



REVIEW

Positive Effects of Biochar on the Degraded Forest Soil and Tree Growth in China: A Systematic Review

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ABSTRACT

Soil degradation threatens the forest sustainable productivity, particularly in afforestation system. Biochar derived from agroforestry waste or biomass can potentially improve the degraded forest soil and promote the tree growth. To expand the application of biochar for forestry productivity improvement, we here reviewed the effects and the underlying mechanisms of biochar on the degraded forest soil and tree growth. Totally 96 studies that conducted from pot to field investigations in China were summarized. The result suggested that biochar generally exerted positive effects on restoration of degraded forest soil such as that with compaction, acidification or soil erosion, which are mainly manifested by improving soil porosity, increasing pH, enhancing erosion resistance and mitigating greenhouse gas emissions. Furthermore, biochar incorporation promoted the growth of tested trees in most cases, which effect was mainly attributing to directly supplying nutrients, improving soil physio-chemical properties, enhancing the root's nutrient absorption capacity, and enlarging the living space. In summary, current studies demonstrate that biochar has a unique potential for improving degraded forest soils and promoting tree growth. However, investigations on the underlying mechanisms and the long-term effects should be strengthened.

KEYWORDS

Biochar; plant root; soil fertility; soil conservation; tree plantation

1 Introduction

As an important constituent of the terrestrial ecosystem, forests play an irreplaceable role in regulating climate, conserving water sources and maintaining ecological balance [1–4]. However, the forest coverage rate and the per capita forest area in China are 1/3 and 3/4 lower than that of the global average, respectively [1]. What is more, according to the Soil Pollution Survey Bulletin issued in 2014, the soil degraded rate of forest lands in China exceeded the standard by 10.0%, of which 1.3% is under the rate of serious degradation, which is largely greater than that of cultivated land, grassland and other land types [5]. The problems of soil compaction and erosion caused by heavy machinery usage in forest production and climate change are becoming increasingly serious [6]. According to the Bulletin of Ecological Environment in 2020, the area of soil erosion has exceeded 2.7 million km² in China [7]. Forest soil degradation will not only accelerate



the loss of ecosystem diversity and the occurrence of natural disaster, but also become an obstacle to increasing forest productivity and improving climatic conditions. Therefore, it is urgent to restore the degraded forest soil considering its sustainable producing capacity.

At present, there are many managements to restore the degraded forest soil, which are mainly classified into the following three categories: physical, chemical and biological ways such as mulches, fertilization and agroforestry management, respectively. As shown in previous studies, for example, organic mulches can enhance soil fertility [8] and alleviate soil wind erosion [9]; long-term fertilization increased soil organic carbon content for sustainable woodland productivity [10] and underwood inter-planting and/or stockbreeding could provide abundant withered litter and thereby improve the soil quality [11]. However, most of these countermeasures are always time-consuming, laborious and expensive, which limit their suitable application for effectively restoring the degraded forest soil. Originating from the investigation of the black soil (*Terra Preta*) in the Amazon Basin, a pyrolysis product of biomass at high temperature, namely biochar, has attracted the attention of numerous researchers. After that, as an emerging soil additive, biochar has been extensively studied in the last two decades.

Biochar is a black solid substance derived from certain agricultural or forestry wastes, such as crop straw, wood chips, poultry manure as well as other organic substances, under a high-temperature (always $>300^{\circ}\text{C}$) and hypoxic condition [12]. Biochar is rich in carbon, hydrogen, oxygen, nitrogen, potassium, phosphorus and other essential elements for plant growth [13,14]. It always has the characteristics of porosity, small bulk density and large specific surface area, and is generally alkaline with high stability and strong adsorption capacity. Therefore, biochar has shown promising application prospects in carbon and nitrogen sequestration, edatope remediation and new-energy materials preparation in agricultural and forestry ecosystems [15,16]. In particular, forest land distributed widely with large areas in China, however, some of them face severe degradation risks, which are caused by pest diseases, pollutant accumulation and human activities [17–19]. Biochar amendment can improve soil porosity condition, neutralize soil acidity and reduce the content of heavy metals in soil [20,21], thus having a meaningful potential for improving the degraded forest soil and promoting tree growth. Presently, more works have focused on the application of biochar to restore the degraded forest soil and tree growth. Therefore, we here summarize the research advances regarding the effects of biochar on restoring the degraded forest soil and clarify the roles that biochar plays in the enhancement of tree growth as well as in the mitigation of greenhouse gas emission (Fig. 1). The study will provide references for the sustainable application of biochar in enhancing forest production.

