnut shells but increased slightly for the other feedstock types, while particle density increased with the pyrolysis temperature increasing. At 500 and 400 °C, bulk density ranged from 0.12 g cm^{-3} in maize stalk to 0.13 g cm^{-3} in black gram biochar [63].

Sewage waste and hazelnut shells had the highest values of bulk densities on the whole [61,62]. At 400 °C, particle density reaches 1.760 g cm^{-3} for waste sludge, followed by Douglas fir at 1.55 g cm^{-3} and hazelnut shells at 1.48 g cm^{-3} (~400 no more than 10% difference); however, maize stalk and black gram exhibited similar values [61–63]. Increasing the pyrolysis temperature to 500 °C changes the sequence on behalf of hazelnut shells to equal Douglas fir 1.57 g cm^{-3} [61–63]. At higher temperatures, 620 °C, the BD in Douglas fir was 1.71 g cm^{-3}, and hazelnut shells accounted for 1.64 g cm^{-3}, followed by Lantana camara with 0.51 g cm^{-3} and black gram with 0.48 g cm^{-3} [61,63].

A heating rate of 10 °C min^{-1} revealed lower biochar bulk and particle density (Table 2). A residence time of 1 h revealed higher porosity and SSA of all feedstock types except for pine, Mesquite, and Miscanthus (Table 2).

Since wood has much more organic matter compared to waste sludge, it has a much lower bulk density than organic matter, which is attributed to a higher sample volume with a relatively lower weight. At the same time, waste sludge is highly mineralized and, therefore, is more compact and denser, with smaller particle sizes if compared with wood biochar [70]. It seems that improvements in internal pores lead to a decline in bulk density, but this was limited to mild temperatures of 500 °C. Pyrolysis temperature above 500 °C might have a negative effect on internal pore structure.

Slow heating rates (less than 1 °C/s) do not result in significant changes in particle shape since volatiles are released through the natural porosity [71] or fast heating rates (higher than 10 °C/s), and the original cellular structure is lost as a consequence of melting [72]. As a result, high heating rates will probably melt the biochar particles and polish the surface of the biochar [73]. Consequently, the woody Douglas fir biochar gained the best physical characteristics with increasing pyrolysis temperature, meaning that controlling the pyrolysis temperature is a decisive way to reach suitable biochar properties.

3. How Can Biochar Be Applied?

3.1. Biochar's Soil Application

The primary biochar application methods in the soil are topsoil incorporation, depth application, and top dressing [74]. Although topdressing tends to be less costly, the trench-and-fill method is better suited for storing large quantities of biochar in soil [75]. In several areas where crops are established, a surface application (top dressing) approach to biochar can be employed. The surface application has been considered extremely risky due to soil erosion [76]; the possibility of it being harmful to the environment and human health; and because it may cause fires, especially in temperate regions [77].

Biochar application below the soil surface, either through direct use in planting holes or in the form of banding, causes negligible loss of biochar due to soil erosion, and it is the most suitable approach for tree crops. The uniform topsoil incorporation method implies biochar amendment properly in the soil before crop establishment. Mixing biochar uniformly with the soil of the layer (0–20 cm depth) at 40 t ha^{-1} was beneficial for improving soil quality and crop productivity in Mollisols for short-term (3-year) cultivation, whereas mixing biochar under 20 cm depth had an effect over time [78]. On the same grounds of timing, switchgrass biochar amendment significantly increased switchgrass yield when rototilled in full dose before planting but not when applied progressively between crop rows with a chisel plow [79].

3.1.1. Biochar Repeated Application

Although the biochar in the soil can act as a carbon sink, it is not a permanent fixture since it disintegrates over time [80]. Biochar decomposition rates for soil amendment application are determined by the condition of the biochar, soil characteristics, and climate [81]. Still, little information is available about biochar reapplication.

Biochar reapplication raised both soil available water and porosity of a silty loam soil after 4 years of addition [82]. Tarnik [83] indicated that older doses of biochar (paper fiber sludge and grain husks (1:1 w/w)) application increased the silt loam soil moisture.

