

## Review Article

### A review on ~~biochar-based~~biochar-based restoration of degraded soils through effective preparation and application

#### Abstract

Soil degradation refers to the decline in the land productive capacity due to both natural and anthropogenic factors. ~~Its -M~~major causes include soil erosion, waterlogging, acidification, salinization, flooding, and unsustainable human activities, all of which negatively impact soil health over time. Improving soil health in a sustainable manner is essential for restoring vegetation cover and enhancing agricultural productivity, which in turn supports socio-economic development. One effective approach to rehabilitating degraded soils is the use of soil amendments. Soil amendments are substances added to improve soil nutrient content, organic matter, and mineral balance to promote healthy plant growth. Biochar, a carbon-rich soil amendment produced through pyrolysis of organic materials, has been widely recognized for its ability to enhance the physico-chemical properties and long-term fertility of soil. This paper reviews properties of biochar, its preparation, feedstock, temperature for pyrolysis, particle size, and application rate of biochar on degraded soils for reversing soil deterioration. ~~The best choice for producing economical biochar is to use the cheapest raw material that is easily accessible locally and slow pyrolysis between 250°C and 500°C as opposed to fast pyrolysis. Small or nanoparticle-sized biochar is always more effective than pure, unground biochar.~~ Although there have been no recorded detrimental effects from applying a higher amount of biochar, the expense of application may increase.

Keywords: Biochar properties; Pyrolysis temperature; Particle size of biochar; Application rate; Soil degradation.

#### 1. Introduction

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Human-induced land degradation poses a more serious and widespread threat to soil health and ecosystem stability than natural degradation processes. Activities such as the use of heavy machinery on sloped terrains, widespread deforestation, overgrazing, and inappropriate agricultural practices including mono-cropping, over-tillage, and inadequate crop rotation are major anthropogenic factors contributing to the rapid deterioration of soil quality. The excessive and unbalanced application of chemical fertilizers and pesticides further disrupts the natural nutrient cycles, microbial balance, and structure of soil, leading to long-term fertility loss. In hilly regions, mechanical disturbances accelerate soil erosion and slope instability, exacerbating degradation risks.

Socio-economic factors, particularly poverty and rapid population growth, also play a significant role in intensifying land degradation. In low-income areas, resource limitations often force communities to exploit land unsustainably, while rising population pressure leads to land fragmentation, reduced fallow periods, and conversion of marginal lands for cultivation. These direct and indirect drivers create a cycle of declining land productivity, reduced agricultural income, and increased vulnerability to food insecurity and climate impacts (Bhattacharyya et al., 2015). Addressing human-induced degradation, therefore, requires integrated land management strategies that consider both environmental and socio-economic dimensions.

Agricultural lands are experiencing significant degradation in soil quality due to the extensive use of various organic and inorganic contaminants by human activities. Additionally, improper land use practices adversely affect soil pore size distribution and water retention capacity (Dlapa et al., 2020; Tamta et al., 2023). Soil erosion, driven by extreme precipitation events and anthropogenic pressures, remains a critical concern (Kushwaha and Kumar, 2016; Kushwaha and Kumar, 2017a, 2017b, 2017c). Climate change has led to increasing variability in precipitation duration, intensity, and seasonal patterns, and these factors significantly influence the extent of soil erosion (Luffman and Nandi, 2020; Navale et al., 2018). Moreover, altered rainfall patterns have also contributed to the processes of soil acidification and salinization. Therefore, the adoption of integrated and sustainable land management practices is strongly recommended to mitigate soil degradation and preserve soil health (Kushwaha and Kumar, 2023; Singh et al., 2020; Zama et al., 2018).

Based on decades' worth of research, it was suggested that biochar is an eco-friendly solution to reclaim contaminated soil improve its physico-chemical properties and reduce soil erosion (Kushwaha and Kumar, 2021; Singh et al., 2023; Zama et al., 2018). Biochar is regarded as a good soil amendment as a part of ex-situ residue management. If rubbed against the skin, it does not feel greasy and does not require soap to wash it off like charcoal. Well-made biochar is lighter in weight and contain less BTUs per volume than the charcoal. It contains most of the carbon and nutrients present in the original biomass with high surface area, CEC and porosity.

