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Short communication

# Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties

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## HIGHLIGHTS

- Higher temperatures produced higher thermal stability biochars.
- Production method showed strong effect on biochar properties.
- Biochars showed no statistically significant effects on plant.

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## ABSTRACT

This work explored the effect of temperature, production method, and feedstock type on the physicochemical and biological properties of biochars and hydrochars. Biochars and hydrochars made at lower temperatures had higher production rates. Higher pyrolysis temperatures not only increased carbon content of biochars but also produced higher thermal stability biochars that did not start to decompose in air after 400–450 °C. The production method showed strong effect on biochar properties. Compared to the dry-pyrolysis biochars derived from the same feedstocks, the hydrochars had more acidic pH values and lower carbon contents. The results showed that feedstock types could also influence characteristics of the biochars. None of the chars showed statistically significant effects on plant seed germination and seedling growth and thus could be used as soil amendments. Our findings indicated that biochars with different properties could be developed by changing production conditions to better satisfy their environmental applications.



## 1. Introduction

Biochar is a pyrogenic black carbon derived from the thermal conversion of biomass feedstocks, including agricultural and forest residuals, in an inert atmosphere. Biochar technology has attracted great attention because of its potential to help mitigate climate change and improve soil fertility [1]. In addition, many researchers have found that biochar can be used as an alternative adsorbent to remove different kinds of contaminants, including heavy metals, nutrients, and pharmaceuticals, from aqueous solutions [2–5]. The functions and applications of biochars may vary because of their different physicochemical properties. In order to promote biochar technology to benefit the environment and society, it is critical to understand the key production factors that control the physicochemical properties of biochars.

A few previous studies have compared the properties of several types of biochars prepared through slow pyrolysis and found that pyrolysis temperature and feedstock type are important factors in determining the most suitable application for biochars. For example, Uchimiya et al. found that pyrolysis temperature can affect the presence of surface functional groups on biochars and thus control their heavy metal sequestration ability in soils [6]. Yao et al. [4] reported biochars made from different biomass feedstocks show large differences in adsorbing phosphate from aqueous solutions. Recent studies have also suggested that conversion/production methods can also play an important role in controlling biochar properties [7]. For example, biochars produced by hydrothermal carbonization, which is also called hydrochar, show unique characteristics and can be used for various applications, such as innovative materials and soil amelioration [7,8]. However, there are very few studies that worked on the characterization of hydrochars [7]. Therefore, more research is needed to compare the differences between biochars and hydrochars in order to

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determine the effect of production method on biochar properties. Also, since biochars/hydrochars are often used as amendment to improve soil quality and stabilize pollutants, it is necessary to find out their influences on plant growth.

The overarching objective of this work was to find out whether different feedstocks, temperatures, or production methods can affect the physicochemical properties of biochar samples, including their impacts on seed germination. Three commonly used feedstocks (i.e., hickory wood, bagasse, and bamboo), different temperatures ranging from 200 °C to 600 °C, and two methods (slow pyrolysis and hydrothermal carbonization) were used for biochar production. Physicochemical properties of the biochars produced were characterized, and laboratory seed germination experiments were conducted as a preliminary assessment of their impact on plant growth. The specific objectives were to: (1) compare the hydrothermal carbonization and slow pyrolysis methods in making chars, (2) compare the physicochemical properties of biochars obtained from different feedstocks and/or different temperatures, and (3) determine whether the biochar and/or hydrochar have impacts on seed germination.

## 2. Materials and methods

### 2.1. Biochar and hydrochar production

Three different types of biomass were used as feedstock materials: hickory wood (HW), bagasse (BG), and bamboo (BB). The dry-pyrolysis biochars were made at three temperatures (300, 450, and 600 °C) through slow pyrolysis inside a furnace (Olympic 1823HE) under an $N_2$ environment. The samples were then sieved to a uniform size fraction of 0.5–1 mm and washed with deionized (DI) water several times to remove impurities. The samples were oven dried (80 °C) for about 12 h and stored for later use. The biochar samples obtained were labeled as HW300, HW450, HW600, BG300, BG450, BG600, BB300, BB450, and BB600, respectively. Detailed information about biochar production can be found in Yao et al. [4].

