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Review

Insight into biochar properties and its cost analysis

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A B S T R A C T

Biochars (BCs) are widely produced and used for the remediation of environmental contaminants as biosorbents. In this review, statistical analysis of different BC physico–chemical properties was conducted. It was observed that woody materials are the most suitable for preparing BCs, among many other potential raw materials such as food wastes and agricultural materials. Currently BCs are produced through a variety of thermal treatment processes between 300 and 900 °C, among which slow pyrolysis is widely used due to its moderate operating conditions and optimization of BC yields. Hydrothermal carbonisation (HTC) is also an effective approach for BC production under certain conditions. As pyrolysis temperature is increased, the carbon content, ash content, surface area, and pore volume tend to be increased while the yield, hydrogen, oxygen, nitrogen content, and H/C and O/C molar ratios tend to decrease. The economic feasibility of BCs depends on a range of factors from raw material price to efficient production technologies. Thus, the overall cost equation of a pilot BC production plant together with the cost equation for BC regeneration has been proposed. The future research directions of BCs are also elaborated.

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1. Introduction

BC is a carbon dominant product which is obtained when biomass feedstocks are heated at elevated temperature in a closed reactor with little or no oxygen present [1]. BC is an ancient material that has been widely used to bolster primarily soil fertility and crop production [2–4]. BC was initially viewed as a source of energy and can be burned to supply process energy, for water and gas purification [5], and as charcoal in home cooking. Other potential benefits including nitrate leaching [6–11], adsorption of inorganic and organic contaminants [1,12–14] and reduction of trace-gas emissions from soil and atmosphere [6,8,10]. BC has been found to reduce carbon and methane emissions and provide an efficacious solution to remove heavy metals from storm runoff. The knack of BCs to hoard carbon and other uses will not only depend on their physical and chemical properties, as they can be changed by the preparatory processes or through the choice of feedstocks, but will also depend on the technical and economic barriers of handling BCs [15,16].

Different types of biomass feedstocks have been used for the production of BCs ranging from agricultural waste to timber based hard materials [17–22]. In order to produce BCs, these feedstocks are mainly converted using different thermal methods including slow and fast pyrolysis, gasification, hydrothermal treatment, carbonization and torrefaction [23–25]. Pyrolysis process can be either slow (<10 $^{\circ}Cs^{-1}$) or fast (>10 $^{\circ}Cs^{-1}$) [26]. Thermal treatment can be performed with different final temperatures and with different heating rates which are responsible for the quality and prices of the BCs [16,27]. In particular, the yield of BCs decreases with increasing the yield of gases as the temperature of the pyrolysis process is raised to high temperatures. Thus the pyrolysis temperature affects both the quantity and quality of BCs produced from a given quantity of feedstocks. The quality of BCs (e.g. surface area, pore volume) is low when pyrolysis temperatures is lower than 350 °C, and is generally increased up to some point (depending on end use) as temperature is increased [28].

To date, there is a major gap in the literature on the analysis of overall BC production and regeneration cost. Only a few articles [29,30] discussed BC production cost in a specified range. As BC is a powerful biosorbent with a wide range of applications, its overall cost should be fully analyzed. In this review, a conceptual model for cost analysis of a BC pilot plant was developed by reviewing and analyzing the published studies related to the potential cost effectiveness of BCs. The focus is also being given on (i) physico–chemical properties of BCs, (ii) different BC production technologies leading to suitable products, and (iii) analysis of overall cost equations for a pilot plant BC production and regeneration. It is expected that this review will help to consider cost analysis for a whole plant and to promote BC application at commercial scale.

2. Physico–chemical properties of BCs

The quality characteristics of BCs will change along several dimensions according to final pyrolysis temperature as well as the heating rate and residence time, and the type of raw materials. For example, the yield, surface area, pore volume, ash, elemental composition, viscosity, calorific value, and water content of BCs vary with pyrolysis temperature. In this section, the discussion is limited on the yield, surface area, pore volume, ash, and elemental composition of different BCs at different pyrolysis temperatures.

2.1. BC production technologies

A range of feedstocks (animal feedings, agricultural materials, woody materials, solid wastes, food wastes, animal litters) have been mainly utilized to produce BCs. BCs can be produced by pyrolysis [31–37] via slow pyrolysis [19,21,38] or fast pyrolysis [39–41], gasification [42,43], torrefaction [23], carbonization [44], flash carbonization [15,45], and hydrothermal carbonization (HTC) [25]. BCs produced by HTC method are sometimes called hydrochar. BC production technologies have already been described in detail [1,46–49], and are summarized in Table 1.

To produce BCs, the most widely used process is slow pyrolysis due to relatively high yields, and the fixed and operation cost of biomass pretreatment is 50% low than that of fast pyrolysis [50]. This is also called conventional carbonization and has been used for thousands of years to produce charcoal. The knowledge about charcoal production and its properties has been accumulated over 38000 years [51]. Slow and intermediate pyrolysis processes are generally favored for BC production [50,52–54]. On the other hand, HTC process is attracting more attention due to its inherent advantage of using wet biomass [55,56] and irregular surface with more oxygen-containing groups and higher cation exchange capacity (CEC) [57,58]. Thus slow pyrolysis and HTC are two of the most efficient BC conversation technologies which can be used for a wide range of feedstocks [1]. A majority of BCs produced by HTC are more acidic than by pyrolysis [55,59]. One of the most important properties of HTC-BC is that it is easily biodegradable (dominated by alkyl moieties), whereas BC from slow pyrolysis is more stable (dominated by aromatics) in case of soil amendment as hydrochar has more nutrient retention capacity [56,60]. Since HTC requires water, this may be a cost effective BC production method for feedstocks with high moisture content [61]. However, hydro-chars are not included in the "European Biochar Certificate" (EBC) standardization due to their different chemical properties including low total organic compound, high ash, low surface area, low porosity and high nutrient content [60,62].

On the other hand, little data is available for carbonization, flash carbonization, torrefaction, fast pyrolysis and gasification as these technologies are commonly favored for bio-oil, solid fuel or synthetic gas yields. BC yields from fast pyrolysis and gasification processes are significantly lower compared to those of slow pyrolysis, flash carbonization, carbonization, hydrothermal and torrefaction, due to more gases being produced hence favoring the bio-oil or syn-gas production. Thus further use of BCs produced by other thermochemical technologies cannot be underestimated [1].

Table 1
A summary of thermochemical processes for BC preparation.

Thermochemical process	Temperature range (°C)	Yield (%)	Residence time	Heating rate
Slow pyrolysis	100–1000	15–40	Minutes to hours	Slow (<10 °C min^{-1})
Fast pyrolysis	300–1000	10–25	<2 s	Very fast (~1000 °C s^{-1})
Torrefaction	200–300	61–77	Minutes to hours	Slow (<10 °C min^{-1})
Gasification	700–1500	~10	Seconds to minutes	Moderate-very fast
HTC	175–300	30–72	30 min to 16 h	Slow
Microwave pyrolysis	550–700	34	5–20 min	Slow
Flash carbonization	300–600	37–50	~30 min	Slow