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Biochar has emerged as a multi-functional soil amendment with the potential to significantly enhance soil health and restore degraded lands. When applied to soil, biochar contributes to the improvement of soil aggregate stability, enhances moisture retention capacity, facilitates carbon sequestration, adsorbs pesticide residues and heavy metals, and supports the breakdown and availability of essential nutrients such as phosphorus and potassium. Additionally, biochar exhibits antimicrobial properties that can suppress soil-borne pathogens, thereby promoting a healthier rhizosphere environment. The stable carbon structure of biochar makes it particularly effective in long-term reclamation of deteriorated soils, contributing to both soil quality enhancement and climate change mitigation through carbon storage.

Biochar is intentionally produced for soil application through pyrolysis which is a thermo-chemical decomposition of organic biomass under limited oxygen conditions. Its properties, and therefore its effectiveness, are largely influenced by the type of feedstock (e.g., agricultural waste, forestry residues, or manure) and key pyrolysis parameters such as temperature, heating rate, and duration (Chan et al., 2007; Kuoppamaki et al., 2016). Higher pyrolysis temperatures generally result in biochars with greater surface area and stability, which improve nutrient retention and microbial activity in the soil. Furthermore, the particle size and application rate of biochar play crucial roles in determining its impact on soil structure, nutrient dynamics, and water holding capacity (Chen et al., 2020).

This review focuses on the critical aspects of biochar use for soil restoration, including its physical and chemical properties, feedstock selection, pyrolysis temperature conditions, particle size distribution, and optimal application rates. Emphasis is placed on how these factors interact

to maximize the effectiveness of biochar in reclaiming degraded soils and improving long-term soil productivity.

## 2. Properties of biochar in the soil

### 2.1 Physical properties of biochar

The physical properties of biochar play a crucial role in influencing the physical environment of soil when incorporated into the soil matrix. Soils possess distinct physical characteristics such as bulk density, porosity, specific gravity, structure, liquid and plastic limits, hydraulic conductivity, and moisture content. Upon application, biochar undergoes gradual decomposition and modifies these properties by enhancing porosity, moisture retention, hydraulic conductivity, infiltration rate, and the liquid and plastic limits, while reducing surface runoff and mitigating soil acidity (Hammes and Schmidt, 2009). Furthermore, biochar alters soil texture and structure by modifying surface area, pore distribution, particle size, and particle packing (Blanco-Canqui, 2017). These changes not only improve water availability to plants but also promote root proliferation and crop productivity. By enhancing soil moisture retention, biochar reduces the risk of drought stress, particularly in drought-prone regions.

### 2.2 Chemical properties of biochar

Since biochar is basic in nature, it helps to raise the pH of acidic soil and neutralise it (Luthra et al., 2024). This characteristic of biochar is known as the liming effect. By preserving nutrients and fertilisers in the soil, biochar also aids in soil retention (Lehmann et al., 2006). Due to its high carbon content, biochar enhances the soil ability to retain nutrients and improves the availability of essential elements such as nitrogen, phosphorus, and potassium. Additionally, it helps the soil access micronutrients like calcium, magnesium, and others. The ability of biochar to collect nutrients from the soil and release them gradually enables plants to get nutrients throughout their whole growth cycle (Ajema, 2018; DeLuca et al., 2015; Liang et al., 2006). Because of less releasing of nutrients, it reduces the non-point source pollution from the agricultural lands, which is a major problem of pollution in water bodies (Cao et al., 2018).

Biochar also helps the farmers not to use heavy fertilizers and pesticides in the fields and provides a healthier environment into the soil. Subsequently, ability of biochar provides habitat

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to the life forms micro-organisms such as helpful bacteria, fungi, protozoa, nematodes, arthropods, and earthworms and increase soil biodiversity (Slapakova et al., 2018). Biochar also makes availability of micro-nutrients in the soil by increasing air and water movement. Biochar is a heterogeneous substance, fine-grained and a form of charcoal. It is mainly made up of elements such as carbon, hydrogen, sulfur, oxygen, nitrogen and minerals in the ash fraction.