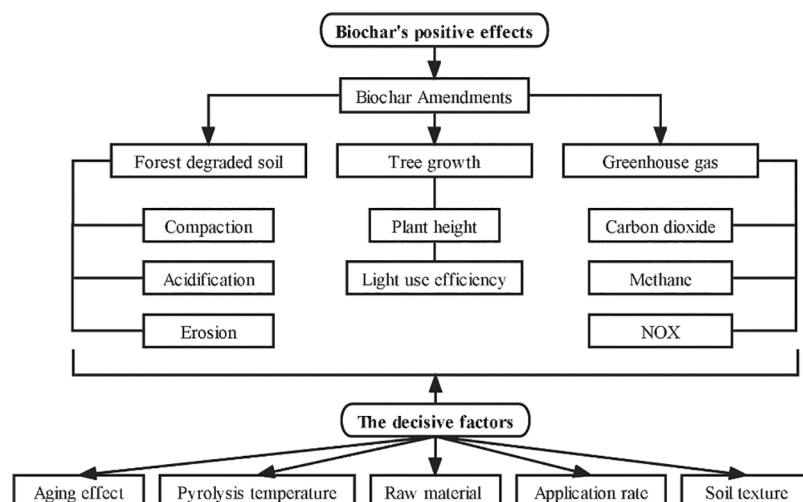


Figure 1: The effects of biochar amendment into forest soil involved in this review

2 Database and Data Selection

In order to obtain comprehensive information about the core topic of the current review, i.e., the effect of biochar on the degraded forest soil and tree growth, we used the academic journals database of China National Knowledge Infrastructure (CNKI) and the core collection database of Web of Science (WOS) for data collection. Both CNKI and WOS are internationally renowned journal citation index databases, from which we can fully and scientifically learn about the concerned information in any certain field [22,23]. This review takes “biochar”, “degraded forest soil”, and “tree growth” as the core topic. The main keywords used for search are: biochar, forest soil, trees, compaction, acidification, soil erosion and greenhouse gas emission, etc. We limited the publication time of literature from 2010 to 2021 and selected the relevant literatures. Then we made a preliminary sorting in Note Express according to the degree of relevance and the object type. The parameters that indicated the improving effects in this review included porosity, soil fertility, aggregate stability, pH, soil organic carbon, plant height, ground diameter, and greenhouse gas emission. The average values of quantifiable parameters were used for description, and the rest were described in qualitative words. Finally, based on the collected literature, how biochar impacts degraded forest soil and tree growth was reviewed and the underlying mechanisms were clarified. Meanwhile, the remaining problems and follow-up research directions were proposed (Fig. 2).

