



# Hydrochars derived from plant biomass under various conditions: Characterization and potential applications and impacts



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## HIGHLIGHTS

- Low temperature hydrochars showed higher yield and surface area.
- Low temperature hydrochars sorbed more methylene blue and lead.
- High temperature hydrochars showed better thermal stability.
- Hydrochars did not significantly affect seed germination rate.
- Two high temperature hydrochars affected root development of seedlings.

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## ABSTRACT

Hydrothermally carbonized biomass (hydrochar) has received increased attention recently as a potential agent for contaminant remediation and soil improvement. There is a need to understand how the properties of hydrochar vary with production conditions. In this work, sugarcane bagasse, hickory, and peanut hull were converted into hydrochars at three different temperatures (200 °C, 250 °C, and 300 °C). Basic physicochemical properties of the nine hydrochars were determined and batch aqueous sorption experiments were conducted to measure ability of the hydrochars to sorb methylene blue, lead, and phosphate. The yield, surface area, and pore volume of the hydrochars decreased with increasing conversion temperatures. Among all the hydrochars, the ones made at the lowest temperature (200 °C) were the best for sorption of methylene blue and lead. However, none of the hydrochars were able to remove significant amounts of phosphate from solution. In addition, the hydrochars did not significantly affect seed germination rate, though some did have a significant effect on root development of seedlings. Findings from this work suggest that lower temperature hydrochars may be optimal for contaminant remediation because of their higher sorption ability and absence of negative effect on plants.

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## 1. Introduction

Biochar is a pyrolysis product that can be utilized for multiple environmental applications, including contaminant remediation, soil amelioration, and carbon sequestration [1,2]. Chars created through hydrothermal carbonization (HTC), also known as hydrochars, can be used for the same purposes as biochars but differ in several aspects [3,4]. Hydrolysis, the first step in HTC, requires lower activation energy than many of the dry pyrolysis decomposition reactions [5,6]. The feedstocks of HTC do not need to be dried and thus it requires less energy inputs [4]. Nutrient-rich soluble materials of possible high value are a byproduct of hydrochar

production whereas gases and bio-oils are produced during biochar production that may be difficult to utilize. Finally, hydrochars have been found to be more efficiently pelletized than biochars, which increases their energy density, reducing transportation costs and handling difficulties [7].

Despite these advantages, hydrochar has not received nearly as much research attention as biochar. Until recently, research on the hydrothermal processing of feedstocks has mostly focused on the resulting liquid products [8]. As with biochar, it has been found that feedstock and processing conditions greatly affect hydrochar properties [9–12]. Similar to biochar, hydrochar yield decreased with increasing highest treatment temperature (HTT), but also varied with the type of feedstock. For example, hydrochar created from waste materials, including waste paper, food waste, mixed municipal solid waste, and anaerobic digestion waste, had yields

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ranging from 29% to 63% [9], pinewood meal had yields between 50% and 60% for HTTs ranging from 225 °C to 265 °C [10], and anaerobically digested sludge had yields ranging from 80.4% to 93.9% for HTTs from 180 °C to 250 °C [11].

While surface area is directly correlated with HTT for dry pyrolysis chars, mixed results are observed for hydrochar. Pinewood hydrochar showed an increase in surface area from 9.65 m<sup>2</sup>/g to 20.43 m<sup>2</sup>/g when the HTT was increased from 250 °C to 300 °C [13]. However, surface area decreased as HTT increased for hydrochar made from urban food waste and anaerobically digested corn silage [14,15]. In biochar, carbon content increases with increasing HTT, while hydrogen and oxygen decrease [12]. Trace mineral contents also increase with higher HTT and thus become more alkaline as well [12,16]. Hydrochars tend to be more acidic than biochar due to their lower trace element contents [12,14].

Because the elemental composition and physicochemical properties of hydrochars vary with production conditions, it is important to optimize the production conditions of hydrochar to its intended uses. While a number of studies have compared hydrochars to biochars for a specific applications, few comprehensive studies have compared hydrochars created under a range of processing conditions and testing them for a variety of applications [4]. Even fewer studies have examined the potential of hydrochars to sorb environmental contaminants and thus be used for environmental remediation.