Basic physico-chemical properties of biochar obtained from rice husk and rice straw biomass is given in Table 1. Literatures stated that slow pyrolysis of rice husk in proximate analysis gives moisture content 3.88% to 3.90%, volatile content 17.27% to 17.30%, ash content 23.45% to 23.50%, fixed carbon 55.40 %. Slow pyrolysis of rice straw in proximate analysis gives moisture content near to 3.80%, volatile content 18.50% to 20.90%, ash content 22.45% to 38.80%, and fixed carbon near to 55.6 %. Total carbon content is high as 67.20% to 67.50% for both rice husk and rice straw. Biochar yield from the feed stock was observed in the range of 38.23% to 43.32% for both rice husk and rice straw. Biochar pH, EC, bulk density, particle density, porosity and cation exchange capacity (CEC) showed huge variations in their values for both rice husk and rice straw. Organic carbon was found in good percent (48.12%) for rice husk in comparison to rice straw (2.93%)

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**Table 1** Basic physico-chemical properties of biochar produced from different feedstocks

S. No.	Property	Peng et al. (2016)	Li et al. (2017)	S. V. Singh et al. (2020)	S. V. Singh et al. (2020)	Kushwaha et al. (2021)
1.	Feedstock	Rice straw	Rice straw	Rice husk	Rice straw	Rice husk
2.	Pyrolysis temperature (°C)	400	500	450	450	450
3.	Proximate analysis					
(i)	Moisture content (%)	-	-	3.90	3.80	3.88
(ii)	Volatile content (%)	20.90	-	17.30	18.50	17.27
(iii)	Ash content (%)	38.80	-	23.50	22.00	23.45
(iv)	Fixed carbon (%)	-	-	55.40	55.60	55.40
4.	Ultimate analysis (i)					
(i)	Carbon (%)	-	-	67.50	67.20	67.49

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(ii)	Oxygen (%)	-		7.90	9.10	30.44
(iii)	Nitrogen (%)	1.26	1.83	0.71	0.64	0.71
(iv)	Hydrogen (%)	-	-	1.30	1.70	1.31
(v)	Sulphur (%)	-	-	0.04	0.14	0.03
5.	Particle size (mm)	34.4%	0.25	< 1	< 1	60% ≤ 0.425
6.	Biochar yield (%)	-	-	43.32	38.23	40.49
7.	pH	-	9.50	6.50	8.10	9.03
8.	EC (µS/cm)	-	336	590	680	156
9.	Bulk density (g/cm <sup>3</sup> )	-	-	-	-	0.30
10.	Particle density (g/cm <sup>3</sup> )	-	-	-	-	1.70
11.	Porosity (%)	-	-	-	-	82.57
12.	CEC (cmol (p+)/kg)	-	64.8	27.1	25.8	26.2
13.	Organic carbon (%)	-	2.93	-	-	48.12

### 2.3 Biological properties of biochar

The source of biochar is biological. Rondon et al. (2007) reported that biochar increases biological nitrogen fixation and helps the plants for better growth in comparison to a biochar-free soil. Biochar increases the plant height and biomass production and subsequently increases agricultural productivity. In some cases it was also observed that addition of biochar reduces the growth of vegetation (Mikan and Abrams, 1995). Application rate, pyrolysis temperature, type of feedstock and other factors are also responsible for changing biochar ability.

## 3. Preparation of biochar

### 3.1 Biochar production unit

There are four types of production units namely kiln, stove, pyrolysis oven and industrial sized unit. Kilns are made up of dirt, bricks and sometimes steel. Preparing biochar in the kiln is economical and with this unit all small/marginal farmer could produce biochar in their own fields (Mandal, 2018). Pyrolysis oven is used for large amount of biochar production. Small stoves are also useful for producing small quantities of biochar and being used in many countries. To achieve ecologically safe production using a sustainable feedstock in industrial biomass

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production systems, due care must be taken. Biomass residence time increases with biomass size in the pyrolysis reactor. It is important and necessary to develop a low cost biochar production system, so that small and marginal farmers could get the benefit of biochar amendment in their fields.

### **3.2 Processing pyrolysis temperature of biochar**

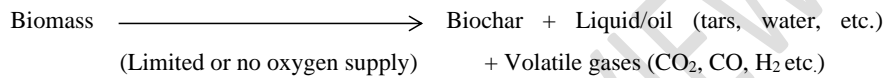
Pyrolysis refers to as breakdown of large molecules of a substance into smaller molecules in the presence of heat without combustion or burning. It depends on the temperature and duration of heating. Selection of pyrolysis temperature is very crucial to produce good quality biochar. Many studies reported the selection of pyrolysis temperature for biochar heating, depending on which type and how much of feedstock is being handed during pyrolysis. In his manner, two types of pyrolysis are generally preferred one is slow pyrolysis and another one is fast pyrolysis. Fast pyrolysis is performed at high temperatures of more than 500°C and duration of heating in seconds with heating rate more than 1000°C/min. It causes smaller pore size of the biochar and more bio-oil and gas components (Nartey and Zhao, 2014).