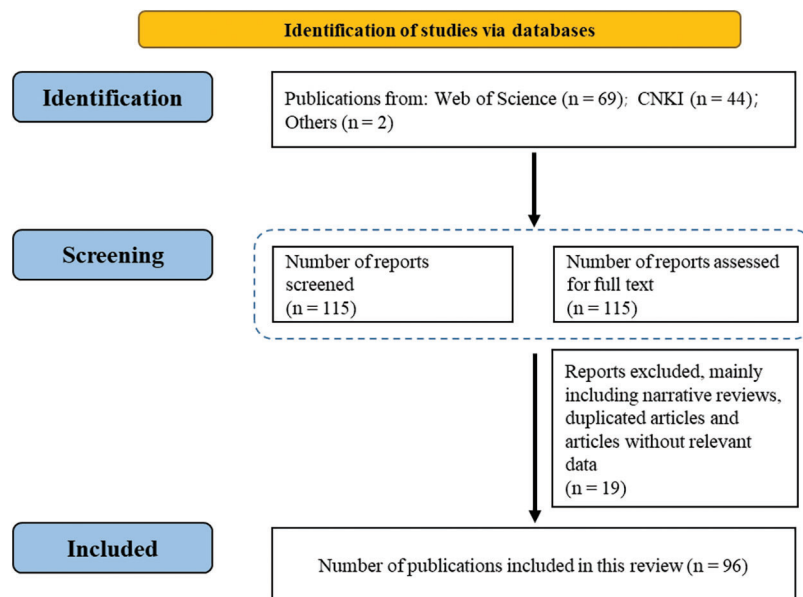


Figure 2: The flowchart showing the identification of publications from different sources

3 Results and Discussion

3.1 The Benefits of Biochar on Improving the Degraded Forest Soil

3.1.1 Alleviating the Compaction of Forest Soil

Compaction leads to an increase in soil bulk density, a decrease in porosity, and results in the constraint of aeration and water permeability, which threaten tree growth and therefore the forest ecosystem stability [24]. Biochar, with porous porosity, large specific surface area and high hydrophilicity, provides an option for alleviating soil compaction [25]. For instance, Blanco-Canqui et al. [26] summarized that biochar incorporation decreased the bulk density of 19 of 22 tested soils by 3%–31% and increased the porosity of all tested soils by 2%–41%. In addition, Meng [27] found that the soil bulk density was on average reduced by 16%, and meanwhile the capillary porosity was increased by approximately 6% after

amending wood and bamboo derived biochar into a Chinese Fir plantation soil. A similar effect was confirmed by one 10-year continuous experiment conducted by Pranagal et al. [28]. This benefit may be mainly due to the large specific surface area, and the irregular and fluffy granular structure of biochar, which consequently promoted the formation of a soil porous structure [29].

What is more, the stability of soil aggregates affects the soil structure and fertility, while compaction will retard the formation of soil aggregates [30,31]. Sun [32] found that the increases in average mass diameter and geometric average diameter of biochar-added soil contributed to the enhancement of the stability of soil aggregates, which effect was also confirmed by a 3-year study on a long-term scale [33]. In brief, biochar has an important application value to improve the compact condition of forest soil in both short-and long-term scales.

3.1.2 Alleviating the Acidification and Aluminum Toxicity of Forest Soil

The acidification and aluminum toxicity of forest soil caused by anthropogenic and natural factors such as excessive chemical fertilizer application and atmospheric deposition have given rise to the decline in forest productivity [34,35]. The alkaline and buffering properties of biochar allowed it to be an effective additive to restore acidified and/or aluminum-toxic soils [36–38]. The acidification of the tea garden soil led to a dramatic decrease in tea production and its damage to the environment could not be underestimated as well [39]. Li et al. demonstrated that biochar pyrolyzed at 350°C–550°C improved the acidity of tea garden soils via decreasing the soil exchangeable acid and aluminum content but increasing the amount of base cations and base saturation degree [40]. In addition, a significant ($P < 0.05$) increase in soil pH value by 0.77–1.16 units was found following the biochar addition [40]. These changes are consistent with the results in previous studies that were also conducted in acidified tea garden and other acidic soils following biochar amendment [39,41–43]. Besides, the soil pH of the acidified eucalyptus plantation increased by 0.17–1.29 units after applying eucalyptus branch biochar (anaerobic pyrolysis under 500°C) [44]. The pH values of the *Phyllostachys praecox* stand, the rubber plantation and the nitrogen-applied bamboo forest soils also significantly ($P < 0.05$) increased after biochar addition [45–47]. These data suggest that biochar can immediately increase the pH value of different types of acidified forest soils. Given the sustainability of forest soil management, the long-term effect of biochar on relieving the soil acidic process needs to be further studied.