The hydrochars (wet-pyrolysis biochars) were made from the same materials (HW, BG, and BB) mentioned above. A mixture of raw material and deionized (DI) water were added into a stainless steel autoclave. The reactor was programmed to heat and then hold at a peak temperature (200 °C) for 5 h. The samples were washed, sieved to a uniform size, and dried using the same procedure as biochar. The hydrochars were henceforth named as HHW, HBG, and HBB. Detailed information about hydrochar production can be found in Xue et al. [8].

### 2.2. Biochar properties

A CHN Elemental Analyzer (Carlo-Erba NA-1500) was used to determine the content of C, N, and H in the different samples via high temperature catalyzed combustion followed by infrared detection of the resulting $CO_2$, $H_2$ and $NO_2$ gases [9]. Major inorganic elements were determined using the AOAC method by inductively coupled plasma with atomic emission spectroscopy (ICP-AES, Perkin Elmer Optima 2100 DV). The pH of the biochar and hydrochar samples was measured by combining 1 g of a sample with 20 mL DI water. The solution was then shaken for 1 h and allowed to stand for 5 min before measurement with a pH meter (Fisher Scientific Accumet Basic AB15). Thermogravimetric analysis (TGA) of biochar samples were conducted using a Mettler's TGA/DSC1 thermogravimetric analyzer under a stream of air atmosphere at a heating rate of 10 °C/min to 700 °C. The surface areas of the samples were measured with a Quantachrome Autosorb-1 surface area analyzer using both $N_2$ (BET) and $CO_2$ adsorption methods to determine macro- and micropore surface area [10,11].

### 2.3. Seed germination

A seed germination assay was carried out by evenly spreading 20 grass seeds (Brown Top Millet) on a layer of cotton in a 4 cm-diameter container. The experiment was conducted in dark environment under room temperature (22 ± 0.5 °C). The amount of biochar samples used should not be too much or too little in order to make sure that the seeds have contact with air, and also so the sample can spread throughout the surface. Hence, 0.2 g biochar samples were measured and then added onto the top of the seeds, with the surface uniformly covered. DI water was added every 24 h to keep the environment wet. Containers were kept in the dark for 72 h, the number of germinated seed was counted, and the length of the bud was also measured.

Statistical analyses were conducted, and one-way ANOVA with a significance level of 0.05 ($p < 0.05$) was performed to study the effect of biochar samples on seed length and germination rate.

## 3. Results and discussion

### 3.1. Biochar production rates

On a mass basis, production rates of biochars and hydrochars ranged from 22.7% to 43.7% and 27.8% to 48.4% of initial dry weight, respectively (Fig. 1). In general, hydrothermal carbonization had a relatively higher production rate than regular slow pyrolysis due to the lower temperature involved, which is consistent with the literature [7,12]. In addition, biochar yields decreased with increasing temperature (Fig. 1). During the dry-pyrolysis process, the temperature kept rising and was then held at the peak temperature for several hours before cooling down to room temperature. Below 250 °C, samples lost weight mainly due to moisture and hydration water loss; while above 250 °C, feedstock begin to decompose and transform into vapor containing complex organic compounds mixed with gases (including water vapor, $CO_2$, CO, $H_2$, $CH_4$, and heavier hydrocarbons) [13]. Therefore, the decrease in biochar yields at higher temperature was probably because more organic matter decomposed when the temperature increased.

### 3.2. Elemental composition

Elemental analysis of the feedstocks showed that all of these materials were carbon rich with carbon contents around 45–46% (Table 1). Pyrolysis temperature during biochar production showed large effects on the chars' elemental compositions. In general, when peak temperature rose from 200 to 600 °C, carbon contents increased from 53% to 83%; and oxygen and hydrogen contents decreased from 39% to 11%, and 6% to 2%, respectively (Table 1). These results are consistent with the findings reported in the literature [6,14]. For bamboo biochars, carbon contents rose and oxygen contents dropped with increasing temperature; while the other two biochar samples (hickory wood and bagasse) reached their peak carbon and oxygen contents at 450 °C and then remained stable. N, P, K, Ca, Mg, Cu, Fe and Al showed low levels (less than 1%) for all the biochar samples, especially for the three hydrochar samples (Table 1).

As the hydrothermal carbonization process was under a lower temperature (200 °C) than slow pyrolysis (300–600 °C), the raw materials might not be fully carbonized, and the elemental analysis results showed that the feedstock and hydrochar samples had relatively little difference in elemental compositions (Table 1). Hydrochar had lower carbon content and higher oxygen content