On the other hand, slow pyrolysis typically requires longer time (30 minutes to several hours) before the feedstock is entirely pyrolyzed. Temperatures in slow pyrolysis vary from 250°C to 500°C, and the heating rate is less than or equivalent to 100°C/min (Brown et al., 2011). According to a report, slow pyrolysis produces more charcoal than fast pyrolysis (Antal and Gronli, 2003; Dutta, 2010; Peng et al., 2011; Stoye, 2011). These factors make slow pyrolysis the favoured method (Joseph et al., 2010; Kushwaha et al., 2021; Li et al., 2017; Peng et al., 2016; S. V. Singh et al., 2020). With an increase in pyrolysis temperature, the total carbon content, ash content, pH, CEC, surface area, and pore volumes all rise (Elnour et al., 2019). Biomass is put through a thermo-chemical conversion process at an appropriate pyrolysis temperature in an atmosphere with little to no oxygen supply to create biochar. The two chemicals cellulose and lignin, which are comprised of carbon, hydrogen, and oxygen, make up the majority of biomass. These substances combine with oxygen during the burning of biomass to produce carbon dioxide and water as well as smoke, ash, and other gases. Fire does not receive enough oxygen for burning during the pyrolysis phase.

The cellulose and lignin are broken down as opposed to burning. Carbon atoms are left

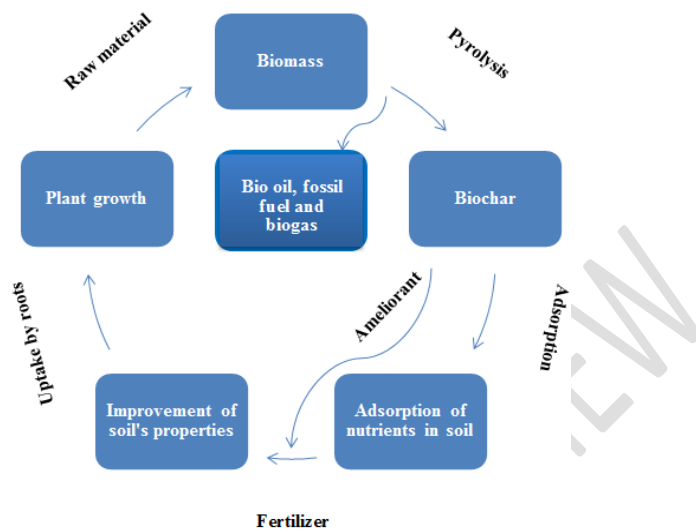
behind as the water molecules are formed by hydrogen and oxygen atoms and biochar is the carbon that remains. In industrial biochar pyrolysis systems, a sizable amount of the residue is put to use for biogas, bio oil, and other uses besides making biochar. In Fig. 1, a typical cyclic process of biochar preparation and subsequently biomass creation is shown. Biomass would be used again as a feedstock to prepare biochar for next crop. Chemical reaction, mass balance and energy balance in the biochar preparation is given below:

Pyrolysis



$$\text{Mass of feedstock} - \text{Mass of biochar} = \text{Mass of (pyro-gases} + \text{Bulk liquid substances)}$$

$$\begin{aligned} \text{Energy in biomass} + \text{Electrical energy to run the blower} - \text{Energy in biochar} \\ = \text{Energy for drying bulk liquid substances} \\ + \text{Energy in exhaust gases} \\ + \text{Energy lost from the kiln} \end{aligned}$$



**Fig. 1** Cyclic process of biochar and biomass production (Singh et al., 2023)

Zhao et al. (2017) investigated the composition and characteristics of biochar generated from apple tree branches at four different pyrolysis temperatures, namely 300, 400, 500, and 600 °C. According to Zhao et al. (2017), pyrolysis temperature significantly affects the characteristics of biochar. The findings demonstrated that while yield and cation exchange capacity decreased, the concentration of fixed carbon and inorganic minerals such as potassium, phosphorus, iron, zinc, calcium, and magnesium increased with increasing temperature. Additionally, it was discovered that pH and ash concentration peaked at 500 °C pyrolysis temperature. Additionally, it was discovered that thermal stability increased as pyrolysis temperature goes up. According to Zhao et al. (2017), the production of biochar that can withstand the specific type of soil and land use conditions for improved crop development may be aided by an appropriate pyrolysis temperature. Elnour et al. (2019) investigated how different pyrolysis temperatures affected the physico-chemical properties and microstructural evolution of biochar. To study the behaviour of the biochar, pyrolysis temperatures were fixed to five ranges of 300, 400, 500, 600, and 700 °C. According to Elnour et al. (2019), pyrolysis temperature has a significant impact on how biochar is formed from any biomass and how it alters the microstructure of the material.