3.1.3 Restoring the Highly Erosive Forest Soil

Soil erosion dramatically reduces soil fertility, silts up downstream reservoirs, and deteriorates the ecological environment, which has severely hindered economic and social development [48]. Soil organic matter (SOM) content is one of the important indicators of soil fertility, which can be increased by biochar application [49]. Biochar can effectively restore soil fertility and support the land productivity via increased SOM content [50,51]. Consistently, previous studies have confirmed that biochar can increase SOM content by 0.30–0.36 g/kg soil [52], and can increase the alkaline hydrolysis of nitrogen and available potassium content in a long-term [53,54]. Interestingly, biochar can also enhance the resistance capacity of soils to heavy rain erosion [55,56]. For instance, Liu [57] reported that biochar application at a high rate (16 g/kg soil or more) can effectively promote the formation of water-stable aggregates and enhance soil anti-erodibility, reflected by reducing the amount of soil erosion in a rainfall event. However, biochar exerted a negative effect on soil erosion in some cases, which might be related to the plant cultivation time, biochar application rate and soil particle size [58,59].

Biochar could change the soil erosion resistance capacity, but generally improve the soil acidity, bulk density and other key physio-chemical properties [53,57,60,61], most of which are favorable for degraded forest soils. Nevertheless, more researches should be carried out to evaluate the improvement effect of biochar with varied application dosages in a long-term, and to clarify the underlying mechanisms

involved meanwhile. Therefore, it is undoubtedly worth looking forward to using biochar as an effective additive to restore the degraded forest soil.

3.2 Biochar's Effect on Tree Growth

3.2.1 Effect of Biochar on Tree Growth

Biochar is widely used as a soil additive to increase stable crop yield in recent years [62–64]. Meanwhile, some forestry workers have applied biochar to forest soil to evaluate the biochar's effect on productivity of woodland. For example, applying wheat straw biochar into Chinese *Torreya* stand for half a year increased the soil nutrient contents and therefore enhanced the fresh weight of nuts by more than 15% on average [65]. Meanwhile, Wu et al. [66] applied biochar into a *Pistacia chinensis* plantation for one year and found that the plant height, ground diameter and crown width of *Pistacia chinensis* significantly ($P < 0.05$) increased by over 20% compared with the control. Moreover, biochar could increase the light and water use efficiencies of tree, and thereby enhanced tree's stress resistance and biomass [66–68]. For *Acer rubrum*, biochar also exerted positive benefits on the pigment content, leaf color and the final economic value [69]. Biomasses of conifer and broad-leaved trees were increased following biochar amendment [70,71], owed to the improved physical properties, increased nutrient contents, and enhanced photosynthesis and gas exchange capacity [72,73].

In contrast, some studies have found that biochar alone application may inhibit the growth of tree seedlings. This is because the biochar's restrictions on the nitrogen use efficiency of nursery-grown plants, which effect could be reversed by the co-application of biochar and a compound fertilizer [74,75]. Also, in some marginal soil environments, conifers only show an unobvious response to biochar because of the resource-conservative growth strategies [76]. In summary, biochar generally plays a positive role but may lead to inhibitory effects in some cases, which effects are as function of biochar type, application dosage and tree varieties [54,69].

3.2.2 How Biochar Affect Tree Growth

Generally, there are two mechanisms explaining how biochar affects plant growth [77]. Firstly, as a source of nutrients, biochar can directly communicate with the tree roots [78,79]. Biochar is always rich in nitrogen and phosphorus nutrients. Therefore, tree roots will be attracted (known as chemotropism) and more distributed between the bulk and rhizosphere soil after biochar addition. This effect makes the branch and spatial structure of tree roots more rational, thereby enhancing the absorption capacity of tree roots on soil nutrients [50,54]. Secondly, soil nutrient contents and forms as well as other physio-chemical properties would be changed following biochar amendment, which indirectly influences the tree growth [80,81]. For instance, Pan et al. found that biochar decreased soil bulk density but increased fertility, which made the nutrients more available to tree roots [74]. What's more, the rhizosphere microbial abundance and their function can also be affected by biochar [74,82]. Biochar addition not only increased the content of dissolved organic carbon [83,84] but also provided habitats for microorganisms [85], thereby promoting the tree absorption ability for soil moisture and nutrients [86]. In addition, biochar could mitigate the reactive nitrogen losses via leaching [87], nitrification and denitrification [88,89], and accordingly enhance the nitrogen use efficiency of tree.

