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Recent advances in utilization of biochar

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ABSTRACT

Biomass thermochemical processes result in a common byproduct char. The char is also called biochar particularly when it is used as a soil amendment for soil health improvement. Effective utilization of biochar is critical for improving economic viability and environmental sustainability of biomass thermochemical technologies. Application of biochar for both agricultural and environmental benefits has been studied and reviewed extensively. However, there are limited reviews on other biochar applications, such as for catalysis and adsorption. This paper provides an overview of recent advances in several biochar utilizations including its use as catalyst, soil amendment, fuel cell, contaminant adsorbent, gas storage and activated carbon. Discussions on biochar production methods, properties and advanced characterization techniques are also provided. Biochar is a valuable resource, however, its effective utilization require further investigation of its structure and properties, and methods to modify those.

Contents

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1. Introduction

Biomass can be converted to biofuels and bioproducts via thermochemical processes, such as pyrolysis and gasification. The net carbon dioxide emissions from biofuel use are considered zero or negative because the released CO_2 was recycled from the atmosphere captured during photosynthesis [1]. In addition, since biomass contains a low amount of sulphur and nitrogen, combustion of biofuels leads to lower emissions of harmful gas, such as nitrous oxides (NO_x) and sulphur dioxide (SO_2), than most of fossil fuels [2]. Such advantages of biomass make it a promising renewable energy resource.

The major products from biomass thermochemical processes are syngas, bio-oil, biochar and tar with yields that depend on the process conditions. Syngas and bio-oil are considered as major intermediate products that can be used to create fuels alternative to conventional fuels. Numerous studies have been conducted involving upgrading and utilization of syngas and bio-oil for various applications [3–6]. Recently, biochar, a product from biomass thermochemical conversion, has received increasing attention for use in several applications. The most common biochar application is soil amendment to mitigate greenhouse gas emission and improve soil health. Other applications include using biochar as a precursor for making catalysts and contaminant adsorbents. These new high-value applications are still in their infancy, and further research and development is needed to reach commercialization. Even though, charcoal, a carbon material similar to biochar, has been used for centuries, using biochar as a sustainable material for these applications (precursor of catalyst and contaminant adsorbents, and soil amendment) has only been studied in last few years.

The potential to utilize biochar for various applications depends on its properties. For example, biochar with high electrical conductivity, porosity and stability at lower temperatures is preferred as electrodes material in microbial fuel cells [7]. Biochar containing relatively high structural bound oxygen groups is preferred in direct carbon fuel cells [8]. Biochar with high porosity and structural bound nitrogen groups is preferred in the development of supercapacitors [9]. Furthermore, the high surface area, low ash content of biochar may be preferred as soil amendments, although the relationship between biochar properties and its applicability as a soil amendment is still not conclusive [10].

Reviews on biochar production, properties and use, especially as a soil amendment, can be found in other works [10–15]. Meyer et al. [15] reviewed production methods, properties, economics and environmental aspects of using biochar as soil amendment. Laird et al. [16] reviewed pyrolysis reactors for producing biochar used as a soil amendment. Several others extensively reviewed effects of different pyrolysis methods on properties of biochar and its impacts on soil [10,12,13]. Although, review on biochar properties and its specific application as soil amendment is available in literature, review on new state of the art applications of biochar is limited. This paper provides an overview of recent advances in utilization of biochar, especially for applications other than soil amendment. This paper also discusses production methods, properties and new characterization techniques that are used to solve underlying problems in identifying novel applications of biochar.

2. Biochar production

Biochar is charred organic matter. The International Biochar Initiative defines biochar as "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" [17]. Biochar is produced in solid form by dry carbonization, pyrolysis or gasification of biomass, and in slurry form by hydrothermal carbonization of biomass under pressure [11]. Typical operating conditions and char yields of different thermochemical processes are shown in Table 1.

2.1. Pyrolysis

The most common method to produce biochar is pyrolysis. Pyrolysis can be categorized into slow pyrolysis and fast pyrolysis depending on the heating rate and residence time. Slow pyrolysis, also called conventional carbonization, produces biochar by heating biomass at a low heating rate for a relatively long residence time (up to several days). This method has been used to generate charcoal for centuries. On the other hand, fast pyrolysis produces biochar at a high heating rate (above 200 K/min) and short residence time (less than 10 s). The major differences between the two pyrolysis methods are the yields of biochar and bio-oil: fast pyrolysis favors high yield of bio-oil while slow pyrolysis favors high yield of biochar.

2.2. Gasification

Gasification transforms biomass into primarily a gaseous mixture (syngas containing CO, H_2, CO_2, CH_4, and smaller quantities of higher hydrocarbons) by supplying a controlled amount of oxidizing agent under high temperature (greater than 700 °C). The typical biochar yield of gasification averages about 10 wt% of biomass [15,25]. The oxidizing agent used in gasification can be oxygen, air, steam or mixtures of these gases. Air gasification produces syngas with low heating values of 4–7 MJ/Nm^3, while gasification with steam produces syngas with high heating values of 10–14 MJ/Nm^3 [5].

2.3. Hydrothermal carbonization

Hydrothermal carbonization (HTC) of biomass takes place in water at elevated temperatures (160–800 °C). Since the water temperature is above 100 °C, the reaction pressure also must be elevated (more than 1 atm) to maintain the water in a liquid form. Based on reaction temperature, hydrothermal carbonization can be divided into high-temperature HTC (between 300 and 800 °C) and low-temperature HTC (below 300 °C) [26]. Since the reaction conditions of high-temperature HTC (above 300 °C) are beyond the stability condition of most organic compounds, the dominant reaction during high-temperature HTC is hydrothermal gasification and the dominant products are gases, such as methane and hydrogen [24]. Below 300 °C, gasification is limited and carbonization of biomass to char dominates the reaction. Low-temperature HTC can mimic the natural coalification of biomass, although the reaction rate is higher and reaction time is shorter compared to the hundreds of years of slow natural coalification of biomass. Char yield of low-temperature biomass HTC varies from 30% to 60% depending on the feedstock properties, reaction temperature and pressure. Since HTC requires water, this may be a cost-effective biochar production method for feedstocks with high moisture content [9].

Table 1
Typical char yield from thermochemical processes.

Process	Temperature (°C)	Residence time (s/h/min/days)	Char yield (wt%)	Reference
Slow pyrolysis	400–600	min to days	20–40	[18–20]
Fast pyrolysis	400–600	~1 s	10–20	[21,22]
Gasification	800–1000	5–20 s	~10	[15]
Hydrothermal carbonization	180–250	1–12 h	30–60	[23,24]