The overarching objective of this study was to determine how feedstock and production temperature affect the physicochemical properties, potential applications, and potential impacts of hydrochar, and thus to determine the optimal processing conditions for effective usage in multiple purposes. Hydrochars were produced from bagasse, hickory, and peanut hull, each at 200 °C, 250 °C, and 300 °C, and their basic physical and chemical properties were determined. To test the ability of hydrochars to sorb organic, cationic, and anionic contaminants, laboratory batch sorption were conducted with methylene blue, lead, and phosphate, respectively. Growth studies were also conducted to investigate whether or not these hydrochars are safe for environmental applications.

## 2. Materials and methods

### 2.1. Hydrochar production

Three different feedstocks were used: sugarcane bagasse (B), hickory (H), and peanut hull (P). The feedstocks were milled to particle sizes of 0.5–1 mm and added to a 500 mL stainless steel pot so that there was about one inch of space between the feedstock and the top of the autoclave. Deionized (DI) water was added to ensure that the feedstocks were submerged. There were 40 g of bagasse, 50 of hickory, and 55 g of peanut hull with 310 mL, 290 mL, and 313 mL of water, respectively. The pots were heated on a hotplate to 200 °C, 250 °C, and 300 °C for 6 h, respectively. The pots were then allowed to cool to room temperature. The resulting hydrochars were then isolated by filtration using 0.45 µm filter paper (Whatman), washed for 1 h by submersion in tap water and 10 min in DI water to remove water soluble volatile matter, and oven dried for 24 h at 70 °C. The hydrochar samples obtained were labeled as B200, B250, B300, H200, H250, H300, P200, P250, and P300, respectively, based on their feedstock type and processing temperature.

### 2.2. Characterization of hydrochar properties

A CHN Elemental Analyzer (Carlo-Erba NA-1500) was used to determine the carbon, hydrogen, and nitrogen contents of the

hydrochars. Inorganic elemental concentrations were measured after dry ashing 0.2 g of each hydrochar in a muffle furnace for 2 h at 550 °C. A 5% HNO<sub>3</sub> solution was added to each of the ashed samples, and the solutions were measured for multiple trace elements through ICP analysis (ICP-AES, Perkin Elmer Optima 2100 DV). Oxygen content was calculated as the difference between the original dried sample weight and the sum of weights of all the measured elements.

The surface areas (SA) and pore volumes (PV) of the samples were measured by N<sub>2</sub> and CO<sub>2</sub> sorption on a Quantachrome Autosorb I, with N<sub>2</sub> at 77 K and CO<sub>2</sub> at 273 K, respectively. Samples were de-gassed under vacuum at least 24 h at 180 °C prior to analysis. SA-N<sub>2</sub> was calculated according to BET theory using adsorption data in the 0.01 – 0.3 relative pressure range, while SA-CO<sub>2</sub> used the <0.02 range relative pressure data and were interpreted using canonical Monte Carlo simulations of the non-local density functional theory. Because N<sub>2</sub> is kinetically impeded from entering micropores (<1 nm), SA-N<sub>2</sub> represents only mesopore-enclosed surfaces (2–50 nm). SA-CO<sub>2</sub> includes micropores because CO<sub>2</sub> diffusion is less kinetically limited and BC is more flexible at 273 K. Mesopore volumes (PV-N<sub>2</sub>) were calculated using Barrett–Joyner–Halenda (BJH) theory and micropore volumes (PV-CO<sub>2</sub>) using the Grand-Canonical-Monte-Carlo (GCMC) method and assuming slit-shaped pores and an equilibrium model.

The thermal stability of the hydrochars were measured with a thermogravimetric analyzer (Mettler Toledo) using a heating rate of 10 °C/min from 25 °C to 700 °C under a steady stream of airflow at 50 mL/min. Ash content was determined as the mass left over after this treatment.

To determine pH, 1 g of each hydrochar mixed with 20 mL of DI water was shaken on a mechanical shaker for 2 h and then measured with a pH meter (Fisher Scientific Accumet Basic AB15). Zeta potential was measured by mixing 10 mg of hydrochar with 100 mL DI water and sonicating the mixture for 3 h to break up the hydrochar particles into smaller fractions. The resulting solution was analyzed with a Brookhaven ZetaPlus zeta potential analyzer.