3.3 Biochar's Effect on Greenhouse Gas Emission from Forest Soil

The forest ecosystem is an important sink or source of greenhouse gases (such as CO₂, CH₄, and NO_x) in the atmosphere. Biochar application affects the physio-chemical properties and biochemical processes of forest soils, thereby directly or indirectly affecting the generation of greenhouse gases. However, the effects of biochar incorporation on greenhouse gas emissions from forest soils were not consistent, which was dependent with the biochar and soil types and their physio-chemical characteristics, as well as the vegetation type. One research with poplar plantation in the coastal area of Dongtai, China, showed that

biochar treatment with 80–120 t/ha resulted in a significant ($P < 0.05$) increase in the average annual CO₂ emission load by more than 20%, while it inhibited the emissions of CH₄ and N₂O from the saline soil [90]. For a pine forest soil, biochar application not only mitigated the N₂O and CO₂ emissions, but also significantly ($P < 0.05$) suppressed the CO₂ emission by 31.5% [91]. However, the CO₂ efflux was overall unaffected by biochar in a recent report [92]. In addition, the effect of chicken manure biochar on CH₄ emission from a forest soil in Dinghushan Nature Reserve, China, was the combined results of biochar and soil moisture [93]. Of which, biochar played a role in reducing CH₄ emission at low soil moisture content. However, it would reversely promote the transformation of soil CH₄ from sink to source at increasing soil moisture. It can be seen that the effect of biochar on greenhouse gas emissions from forestland soils is variable, depending on three principal factors including the biochar type, soil property and vegetation type [81,90].

3.4 Factors Deciding the Effects of Biochar

3.4.1 The Raw Material and Pyrolysis Temperature of Biochar

Raw material and pyrolysis temperature decide the physical and chemical properties such as specific surface area, pore structure, stability and element composition of biochar [94], which may affect its effects on improving the degraded forest soil and tree growth. For instance, biochar derived from Chinese Fir (*Cunninghamia lanceolata*) sawdust had a greater impact on the community structure of the understory vegetation of a Chinese Fir plantation than the biochar derived from rice straw, which was indicated by the higher diversity index after sawdust biochar application [95]. Increases in pyrolysis temperature would lead to losses of aliphatic and oxygen-containing functional groups but produce more aromatic structures of biochar [96]. Consequently, biochar that pyrolyzed at high or low temperature was more suitable for adsorbing and immobilizing the organic or ionic pollutants in soils, respectively [96]. Therefore, raw material and pyrolysis temperature are the two major factors that decide the effects of biochar.

3.4.2 The Biochar Application Rate

Both soil fertility and structure could be improved following the biochar application [37]. The application rate decides the biochar's effect in what degree and even in adverse direction. Lu et al. [97] added bamboo leaf biochar at four rates to chestnut forest soil and found that the inhibiting effect of biochar on soil N₂O emission was increased with the application rate. This effect was confirmed by a study conducted under a poplar plantation ecosystem [90]. Nevertheless, there was also a work reporting that the N₂O emission was increased when biochar was overused [98]. Biochar application rate also affect the growth vigor and survival rate of tree seedlings [99]. For example, application of biochar at a medium rate (600 kg/ha) could improve the survival rate of transplanting and the growth of camphor seedlings in a dryland red soil in Southern China, which was attributed to the increased soil nutrients following biochar application. Nevertheless, camphor seedlings are habituated to slightly acidic soil, but the high amount of biochar addition just increases the soil alkalinity, which conversely inhibited the plant seedlings' growth [99]. Meanwhile, it is necessary to explore the underlying mechanisms regarding how biochar affects tree plant, in particular when it is amended at various rates.