S. V. Singh et al. (2020) studied the effect of pyrolysis temperatures on biochar behavior on physico-chemical properties of soil and sorption/desorption pattern of bio-urea. Two types of biochar were used namely rice straw based biochar and rice husk based biochar. Three pyrolysis temperatures namely 300, 450 and 600 °C were selected for this purpose. S. V. Singh et al. (2020) observed that pyrolysis temperature reduced the biochar yield but increased its carbon content, pH and EC values. The maximum value of urea adsorption was reported at the pyrolysis temperature of 450 °C, of more than 90% sorption in both rice straw and husk biochar according to S. V. Singh et al, (2020). Crop yield and nitrogen use efficiency were observed promising in rice residue based bio-urea composites.

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### 3.3 Feedstock and its effect on biochar properties

The waste that is readily available locally, such as manure, wood debris, bamboo pieces, construction waste, slash from forest thinning, food processing waste, residue from methane digesters, urban tree trimming waste, grasses, rice husk, wheat straw, sugarcane straw, maize straw, and other agricultural residues and grasses, are the most sustainable feedstock for the production of biochar (Kiran et al., 2017; Ronsse et al., 2013). Air-dried dairy effluent sludge was used to create biochar, according to Sadeghi et al. (2018). Using this biochar, severely deteriorated soil is recovered. To evaluate the behaviour of the produced biochar, carbon, nitrogen, organic matter, and carbon/nitrogen ratio are determined. Different doses of biochar were applied to check produced biochar behavior in degraded soil. The results showed that biochar was having multi-objective and eco-friendly behavior to maintain soil environment and improve soil quality. Liu et al. (2018) used biochar to study the cadmium accumulation in leafy vegetable cultivars. They used two types of feedstock to prepare the biochar, one was bamboo and another one was rice straw. They applied these amendments in an artificially created contaminated soil plots to study the decreasing rate of cadmium. Results demonstrated that rice straw based biochar was more effective in reducing the availability of cadmium in comparison to bamboo based biochar.

The behaviour of soil characteristics and cowpea yield in response to three distinct feedstocks namely baby corn peel, mango tree branches, and rice husk biochar was examined by Rafael et al. (2019). In acidic sandy soil, all the charcoal was applied in combination with NPK

fertiliser. In the treatments using biochar made from baby corn peel and mango tree branches, the pH of the soil increased. Additionally, this amendment permits the field to use the recommended amounts of NPK fertiliser without endangering the soil or plant growth. An effective increment in the cowpea yield was also obtained using biochar.

### 3.4 Effect of small-sized biochar particle

Huge application rate of biochar ~~is making this amendment~~ makes it less demanding for maintaining soil properties. To resolve such problem, small size or nano-sized biochar for reclaiming degraded soil could be a better option. Nano-size biochar effectively reduced the runoff rate, soil erosion and nutrients losses from sloping surface (Chen et al., 2020). Nano-biochar helped the nitrate to move towards the deep profile of soil due to which nitrogen loss through runoff water reduced up to great extent. Li et al. (2019) used three different types of biochar, with particle sizes namely < 0.25, 1 to 0.25 and 1 to 2 mm, and found that the smallest biochar particles were more efficient at reducing soil erosion and runoff as well as increasing the amount of water-stabilized soil aggregate and saturated hydraulic conductivity.

Kushwaha et al. (2021) found that big size biochar is less reactive with soil than the small/fine sized biochar particles. Due to this reason, the biochar particles were ground manually in the form of thin powder and it was ensured that while hand grinding, at least 60% of the biochar particles should be smaller than 0.425 mm. Peng et al. (2016) used biochar of various sizes, and the majority of it 34.4% was in the range of 0.5-2 mm size. Biochar with particle sizes of 0.25 mm and 1 mm were utilised by Li et al. (2017) and S. V. Singh et al. (2020), respectively, to promote healthy vegetation and reclaim degraded soil (Table 1).