A new dosage of biochar had no effect on soil moisture, either favorably or negatively, in 2018. More significant alterations were detected following the reapplication of biochar (paper fiber sludge and grain husks (1:1)) to silt loamy soil than after its first application. In the same vein, the application of biochar alone at a rate of 20 t ha^{-1} was more effective than at a rate of 10 t ha^{-1}. In comparison to the control, the treatment with reapplied biochar at a rate of 20 t ha^{-1} without N fertilizer produced the most substantial changes in soil structure parameters [84]. The reapplication of rice husk biochar after 2 years at a rate of 20 t ha^{-1} combined with NPK produced an outstanding response in sandy loam soil nutrient retention, soil stability, and TC and TN sequestration potential in micro- and macro-aggregate fractions, while it had a limited effect for C and N sequestration in soil aggregates when it was applied without NPK [85].

3.1.2. Biochar Combining

Generally, combining biochar with non-pyrogenic organic additions (NPOAs) such as animal manure and urine, compost, or plant litter increased crop yields more than utilizing biochar alone [86–88].

Nobile et al. [89] indicated that compost–biochar mixtures at 8 and 4 t ha^{-1}, respectively, increased organic carbon and exchangeable potassium and yield of wheat maize cropping system growing in loamy soil in wheat–maize cropping system during 2019, reaching the same as mineral fertilization. The addition of olive mill wastewater and citrus tree biochar to sandy soil enhanced overall porosity and organic matter [90]. Furthermore, supplying 2.5% molasses pellets and bamboo biochar for each to sandy loam soil boosted the fruit output of *Pyrus communis* from 4.5 to 5.9 tree kg^{-1} compared to the control with no amendment [91].

The co-application of rice residue biochar at 1% with rice residue and animal manure enhanced C mineralization by 63% and 37%, respectively [92]. Similarly, adding straw and wheat straw biochar to loamy sand at doses of 0.2%, 0.5%, 1%, and 2% significantly increased the dissolved organic nitrogen content in all treatments compared to the treatment with no fertilization [93].

Cotton yield and root and shoot dry weights increased significantly after combining chicken manure at 3% with cotton straw biochar at 1% [94]. Biochar (coffee husk), compost, and organic manure soil application at a ratio of 50:50 significantly rose grass pea shoot dry weight and nodule number per plant in comparison to the control with no amendment [95].

Dual application of biochar and glycine betaine significantly decreased soil EC and pH at all tested irrigation intervals under saline soil conditions. On the other hand, it significantly increased the grain yield and its components (number of panicles per m^2, 1000-grain weight, number of grains per panicle, grain yield, straw yield, and harvest index in Rice (*Oryza sativa* L.) [96].

The co-application of chemically enhanced biochar (5 t ha^{-1}), derived from cotton stalks treated with urea-N (loaded with a full N dose) and biofertilizer (4.94 kg ha^{-1}), to silt loam soil significantly increased the crop growth rate (CGR) and leaf area index (LAI) of wheat. This resulted in an 11% higher grain yield compared to the control [97].

3.2. Biochar Foliar Application

Alternative methods of minimizing biochar application doses and losses include spraying aqueous extracts of biochar, similar to how foliar applications of chemical fertilizers are used to increase production of crops [88], paving the way for a new trend to use biochar, as it contains carbon nanoparticles. In this regard, wheat seeds treated with these carbon nanoparticles at a concentration of 50 mg L^{-1} showed higher growth rates [98]. Many preparation methods of foliar application were mentioned in the literature, including the following:

1. Dried biochar powder + 1000 mL+ distilled water + boiled (30 h) + shaking for 2 hours at 120 rev min^{-1} in the dark. The mixtures were filtered through Whatman No. 2 filter paper and then through a membrane filter with 0.45 μM pore size [99].

2. An amount of 10 g of wheat straw biochar was added to 200 mL of desalinated water and heated in a water bath at 100 °C for 3 h. The mixture was then shaken on a rotatory shaker at 180 rpm at room temperature (25 °C) for 24 h and subsequently vacuum-filtered through a 30 µm ceramic filter. Before analysis and pot testing, the liquid extracts were kept at 4 °C [100].
3. An amount of 10 g of biochar powder (particle size < 2.0 mm) was added to 200 mL of milli-Q water, and the mixtures were boiled for 3 h, brought back up to the initial volume by adding milli-Q water as some of the water was evaporated, and then shaken on a rotary shaker at 180 rpm at 25 ± 2 °C for 20 h. The mixtures were centrifuged at 5000 rpm for 10 min at 25 °C, and the supernatants were collected and filtered (0.45 µm PVDF filter) [101].