3.4.3 The Aging Effect of Biochar

The process of alterations of the physicochemical properties of biochar exposed to the combined effects of soil organisms and soil environment is called biochar aging [100,101]. Aged biochar is different in its physicochemical properties from those of fresh biochar, which may either enhance or weaken the improvement effect of biochar after being amended to forest soils [102–104]. After three freeze-thaw cycles under natural conditions, the surface of aged biochar was partially broken and covered with more oxygen-containing functional groups, providing more Cd adsorption sites [105]. Pei et al. [106] found that eucalyptus biochar aged with 15% hydrogen peroxide increased the microbial carbon use efficiency

and thereby benefitted the soil carbon sequestration, which might be the results of the changes in soil pH and the composition of fungal-bacterial communities [107,108]. However, some studies revealed that the improvement effect of biochar was weakened during its aged process [109–111]. For instance, both manure and sawdust biochar aged with dry-wet and freeze-thaw cycles had an increase in acidity, which is not conducive to Cd immobilization [109]. The pH of naturally aged biochar might also be decreased, and its effect on soil acidity was weakened with decreasing carbonate content, soluble and exchangeable alkaline cations [110,111]. Therefore, the effects of aged biochar exposed to different environments showed great uncertainties, which need more long-term investigations to have a comprehensive understanding of the aging effect of biochar.

3.4.4 Texture of the Tested Soil

According to the Chinese Soil Classification Standard, soil texture can be divided into sandy, loam and clay [112]. Soils with different textures and water holding capacity distinctly decided the functions of biochar after it was incorporated into forest soils [113,114]. Tian et al. [115] added straw and peanut shell derived biochar into silt loam and sandy soils and measured the changes of hydraulic characteristics. They found that sandy soil with more grit had a decreased bulk density and increased porosity and improved water holding capacity, but this effect did not occur in silt loam soil [115]. Dugan et al. [116] also reported similar finding in the comparative experiments with silt loam, sandy loam and sandy soils. What is more, Li et al. [117] demonstrated that biochar showed different effects on nitrate transport in soils with different textures in China, i.e., biochar decreased the nitrate leaching loads from coarse loess and aeolian sandy soils, but increased the nitrate leaching loads from Lou soil. The transference of soil solutes is affected by soil pore conditions, in particular the soil macro pores, which might be reduced as result of biochar addition. This change had adverse effect on the fixation of available nitrogen according to previous works [118,119].

Therefore, biochar has been widely used as a potential amendment used for forest production, degraded forest soil improvement, tree growth enhancement and greenhouse gas mitigation, which main details are presented in Table 1.

Table 1: Effect of biochar on forest soil properties, plant growth and greenhouse gas emission

No.	Object/ Property	Effects	Soil type/Vegetarian type	Biochar type	Biochar application rate	Mechanism	References
1	Bulk density	Decreased	Chinese fir plantation soil	Chinese fir (400°C)	12.5 g charcoal/kg soil	Low density, high porosity, large surface area of biochar and irregular and fluffy granular structure.	[27]
			Podzol originating from glaciofluvial finegrained loamy sand	Winter wheat straw (650°C)	10 Mg $\times \text{ha}^{-1}$ 20 Mg $\times \text{ha}^{-1}$ 30 Mg $\times \text{ha}^{-1}$		[28]
			Ultisols from Tertiary red sandstone, Quaternary red earth and granite and an oxisol form basalt	Corn straw (400°C)	72 t/ha 120 t/ha		The abundant carboxyl groups on the biochar surface. The biochar incorporation decreases the Al pool. The release of ashing alkali in biochar and the mineralization of organic nitrogen.
Tea garden soil	Wheat straw (550°C)	45 t/ha 90 t/ha	[40]				
Tea garden soil	Wheat straw (600°C)	18 t/ha 54 t/ha 108 t/ha	[41]				