### 4. Application rate of biochar

Biochar is lighter than other soil additives, because of that it is applied at a higher rate, but its impact on the soil lasts for a long time and does not require yearly application. Chen et al. (2020) used total five doses of nano-biochar namely 0%, 0.1%, 0.5%, 0.7% and 1.0% and observed that efficacy of biochar increases with the application rate. Gholami et al. (2019) investigated three different biochar concentrations, namely 0.4, 0.8, and 1.6 t ha<sup>-1</sup>, and discovered that runoff and soil erosion decreased as the biochar concentration increased.

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According to Gholami et al. (2019), the optimum method for reducing soil erosion and runoff while maintaining the physico-chemical properties of the soil is to apply  $1.6 \text{ t ha}^{-1}$  of biochar at a 10% moisture content of the soil.

Kumar et al. (2019) suggested different doses of biochars to be mixed in compacted soil at 5% and 10% (by weight). It was found that biochar reduced erosion in dry state of soil, but in wet state, it had opposite behavior. Kumar et al. (2019) have also found that biochar helps to grow healthy vegetation when it is applied at higher rate of application. Xia et al. (2020) used biochar at five levels namely 0, 7.5, 15, 30 and  $45 \text{ g kg}^{-1}$  with combination of two N levels namely 0 and  $0.2 \text{ g kg}^{-1}$  for improving soil quality in terms of increasing nitrogen use efficiency and acidic toxicity of soil. Xia et al. (2020) showed that root with shoot biomass as well as nitrogen utilization rate were increased due to increment in biochar level of application. Ahmadi et al. (2020) mixed biochar with 0-1.5 cm of top soil and applied at the rates of 0, 1, 2, and  $3 \text{ kg m}^{-2}$  into the soil bins to understand the behavior of rice husk based in loamy soil. Ahmadi et al. (2020) indicated that  $3 \text{ kg m}^{-2}$  rate of biochar is more significant to reduce runoff, soil erosion, and salinity of runoff and percolation water.

Gao et al. (2020) employed biochar made from maize stover in farmlands with seasonally frozen soil at several recommended doses, including 0, 15, 30, 45, and  $60 \text{ t ha}^{-1}$ . According to Gao et al. (2020), biochar helped lower soil temperature and thermal conductivity, which are connected with the rate at which it is applied (Singh et al., 2018). Wang et al. (2019) used three rates of biochar namely 0%, 2%, and 5% and three rates of PAM namely 0%, 0.4%, and 1% to enhance vegetation and reduce soil degradation in silt loam soil and stated that 5% biochar and 1% of PAM is the best combination. Liu et al. (2018) applied biochar in the soil at four different rates namely 0.5, 1, 2.5 and 5% and observed that higher rates of biochar is more effective to reduce the cadmium accumulation in leafy vegetable cultivars. According to Kushwaha et al. (2021), applying biochar at a rate of  $15 \text{ t ha}^{-1}$  or higher on slopes with silty clay loam soil is beneficial in reducing runoff and soil erosion as well as improving the soil physico-chemical characteristics.

All these review stated that application rate of biochar depends on soil type. All soil requires different treatments and hence biochar application rate differs. Notwithstanding, higher

dose of biochar is safe but its application cost may be increased. More studies are still required to understand the optimal application rate of biochar in other type of soil and other climatic and terrestrial conditions.

## 5. Conclusions and perspectives

The review included the features of biochar in soil, its production processes, the ideal pyrolysis temperature, the raw materials and particle sizes of biochar, and the application rate for reclaiming deteriorated soil. By using biochar properly in the field, soil physico-chemical characteristics can be improved, and runoff and soil erosion can be decreased. Slow pyrolysis between 250°C and 500°C is preferable to quick pyrolysis, and the cheapest raw material readily available locally is the best option to make affordable biochar. Pure, unground biochar is never as effective as small or nano-sized particles. Higher dose of biochar is safe and no any negative effect was reported but the cost of application may go up. More researches are still needed to determine the best biochar application rate with its nano-size effect under various soil, meteorological and terrestrial circumstances. To fully understand how biochar behaves in environmental conditions, further research is needed, with an emphasis on fieldwork rather than laboratory work.

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