### 2.3. Batch sorption experiments

Three different contaminants were tested: methylene blue (20 ppm), lead (20 ppm), and phosphate (50 ppm). All chemicals used were ACS certified and obtained from Fisher Scientific and solutions were prepared using DI water (Nanopure water, Barnstead). Mixtures of 30 mL of each solution and 0.1 g of hydrochar in digestion vessels were shaken on a mechanical shaker at 40 rpm for 24 h. The solutions were then immediately filtered through 0.45 µm filter paper (Whatman). Lead and phosphate contents were analyzed using the ICP spectroscopy, and methylene blue was measured with a UV spectrometer at a wavelength of 665 nm.

### 2.4. Seed germination and seedling growth

To test the effects of hydrochars on seed germination and growth, filter paper (Whatman 42 Ashless) was cut to fit snugly in the bottom of plastic beakers. Then 0.2 g of each hydrochar was sprinkled on the filter paper along with 20 brown top millet seeds and 3 mL of DI water. In the control group, 20 brown top millet seeds and 3 mL of DI water were sprinkled on the filter paper. The beakers were covered with aluminum foil and kept at room temperature in the dark for 72 h. Afterwards, the number of seeds that germinated was counted and the lengths of the roots and shoots of each germinated seedling were recorded in a fully extended position.

### 3. Results and discussion

#### 3.1. Hydrochar production rates

Hydrochar yield ranged from 26.8% to 54.6% from the initial dry weight of the feedstocks (Table 1). For all feedstocks tested, hydrochar yield decreased with increasing production temperature. Sugarcane bagasse had the lowest char yield for all three temperatures. This is likely because a greater degree of biomass dissolution occurred at higher temperatures; more volatilization loss of biomass occurs at higher pyrolysis temperatures, decreasing biochar yield [17,18]. When the pyrolysis temperature was the same, hickory had the highest char yield percentage among the three feedstocks for 200 °C and 250 °C, while peanut hull had the highest char yield percentage for 300 °C. The lower yield of sugarcane bagasse for all three temperatures is likely related to its lower lignin content than woods and husks [19]. Lignin has a stable phenolic structure that allows it to resist breaking down into liquid and gaseous fractions. For example, pure lignin was previously shown to have the highest char yield during HTC compared to pure cellulose and pine wood meal [10]. Furthermore, the high cellulose content of bagasses also caused its hydrochar yield to decrease at a greater rate from 200 °C to 250 °C than that of hickory and peanut hull.

#### 3.2. Surface area and pore volume

Hydrochar surface areas and pore volumes (Table 1) were low (mesopore SA < 10 m<sup>2</sup> g<sup>-1</sup> and micropore SA < 150 m<sup>2</sup> g<sup>-1</sup>), similar to that of the original biomass and pyrolytic biochars made at low temperatures (<400 °C) [18]. Hydrochars with the highest surface area and pore volume were those produced at 200 °C regardless of feedstocks (Table 1). This is different from dry pyrolysis chars, where production temperature is often positively correlated with surface area and pore volume [20]. The decrease in surface area and pore volume as HTT increased was a phenomenon observed in oil palm stone biochars, where surface area steadily increased

from 400 °C to 800 °C before decreasing [21]. In pine biochar, surface area also began to decrease as HTT went over 750 °C [22]. The decrease in surface area is due largely to the pore wall collapse as a result of deformation, melting, and fusion at high HTTs, which occurs at a lower temperature threshold for hydrochars than it does for dry pyrolysis chars, probably because the HTC pressure increases exponentially with the temperature [23].

#### 3.3. Elemental composition

Carbon content was directly related, and oxygen and hydrogen contents were indirectly related to temperature for all feedstocks (Table 2). This is consistent with results observed previously for both biochars and hydrochars [12,24]. At higher temperatures, cleavage and cracking of weak oxygen and hydrogen bonds occur during pyrolysis, resulting in carbon content increase in the biochar [24]. In the case of hydrochars, it is likely that O and H-containing chemical moieties are more soluble and thus preferentially lost at higher temperatures and pressures.

