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Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review

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ABSTRACT

Pyrolysis is one of the most promising technologies for the conversion of biomass into high-value products such as bio-oil, syngas, and biochar in the absence of oxygen. High yield biochar can be produced through torrefaction or slow pyrolysis. The efficiency of biochar production from biomass is highly dependent on the pyrolysis temperature, heating rate, type and composition of feedstock, particle size, and reactor conditions. Application of biochar to agriculture may have a significant effect on reducing global warming through the reduction of greenhouse gas (GHG) emissions and the sequestering of atmospheric carbon into soil. At the same time, biochar can help improve soil health and fertility, and enhance agricultural production. Livestock manure, along with waste-feed residues and bedding materials, is a potential source of biochar. This waste emits significant amounts of GHGs adding to global warming and threatening the environment in other ways. The environmental challenges caused by agricultural and animal-waste disposal can be reduced by recycling the waste using pyrolysis, into biochar, energy, and value-added products. Biochar can act as a sorbent for organic and inorganic contaminants and can efficiently remove these materials from affected waters. Contaminant removal is mainly based on the presence of functional groups and charges on the surface of the biochar. Thus, biochar can help to improve food security by contributing to sustainable production systems and maintaining an eco-friendly environment. This review details the principles and concepts involved in biochar production, the factors that affect biochar quality, as well as the applications of biochar.

1. Introduction

Recently, biochar has attracted much attention due to its promising role in many environmental management issues [1,2]. Hence, biochar, a product of slow pyrolysis and/or the byproduct of fast pyrolysis, gasification, or combustion processes [3], can be produced from different organic materials such as plant tissue [4,5], anthropogenic sources [6], raw pine chips [7], peanut hulls and pecan shells [8], forage plant biomass [9], pine chips and poultry litter [10], paper-mill waste [11], woody debris, corn stalks, and macadamia shells [12], citrus wood [13], cottonseed hulls [14], empty fruit bunches [15], rubber wood sawdust [16], rice husks [17], sewage biosolids [18], poultry manure [19,20], goat manure [21], human manure [22], swine manure [23,24] and agro-industrial biomass [25]. Different types of biomass, and the thermochemical conditions used to pyrolyze it, greatly influence the quality of biochar and its potential uses [26].

The production of biochar is quite similar to that of charcoal, the production of which is one of the oldest developed technologies [27]. However, biochar is quite different to charcoal as it is not primarily used as a fuel, but for atmospheric carbon (C) capture and storage, or bio-sequestration. Biochar is a carbon-rich (65–90%) solid product of biomass pyrolysis that contains numerous pores and oxygen functional groups and aromatic surfaces. The porous structure of char particles enhances the water-retaining capacities and nutrient retention of soil, as well microbial accumulation. Due to its beneficial characteristics, biochar is used as a soil conditioner that is very promising for agricultural applications. The soil organic carbon (SOC) pool declines on a day-by-day basis due to agricultural operations. The resistant biochar carbon fraction can increase the total carbon pool of soil [28], in turn increasing soil fertility. The presence of SOC is vital for sustainable agricultural yields, as well as the retention of water and nutrients, especially nitrogen, phosphorus, and potassium (NPK), and

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provides a habitat for soil microorganisms that improve soil structure [13,29]. SOC is also a major carbon resource that contains over twice the total carbon present in the atmosphere. Land used for farming practices have already led to a marked reduction in SOC, and with increased temperatures expected with climate change, it is likely to fall further [30]. SOC loss reduces soil fertility and further exacerbates climate change. The utilization of biochar for soil amendment has been suggested as a way to increase both SOC levels and soil fertility. Depending on the source material, the reported organic carbon (OC) content of biochar can be as high as 90% [31], and this material has enhanced activity for C sequestration applications [32]. In addition to soil fertility and C sequestration, biochar reduces the emission of greenhouse gasses (GHGs) that result from biomass degradation and, hence, contributes positively to the global warming issue [33–35].

Biochar can be utilized as an adsorbent for the removal of toxic contaminants from wastewaters or polluted soils [36–41]. Relatively high levels of matrix-bound carbon in biochar, along with a high degree of porosity and large surface area, helps to play vital roles in the adsorption of heavy metals and other pollutants from contaminated environments [14,20,42,43]. Since biochar has a strong affinity for non-polar substances such as dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), and other compounds, due to high surface-to-volume ratios, it is a potential sorbent for organic and inorganic pollutants [16,44–47]. The presence of functional groups on the surface of biochars impart adsorption potential for toxic substances, such as manganese (Mn) and aluminum (Al) in acidic soils, and arsenic (As), nickel (Ni), copper (Cu), cadmium (Cd), and lead (Pb) in heavy metal contaminated soils [12,43]. Therefore, possible reductions in heavy metal accumulation from sewage sludge or other contamination sources may be accomplished if biochar is present in the soil. However, biochar properties are highly variable and biochar quality is also influenced by the feedstock materials, pyrolysis conditions, and reactor types.

