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Review

Production and utilization of biochar: A review

Jin Sun Cha [a,b], Sung Hoon Park [c], Sang-Chul Jung [c], Changkook Ryu [d], Jong-Ki Jeon [e], Min-Chul Shin [b], Young-Kwon Park [a,*]

[a] School of Environmental Engineering, University of Seoul, Seoul, 02504, Republic of Korea
[b] Korea Testing Laboratory, Seoul, 08389, Republic of Korea
[c] Department of Environmental Engineering, Sunchon National University, Suncheon, 57922, Republic of Korea
[d] School of Mechanical Engineering, Sungkyunkwan University, Suwon, 16419, Republic of Korea
[e] Department of Chemical Engineering, Kongju National University, Cheonan, 31080, Republic of Korea

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ABSTRACT

Biochar produced during the thermochemical decomposition of biomass not only reduces the amount of carbon emitted into the atmosphere, but it is also an environment-friendly replacement for activated carbon and other carbon materials. In this review paper, researches on biochar are discussed in terms of production method and application. Different processes for biochar production, such as pyrolysis, gasification, hydrothermal carbonization, etc., are compared. Physical and chemical activation methods used to improve the physicochemical properties of biochar and their effects are also compared. Various environmental application fields of biochar including adsorption (for water pollutants and for air pollutants), catalysis (for syngas upgrading, for biodiesel production, and for air pollutant treatment), and soil conditioning are discussed. Recent research trend of biochar in other applications, such as fuel cell, supercapacitor, and hydrogen storage, is also reviewed.

Contents

* Corresponding author. Tel.: +82 2 6490 2870; fax: +82 2 6490 2859.
E-mail address: catalica@uos.ac.kr (Y.-K. Park).

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Introduction

The combustion of fossil fuels emits CO_2, which causes global warming and climate change as well as the production of air pollutants, such as the oxides of sulfur and nitrogen [1]. Fossil fuel exhaustion, increasing oil price, and the rise of global environmental problems are calling for the development of alternative energy resources to replace conventional fossil fuels. Organic materials originating from living matter or complexes of organic and inorganic materials from said sources are referred to collectively as biomass. Biomass includes not only living organisms, such as plants and animals, but also the excrement of animals, sludge, and waste wood [2]. Thermochemical decomposition processes convert biomass materials to syngas, bio-oil, and biochar. The gas product syngas and the liquid product bio-oil are regarded as alternative fuels to fossil fuels, and extensive research is being conducted on their formation, upgrading, and applications [3–7]. Biomass is considered carbon neural because the carbon dioxide emitted from biomass is compensated for by the carbon assimilation occurring during the photosynthesis of biomass. Biomass is also known to have fewer adverse effects on the atmosphere because it contains less S and N, resulting in lower SOx and NOx emissions than fossil fuels [1].

Biochar, the solid material formed during the thermochemical decomposition of biomass, is defined, by the International Biochar Initiative (http://www.biochar-international.org/biochar), as "a solid material obtained from the carbonization of biomass". As biochar is inexpensive, environment-friendly, and can be used for a variety of purposes, such as soil remediation, waste management, greenhouse gas reduction, and energy production, several studies have been conducted to develop new applications of biomass [8]. Although the main element of biochar is carbon (C), it also contains hydrogen (H), oxygen (O), ash, and trace amounts of nitrogen (N) and sulfur (S) [9]. The elemental composition of biochar varies according to the raw biomass material from which the biochar was produced and the characteristics of the carbonization process [10–12]. Because of its large specific surface area, porous structure, surface functional groups, and high mineral content, biochar has been used as an adsorbent for water and air pollutants [12,13], a catalyst to remove tar or produce biodiesel [14,15], and as a soil amendment [12,16]. Recently, the applications of biochar to fuel cells [17,18] and supercapacitors [19,20] have also been reported.