The O/C and H/C of the hydrochars decreased with increasing temperature (Table 2), suggesting that higher temperature hydrochars have relatively high levels of aromaticity and will thus be of greater stability when applied to soils [25]. Previous studies have shown that biochars with an O/C ratio below 0.2 will have a half-life of at least 1000 years [26]. It might follow that the 300 °C bagasse hydrochars (B300) produced in this work can be similarly used to enhance soil C sequestration.

The high O/C of hydrochars obtained at low HTC temperatures indicate greater abundances of oxygenated surface functional group such as hydroxyl, carboxylate, and carbonyl groups [27]. These functional groups yield a greater cation exchange capacity (CEC), which is beneficial for nutrient retention in soils and sorption of positively charged contaminants such as heavy metals [3,28,29]. Thus, low temperature hydrochars may be useful for soil amelioration and contaminant remediation purposes.

C/N ratios ranged from 37 to 392 (Table 2). The relationship between HTT and C/N ratio was inconsistent. For bagasse hydrochar,

**Table 1**  
Properties of hydrochars produced from bagasse (B), hickory (H), and peanut hull (P) at 200 °C, 250 °C, and 300 °C.

	Yield (%)	SA-N <sub>2</sub> (m <sup>2</sup> /g)	PV-N <sub>2</sub> (cm <sup>3</sup> /g)	SA-CO <sub>2</sub> (m <sup>2</sup> /g)	PV-CO <sub>2</sub> (cm <sup>3</sup> /g)	pH	Zeta potential (mV)
B200	47.75	10.7	0.215	106.3	0.034	4.0	-24.43
B250	33.50	3.9	0.035	93.2	0.030	5.3	-35.27
B300	26.75	4.9	0.034	86.8	0.027	5.8	-21.79
H200	54.60	7.8	0.121	137.2	0.043	4.9	-25.91
H250	49.60	8.9	0.110	121.6	0.038	5.1	-27.97
H300	27.80	1.8	0.008	120.0	0.037	5.4	-26.04
P200	50.55	7.1	0.010	100.1	0.032	6.2	-29.51
P250	44.91	1.1	0.010	56.3	0.019	6.2	-23.23
P300	36.91	UD	UD	64.7	0.023	6.0	-34.49

UD = under detection limit, SA = surface area, and PV = pore volume.

**Table 2**  
Bulk composition of hydrochars.

	C%	H%	N%	O%	K%	Na%	Ca%	Mg%	S%	Fe%	P%	Al%	O:C	H:C	C:N
B200	69.15	5.11	0.54	25.74	0.01	0.03	0.03	0.02	0.05	0.01	0.00	0.01	0.37	0.07	128.06
B250	75.08	5.64	0.76	19.28	0.01	0.03	0.04	0.03	0.08	0.01	0.02	0.01	0.26	0.08	98.79
B300	79.31	5.34	0.88	15.35	0.01	0.04	0.06	0.03	0.11	0.01	0.03	0.01	0.19	0.07	90.64
H200	68.66	5.31	0.18	26.03	0.01	0.02	0.08	0.03	0.05	0.01	0.00	0.01	0.38	0.08	392.34
H250	70.00	5.02	0.54	24.98	0.01	0.04	0.07	0.04	0.09	0.03	0.00	0.01	0.36	0.07	129.63
H300	78.465	5.14	0.33	16.39	0.01	0.01	0.13	0.01	0.06	0.04	0.01	0.01	0.21	0.07	241.43
P200	70.575	6.04	1.86	23.39	0.03	0.02	0.07	0.02	0.14	0.04	0.06	0.01	0.33	0.09	38.05
P250	74.745	6.14	1.83	19.11	0.03	0.03	0.08	0.03	0.15	0.02	0.07	0.04	0.26	0.08	40.84
P300	76.415	6.07	2.06	17.52	0.03	0.02	0.16	0.05	0.13	0.03	0.17	0.04	0.23	0.08	37.09