(Continued)

Table 1 (continued)

No.	Object/ Property	Effects	Soil type/Vegetarian type	Biochar type	Biochar application rate	Mechanism	References
3	CH ₄ emission	Decreased	Loam paddy soil, loam forest soil	Chicken manure (540°C)	10% w/w	The enhanced CH ₄ oxidation activity of methanotrophs in soils.	[93]
4	N ₂ O emission	Decreased	Poplar plantation soil	Wood charcoal (600°C)	40 t/ha 80 t/ha	Biochar absorbs and immobilizes ammonium and nitrate nitrogen. Biochar decreases soil enzyme activity.	[90]
			Soils from <i>Pinus massoniana</i> Lamb. forest	Wheat straw (450°C)	30 t/ha	Biochar can facilitate the activity of soil-denitrifying microorganisms.	[91]
5	Soil organic matter	Increased	Calcareous soil	Rice Husk (500°C)	1% w/w 2% w/w 4% w/w	Improved soil structure and moisture condition; Biochar's porous structure and adsorption capacity.	[50]
6	Surface runoff	Decreased	Yellow cinnamon soil	Rice straw (500°C)	20 t/ha	Enhanced soil water retention, infiltration and physical properties against crusting.	[51]
7	Rill erosion	Decreased	black soil in sloped farmland	Corn straw (500°C)	6 kg/m ² 12 kg/m ²	The increase of the coulomb force and van der Waals force between soil particles results in stable soil aggregates.	[55]
8	Soil loss	Decreased	Silt loam	Apple branches (550°C)	1% w/w 3% w/w	Enhanced vertical movement of water and infiltration; Increased content and stability of soil aggregates.	[56]
		Increased			7% w/w	Higher biochar application rate leads to increased water repellency.	
9	Crop yield	Increased	Paddy soil	Wheat straw (550°C)	10 t/ha 40 t/ha	Biochar can increase N availability to crops; Improved soil physical and biochemical properties.	[64]
10	Microbial abundance	Increased	Sandy loam	Wheat straw (600°C)	5% w/w	Biochar increases the amount of dissolved organic carbon and provided habitats for microorganisms.	[83]
			Sandy-silt soil	Birch wood (475°C)	20 g/L 80 g/L		[84]

(Continued)

Table 1 (continued)								
No.	Object/Property	Effects	Soil type/Vegetarian type	Biochar type	Biochar application rate	Mechanism	References	
11	Tree growth	Increased	<i>C. lanceolata</i> plantation, mountain acidic red loam soil Hardwood forest	Woodchips and leaves (600°C)	1% w/w 3% w/w	Biochar as a source of nutrients. Improved soil nutrient contents and physio-chemical properties.	[78]	
				Maple and spruce sawdust (450°C)	5 t/ha		[79]	
				Rice husk biochar (unknown)	2% w/w 4% w/w 6% w/w		[80]	
		Decreased	Latosol Sandy loam	Rubber wood biochar (500°C)	2.5% w/w 5% w/w	Biochar application inhibits the nitrogen use efficiency of trees.	[74]	
					Mixed Wood (700°C)		20 t/ha 30 t/ha 40 t/ha	[75]

4 Conclusion

Both agricultural and forest wastes can be pyrolyzed into biochar as an additive applied into the degraded forest soil. In brief, biochar exerted the benefits as follows: 1) improving the physicochemical properties, in particular the chemical characteristics; 2) mitigating the greenhouse gas emissions in most cases; 3) enhancing the nutrient use efficiency and therefore the tree growth. These effects are a function of the raw material, pyrolysis temperature, application rate and the aging process of the biochar after application, as well as the soil and plantation types.

Meanwhile, more attentions should be paid to study the interaction effects between specific soil and tree and biochar as well as the underlying mechanisms, especially in a long-term. What is more, how biochar influences the forest soil animal needs urgent investigation.

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