As indicated by the results of all researchers in Table 3, foliar application of biochar has important effects on chlorophyll content, plant growth, and yield parameters, ranging from low rates to the highest ones depending on both the biochar-derived feedstock and the preparation procedure. These effects might be attributed to the presence of different materials with a variety of properties in the biochar spray that impact plant physiology. To be more specific, the presence of Mg and Fe in the biochar used to spray plants has a role in the stimulation and formation of chlorophyll [102]. The incorporation of nanocarbon into the exterior lipid membrane of chloroplasts increased photosynthetic activity via an increase in electron transport [103,104]. Furthermore, biochar-labile organic compounds formed at temperatures lower than 500 °C include a variety of low-molecular-weight organic acids, phenols, aromatic hydrocarbons, and alkanes [105,106]. These compounds have also been identified in wood vinegar and smoke water, which are effective foliar sprays for some plants [107,108].

Table 3. Foliar application of biochar.

Property	Study Type	Duration	Biochar Feedstock	Plant	Application Rate (mg L^{-1}/g 100 mL^{-1}/ mL 100 mL^{-1})	Soil Fertilization	Values	References
Total chlorophyll (mg g^{-1})	Field	2 years	NA	Wheat	0 75 150 225 300	NPK soil and organic matter	2.55 2.64 2.69 2.76 2.99 $LSD_{0.05}$ = 0.171	El-Menoufia, Egypt [109]
Grain yield (t ha^{-1})	Field	2 years	NA	Wheat	0 75 150 225 300	NPK soil and organic matter	6.6 ^{b} 7.23 ^{b} 7.5 ^{b} 8.71 ^{b} 11.35 ^{a}	El-Menoufia, Egypt [109]
Leaf area (cm^2 plant)	Field	2 years	NA	Wheat	0 75 150 225 300	NPK soil and organic matter	672.8 ^{i} 744 ^{f} 822.4 ^{c} 946.8 ^{b} 1236 ^{a}	El-Menoufia, Egypt [109]
Leaf relative chlorophyll SPAD	Nursery	1 year	Gazwarina trees wood	Sweet pepper	Daily irrigation 0 2 4 Biochar extract Irrigation every two days 0 2 4 biochar extract		31.00 ^{i} 37.90 ^{f} 39.00 ^{e} 37.60 ^{f} 47.00 ^{c} 48.40 ^{a}	Qulubia, Egypt [110]

Table 3. *Cont.*

Property	Study Type	Duration	Biochar Feedstock	Plant	Application Rate (mg L^{-1}/g 100 mL^{-1}/ mL 100 mL^{-1})	Soil Fertilization	Values	References
Total yield (t Fed^{-1})	Nursery	1 year	Gazwarina trees wood	Sweet pepper	Daily irrigation 0 2 4 Biochar extract		24.01 ^{e} 26.91 ^{bc} 28.09 ^{ab}	Qulubia, Egypt [110]
					Irrigation every two days 0 2 4 Biochar extract		23.96 ^{e} 26.30 ^{cd} 28.56 ^{a}	
Vitamin C (mg kg^{-1})	Green house	45 days	Wheat straw	*Brassica rapa*	0 1:25 1:50 1:100 (v/v) dilution	Soil NPK	42.2 ^{c} 40 ^{c} 117.7 ^{b} 71 ^{a}	Nanjing, China [100]
Vitamin C (mg kg^{-1})	Green house	45 days	Maize stalks	*Brassica rapa*	0 1:25 1:50 (1:100) (v/v) dilution	Soil NPK	42.2 ^{c} 107.5 ^{b} 100.7 ^{b} 121.5 ^{a}	
Plant fresh biomass (g)	Pot	32 days	Pinewood: clay:sand (PCS-BC; 70:15:15 (w/w))	*Lactuca sativa L.*	PCS-BC extract dilutions was diluted 1:25 (PCS25) and 1:50 (PCS50)	NPK soilless	Significantly increased ($p < 0.05$)	[101]
Plant fresh biomass (g)	Pot	32 days	Wheat straw: bird (chicken) manure (WB-BC; 50:50 (w/w))		WB-BC extract dilutions 1:50 (WB50) 1:100 (WB100)			

Pine wood/clay/sand (PCS-BC; 70:15:15) and wheat straw/bird manure (WB-BC; 50:50). NA: not available. Different superscript letters mean there is a significant difference between the treatments.