**Table 3**  
Elemental composition of the processing liquid (mg/L).

	K	Na	Ca	Mg	S	Fe	Mn	Mo	Cu	P	Al	B
B200	172.9	10.9	157.2	74.8	142.8	57.3	1.7	0.4	1.7	11.0	1.5	0.8
B250	175.1	11.9	157.5	71.7	100.4	8.4	1.8	0.4	1.7	9.4	1.6	0.8
B300	164.9	10.9	149.8	40.5	89.2	UD	1.8	0.3	1.7	6.7	1.5	0.8
H200	181.3	6.8	186.7	108.2	49.6	0.5	16.7	0.4	1.7	6.8	1.7	0.9
H250	137.8	7.2	110.9	68.6	69.6	105.4	8.5	0.3	1.7	10.9	1.7	0.9
H300	174.0	6.1	138.4	107.0	65.8	60.1	16.2	0.3	1.7	1.7	1.7	1.0
P200	1013.6	8.3	86.7	116.4	319.0	32.5	5.0	0.4	1.7	33.1	1.7	1.0
P250	1079.2	12.1	81.5	124.3	362.6	0.5	4.6	0.4	1.7	45.6	1.6	0.7
P300	1036.8	10.5	40.5	99.0	327.4	0.0	2.5	0.3	1.7	7.4	1.5	0.7

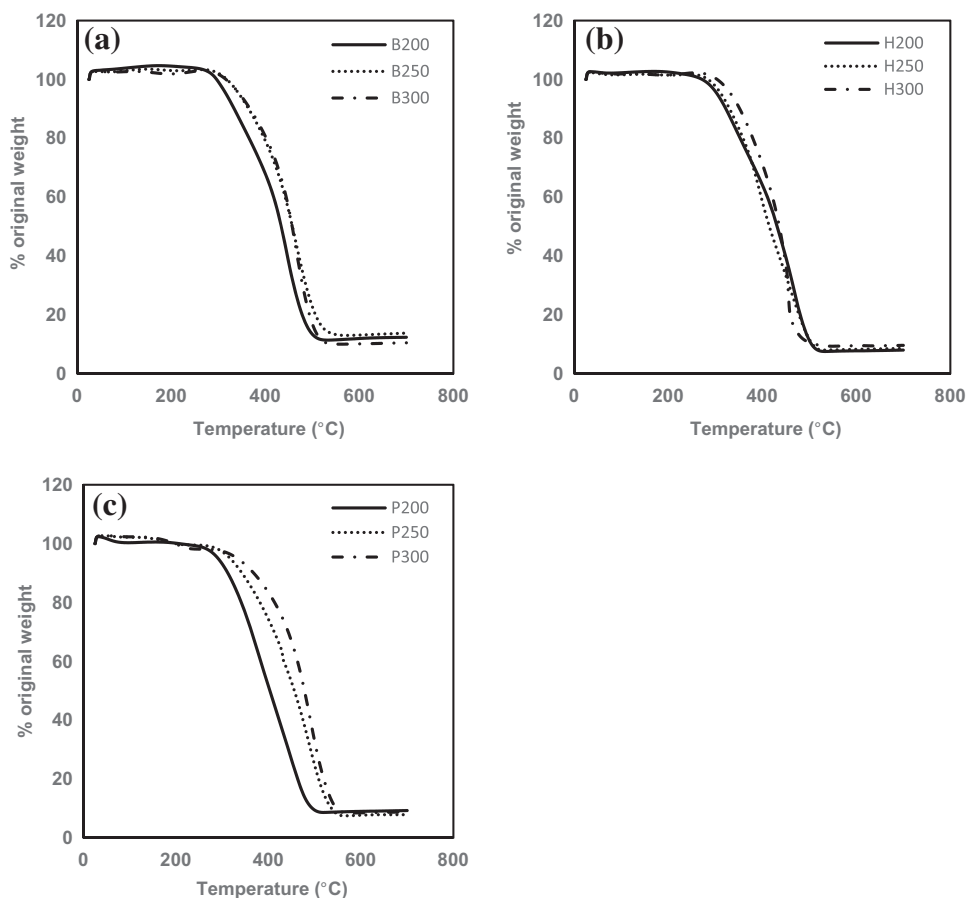
UD = Under detection limit.