Livestock populations increase every year in order to fulfill the demand of the increasing human population. With increasing livestock populations, ever increasing (large) amounts of manure are produced that can be useful resources if utilized properly. Pyrolysis is an alternative solution to the management of large amounts of manure, while simultaneously producing renewable and sustainable energy [21–24,48–50] by converting biomass into high-value products such as biooil, syngas, biochar, and chemicals, in the absence of oxygen at high temperatures (300–800 °C) [51]. The thermochemical conversion of manure into bioenergy and biochar ensures the complete destruction of pathogens, a dramatic reduction in waste volume, as well as a pollution-free environment [49,52,53]. The conversion of manure into biochar using hydrothermal carbonation (HTC), a thermochemical treatment at 150–300 °C in water under self-generated pressure, can be cost effective and can provide higher char yields with lower gas emissions (2–5%), while increasing available P, and decreasing apatite P and soluble Ca, compared to pyrolysis or combustion [54]. The objectives of this review are to discuss: i) biochar production and properties, ii) factors affecting the quality of biochar such as temperature and feedstock composition, and iii) applications of biochar to carbon sequestration, GHG mitigation, soil improvement, waste management, and wastewater treatment.

2. Biochar production techniques

Thermochemical processes such as pyrolysis, gasification, hydrothermal carbonization (HTC), and torrefaction convert biomass into biochar, biofuel, and other bio-based products under various temperature conditions [3,55,56]. The thermochemical decomposition of organic matter converts biomass into biochar in the absence of oxygen at high temperatures and pressures. This process irreversibly changes the chemical composition and physical state of the organic matter. The structural building blocks of biomass (cellulose, hemicelluloses, lignin and pectin) undergo cross-linking, depolymerization and fragmentation at different temperatures during pyrolysis [57]. Biomass is primarily transformed into biochar, small quantities of condensable liquid (biooil), and non-condensable gasses (syngas). Several types of pyrolysis units or reactors have been developed for this process. These reactors operate on similar principles regarding O_2 availability, but might differ in heating rates, pressures, and residence times, and these differences can alter the proportions of the final products [3,56,58]. The yield of biochar, biooil, and syngas depends on the type of pyrolysis used, as well as the pyrolysis conditions. Pyrolysis reaction conditions and associated product distributions are summarized in Table 1. In the past, biomass pyrolysis has generated considerable interest for biofuel production, with yields up to 80% based on dry biomass. Recently, research aimed at obtaining quality biochar from green waste, for the improvement of soil fertility and soil water conservation with simultaneous C sequestration, has been undertaken. Based on the temperature, heating rate, pressure, and residence time, pyrolysis can be classified into following subclasses, namely slow and fast pyrolysis [3,59].

2.1. Slow pyrolysis

Slow pyrolysis is a thermal conversion processes characterized by long residence times and slow heating rates that produce approximately equal compositions of solid, gas, and liquid products. Slow pyrolysis is conducted at atmospheric pressure, with heat provided by partial combustion of the feed, by external heaters, or by hot-gas recirculation. In this slow pyrolysis process, different types of reactors have been used for biochar production such as agitated drum sand rotating kilns, along with screw pyrolyzers [57,60]. Sohi et al. described a typical slow-pyrolysis reactor developed by BEST energies. This reactor uses low pyrolysis temperatures (300–700 °C), high pressures, long vapor residence times (hours to days), extended vapor/solid times, low heating rates (0.01–2 °C s^{-1}), and optimized heat integration [56,57,60]. Comparatively higher biochar yields are favored by biomasses with high lignin and ash content, along with large particle sizes during slow pyrolysis conditions [61]. These conditions enhance biochar yield by increasing cracking reactions that reduce the production of liquids or biooil [56]. According to Song and Guo, slow pyrolysis is a simple, robust, and inexpensive process that is applicable to small-

Table 1
The reaction conditions and product distribution of various modes of pyrolysis [3,56,57,59,110,215].

Process	Temperature (°C)	Residence time	Yields %		
			Biochar	Bio-oil	Syngas
Slow pyrolysis	300–700	hour-days	35	30	35
Intermediate pyrolysis	~500	10–20 s	20	50	30
Fast pyrolysis	500–1000	< 2 s	12	75	13
Gasification	~750–900	10–20 s	10	5	85
Hydrothermal carbonization (HTC)	180–300	1–16 h	50–80	5–20	2–5
Torrefacation	~290	~10–60 min	80	0	20