4. Upgraded biochar

Currently, numerous modification approaches, including chemical treatment, steaming, gaseous activation, natural aging, and ball milling, are recommended for improving biochar [103,111,112].

First, acidic agents significantly affect the structural characteristics of biochar, such as O-containing functional groups (OFGs), specific surface area, porosity, and cation exchange capacity, in contrast to the majority of oxidative agents, such as alkaline, metal oxides, or steaming [113]. When nitric acid, sulfuric acid, or phosphoric acid are applied to biochar, various functional groups, such as N=O, SO_3H, and P=OOH, can be introduced [9]. Oxidized biochar using hydrogen peroxide (H_2O_2) showed greater specific surface area, porosity, oxygen and cation exchange capacity (CEC) values in all oxidized biochars as well as introduced oxygen functional groups on biochars' surface [113].

Secondly, steamed and purged activated biochar has a higher surface area and pore volume compared to the original biochar [114]. Third, biochar undergoes significant changes during aging, including (1) increasing O content, CEC, SSA, and the formation of OFGs and (2) decreasing carbon content, aromatic components, ash content, and pH value [115–118].

Fourth, ball-milling biochar revealed better physicochemical properties, including higher external and internal surface area and more acidic surface functional groups [119] (Figure 1).

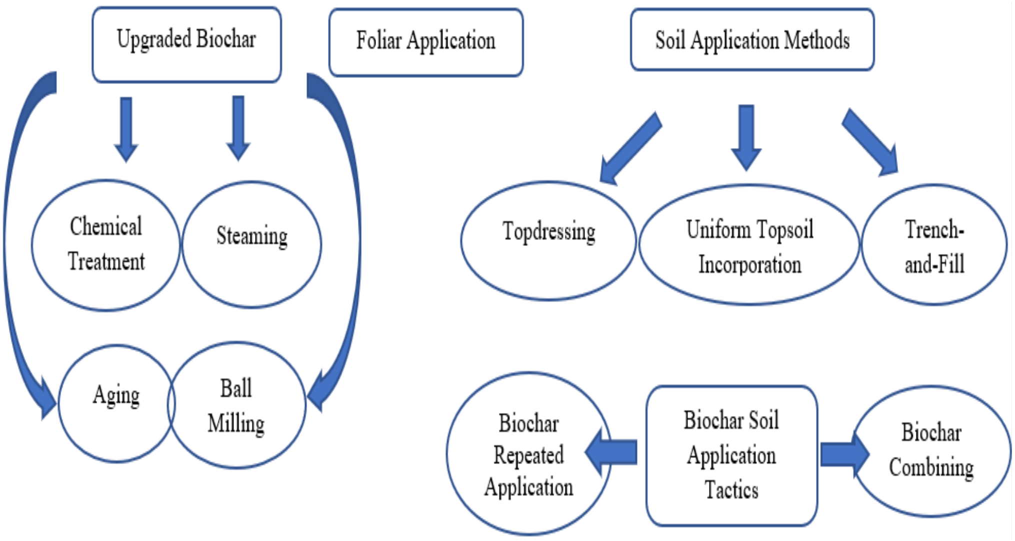

Figure 1. A schematic chart of biochar application methods, tactics, and upgraded biochar.

4. Summary and Future Perspective

Future biochar research is of primary importance due to the increased number of areas affected by wildfires due to the rising impacts of global warming. This review highlighted some aspects of biochar: Firstly, regarding biochar chemical and physical properties using different pyrolysis conditions, it was found that increasing pyrolysis temperature raises the values of biochar chemical properties such as pH, EC, ash content, and TP, as well as the values of biochar physical properties, such as porosity and SSA, while reducing biochar yield and TN. As a result, managing the pyrolysis temperature is of great importance for obtaining appropriate biochar. Secondly, this review discussed how biochar could be used for soil and foliar application, concluding that the response of soil biochar reapplication was greater in comparison to fresh doses. It also indicated that biochar foliar application is a paramount method to improve plant growth across all feedstock types, reaching the highest performance at the highest biochar rates. Thirdly, upgraded biochar has better characteristics than pristine biochar. It is apparent that biochar is an interesting organic option to improve soil and plant characteristics as it is suitable for sustainable agriculture management. Future work should focus on addressing the gap in comparing various soil biochar application methods to determine the best approach using available farm resources.

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