C/N ratio decreased with increasing HTT. Hickory 250 °C hydrochar, however, had the lowest C/N ratio, while C/N ratio in peanut hull experienced little change with HTT. In any case, hydrochars are not likely to be significant sources of N to microbes or plants [30,31].

All of the hydrochars were low in minor and trace element concentrations (less than 1% for the elements tested, Table 2). Thus, they would not likely be useful as direct sources of nutrients, such as K, Ca, and P. The processing liquid was rich in nutrients as most of the nutrients in the biomass feedstocks were released during the HTC process and thus might be applied to agricultural land to fertilize crops (Table 3). Furthermore, when hydrochars are applied with commercial fertilizers to soils, they may retain nutrients from leaching and improve soil fertility as well as promote carbon sequestration [4]. Additionally, hydrochars with low inorganic element contents could be “clean” sorbents in aqueous solutions, as they will not alter the chemistry of the solution being remediated.

### 3.4. pH and zeta potential

Consistent with results of previous studies [17,32], all the hydrochars were slightly acidic (Table 1). At all temperatures, hydrochars produced from bagasse are more acidic than those from hickory and peanut hull. The pH of the hydrochars has been found to be controlled by the inorganic mineral contents of the feedstock [14]. As the mineral content of these samples was found to be so low, however, it may also be dependent upon their organic acid content as has been suggested previously for low temperature biochars [33]. While higher temperature chars tend to be alkaline, the acidity of the hydrochars are similar to that of low temperature biochars, which have both lower mineral contents and higher levels of volatile organic matter [33]. Thus, while hydrochars would not be useful for neutralizing soil acidity, their pH buffering capacity may help a soil to retain nutrients.



**Fig. 1.** Thermogravimetric analysis curves of bagasse (a), hickory (b), and peanut hull (c) hydrochars.

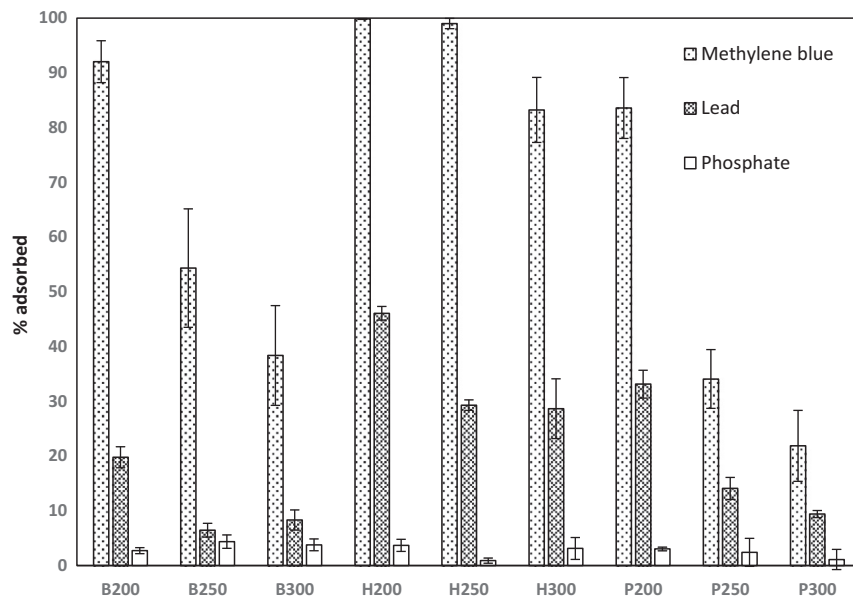


Fig. 2. Hydrochar sorption of methylene blue, lead, and phosphate in aqueous solution (error bars represent standard deviations).

The zeta potential for all of the hydrochars was moderately negative (Table 1), indicating that they have negative surface charges [34]. Thus, hydrochars may be suitable as sorbents of positively charged ions, such as heavy metals. No specific pattern was observed for zeta potential measurements of the hydrochars, although zeta potentials of those derived from bagasse produced at 250 °C and peanut hull at 300 °C were the lowest.