In this article, before looking into the application instances of biochar, the thermochemical decomposition processes for the production of biochar and previous studies on the biochar modification to improve its properties are reviewed to enhance the understanding of biochar formation. Most previous review articles on biochar application discussed the removal of pollutants in water [13,21,22] and soil [23–27] using biochar. Only recent research trend in those fields is briefly presented in this article, whereas the applications of biochar to the removal of hazardous pollutants (including air pollutants and tar) and other recently developed application fields, such as fuel cell, supercapacitor, and hydrogen storage, are discussed in detail.

Production of biochar

This section summarizes several different carbonization processes to produce biochar along with their characteristics.

Pyrolysis

Pyrolysis is a process for decomposing organic materials thermally under oxygen-free conditions in the temperature range, 300–900 °C [28–31]. During thermal decomposition, cellulose, hemicellulose and lignin that comprise biomass undergo their own reaction pathways, including cross-linking, depolymerization and fragmentation at their own temperature, producing solid, liquid and gaseous products. The solid and liquid products are referred to as char and bio-oil, respectively, whereas the gaseous mixture containing CO, CO_2, H_2, and C_1–C_2 hydrocarbons are called syngas. The yields of the pyrolysis products depend on the characteristics of the raw biomass materials and the pyrolysis processes adapted.

The parameters that influence the products of the pyrolysis processes include the reaction temperature, heating rate, and residence time. In general, the biochar yield decreases and the syngas yield increases with increasing pyrolysis temperature [32–35]. Mohammad et al. [35] and Zhang et al. [36] reported that the yields of biochar and acidic functional groups decreased with increasing pyrolysis temperature, whereas those of the basic functional groups, ash content, pH, and carbon stability increased. The increase in pH with increasing pyrolysis temperature was attributed to the reduction of organic functional groups, such as –COOH and –OH. The bio-oil yield was reportedly highest at approximately 500 °C because cracking takes place at higher temperatures [34]. Fig. 1 shows the elemental compositions of biochar produced at different pyrolysis temperatures [37]. Pyrolysis processes are divided into slow pyrolysis and fast pyrolysis depending on the rate of the increase in temperature. In a slow pyrolysis, in which the pyrolyzed vapors reside for a long time in the reactor at low temperatures, continuing vapor-phase reactions increase the char yield [32,34,38]. Inguanzo et al. [39] evaluated the characteristics of the chars produced at two different temperature rising rates of 5 °C/min and 60 °C/min. They reported that the char produced at the higher temperature rising rate had a lower volatile matter content and a higher ash (including fixed carbon) yield and concluded that a high temperature rising rate is preferable in terms of the quality of the product biochar. This effect of the temperature rising rate was not observed at high pyrolysis temperatures [40]. Therefore, fast pyrolysis is generally aimed at producing a liquid product in high yield [41,42]. To suppress the gas production due to secondary cracking, the vapor residence time is controlled short and rapid cooling is used to maximize the liquid product yield.

Regarding the effects of the residence time on the product composition in a pyrolysis process, Zhang et al. [36] reported that the biochar yield decreased with increasing residence time at the same pyrolysis temperature. In a study of the effects of the residence time on the specific surface area and pore characteristics of biochar, Lu et al. [43] reported that the specific surface area and pore area increased with increasing residence time up to 2 h at 500–900 °C but they decreased when the residence time exceeded 2 h. In particular, the specific surface area and pore area decreased rapidly when the residence time exceeded 2 h at high temperatures. Bandosz et al. observed in a study of the pyrolysis of sewage sludge that the specific surface area decreased from 141 m^2/g to 125 m^2/g and the pore volume decreased from 0.209 cm^3/g to 0.187 cm^3/g when the residence time was increased from 30 min to 1 h at a pyrolysis temperature of 950 °C [44]. Lu et al. attributed the results of Bandosz et al. to a narrowing and closure of the pore entrances owing to the sintering of char, resulting in a reduction of the specific surface area [43]. Table 1 summarizes the characteristics of biochar produced under various pyrolysis conditions.

Gasification

Gasification is a thermochemical partial oxidation process converting carbonaceous materials, such as biomass, coals, and plastic materials, to gaseous products using gasification agents (air,