### 3.5. Thermogravimetric analysis (TGA)

Thermal decomposition of all the hydrochars began at around 300 °C and was complete by about 550 °C (Fig. 1). As one would predict, thermal stability increased with HTT for all three feedstocks. Although peanut hull was the most thermally stable, the differences in thermal stability among the feedstocks was not as distinct as it generally is for biochar [12].

Previous studies have shown that thermal stability is a good predictor of biogeochemical stability of biochars [35,36]. The TGA results suggest that hydrochars will be likely to remain stable in the soil if used for carbon sequestration purposes as they will be more resistant to microbial oxidation [37]. If thermal stability is used as a predictor for biogeochemical stability, hickory and bagasse hydrochars do not show any notable improvement in recalcitrance when HTT is increased to 300 °C.

### 3.6. Sorption of contaminants

Results from the batch sorption experiments showed that the higher the HTC temperature, the lower the sorption rate for lead and methylene blue onto the hydrochars, regardless of the feedstock types (Fig. 2). Hickory hydrochars were most effective at sorbing the two contaminants and H200 and H250 removed nearly 100% of methylene blue from the solution. The higher sorption rates of lead and methylene blue at lower temperatures correspond with the fact that lower temperature hydrochars have higher surface areas. The only exception was P300, which showed lower sorption rates than P250, despite a higher surface area. This could be explained by the lower oxygen content of P300. The higher oxygen content in P250 means that there are more oxygen based functional groups for cations to be adsorbed to. Previous studies have demonstrated that oxygen containing functional

groups such as carboxyl and hydroxyl groups play an important role in controlling the sorption of lead and methylene blue on biochar and other carbon materials [2,38,39]. In this work, it is anticipated that the sorption of lead by the hydrochars was mainly attributed to the electrostatic (interaction with negatively charged sites) and complexation (with carboxyl and hydroxyl groups) mechanisms [16,29,38], while the sorption of methylene blue by the hydrochars could be mainly controlled by the electrostatic interactions between the cationic contaminant and the negative charge of the carbon surface [38,39].

None of the hydrochars, however, showed significant affinity for phosphate (Fig. 2). This is due to the fact that they have negative surface charges, which repel negatively charged compounds such as phosphate [40–42]. Several studies have shown that the repulsive electrostatic interactions can reduce the sorption of phosphate ions onto negatively charged carbon surfaces [42–44].

Hydrochars derived from bagasse and peanut hull at 250 °C displayed a more drastic decrease in sorption ability from those produced at 200 °C, while this pattern did not become apparent in those derived from hickory. Compared to hickory, the peanut hull char's surface area decreased significantly when the target heating temperature was increased from 200 °C to 250 °C.

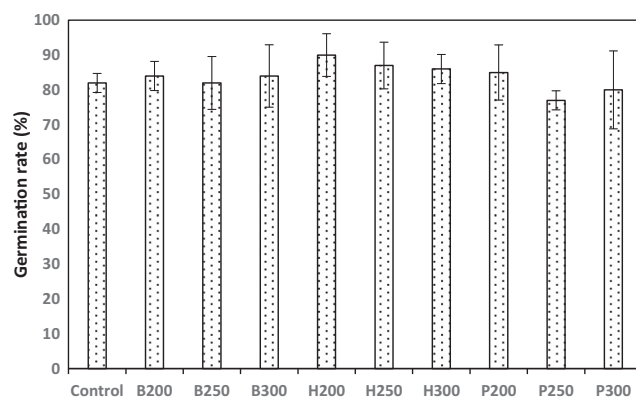


Fig. 3. Effects of hydrochars on seed germination (error bars represent standard deviations).

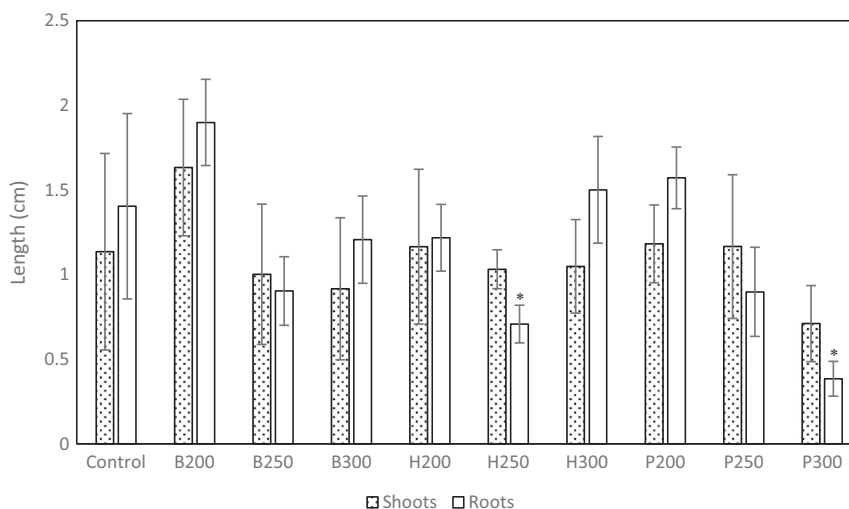


Fig. 4. Effects of hydrochars on seedling growth (error bars represent standard deviations). "\*" indicates statistical difference from the control ( $p \leq 0.05$ ).

Bagasse did not experience a dramatic decrease in surface area, but the decreased sorption ability can be explained by the oxygen contents of the chars – from 200 °C to 250 °C, the oxygen content decreased more for bagasse than it did for hickory, by 6% and 2%, respectively.

### 3.7. Seed germination and growth

None of the hydrochars showed any statistically significant effects on seed germination rates of brown top millet (Fig. 3). The hydrochars used in our experiment had been washed with DI water. These results are consistent with those shown in previous studies conducted on hydrochar application to spring barley, which indicated that phytotoxic volatile compounds found in unwashed hydrochar were responsible for the reduced seed germination rate [45]. When seeds germinated on water washed hydrochars, the difference in germination rate was insignificant compared to control treatments. In the same study, biochar was found to have no harmful effects on seed germination because much of the volatile matter was evaporated during pyrolysis [45]. In the studies of chars produced from dry pyrolysis, higher temperature biochars were found to have a more positive effect on plant growth than lower temperature biochars. The lower temperature biochars had volatile compounds on the surface that blocked the pores on the char, but after washing, no difference was observed [46].

Hydrochars derived from lower temperature tended to be better for seedling growth than those produced at higher temperatures (Fig. 4). Among the entire tested samples, the group with B200 had the longest average root and shoot lengths. ANOVA tests were conducted, and hydrochar amendment was not observed to have a significant effect on shoot lengths. However, the results showed that the root length of seedlings produced with H250 and P300 were significantly reduced compared to that of the control and other hydrochar treatments (Fig. 4). In addition to the physical and chemical properties, it is possible that some unknown factors may affect seedling growth. For example, volatile matter was able to be removed from the hydrochars through prewashing treatment; however, the tars, which the higher temperature hydrochars had a higher content of, are not water soluble. Tar remnants on the hydrochar may affect the growth of the seedlings. Nevertheless, our results showed that seedlings grown with hydrochars produced at 200 °C were generally comparable to those produced from the control treatment.

## 4. Conclusions

Hydrothermal carbonization provides an alternative to dry pyrolysis to convert waste biomass to a useful product that can be used for soil amelioration or contaminant remediation. In addition to higher yields and lower energy inputs during its production, the hydrochars produced by HTC had unique physical characteristics and good ability to sorb aqueous cationic contaminants. None of the hydrochars had any negative effects on seed germination and shoot growth, though two of the higher temperature hydrochars showed a tendency to decrease root growth.

While the higher temperature chars were more thermally stable than lower temperature chars, the difference was not as pronounced as it is in biochars. Because hydrochars created at lower temperature (200 °C) require less energy to produce and showed higher yields, better sorption ability, and no negative effect on plants, low temperature HTC of plant biomass should be recommended for most environmental remediation and soil amendment purposes unless soil acidity is of concern. At present, our understanding of hydrochar surface chemistry and its interaction with nutrients, contaminants, and other soil organic matter is immature. Further research should focus on developing production conditions and modification/activation methods that can produce hydrochars with characteristics tuned to meeting the needs of specific environmental applications.

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