

Sorption properties of greenwaste biochar for two triazine pesticides

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ABSTRACT

Biochar is a carbon-rich product generated from biomass through pyrolysis. This study evaluated the ability of an unmodified biochar to sorb two triazine pesticides – atrazine and simazine, and thereby explored potential environmental values of biochar on mitigating pesticide pollution in agricultural production and removing contaminants from wastewater. A greenwaste biochar was produced by heating waste biomass under the oxygen-limited condition at 450 °C. The effects of several experimental parameters, including biochar particle size, contact time, solid/solution ratio, and solution pH on the sorption of atrazine and simazine were comprehensively investigated. The biochar with small particle size needed less time to reach sorption equilibrium. The sorption affinity of the biochar for the two pesticides increased with decreasing solid/solution ratio. The sorbed amounts (C_s) of atrazine and simazine increased from 451 to 1158 mg/kg and 243 to 1066 mg/kg, respectively, when the solid/solution ratio decreased from 1:50 to 1:1000 (g/mL). The sorption of the biochar for both pesticides was favored by low pH. The sorption isotherms of atrazine and simazine on the biochar are nonlinear and follow a Freundlich model. When atrazine and simazine co-existed, a competitive sorption occurred between these two pesticides on the biochar, reflecting a decrease in sorption capacity (K_f) from 435 to 286 for atrazine and from 514 to 212 for simazine. Combined adsorption and partition mechanisms well depicted sorption of atrazine and simazine on carbonized and noncarbonized fractions of the biochar in the single-solute and co-solute systems.

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1. Introduction

Fossil oil reserve depletion and global climate change are two major energy and environmental challenges of our time. Biomass as an alternative to fossil fuels is receiving great attention because it is a renewable and carbon-neutral energy resource. Burning biomass in a closed system under limited supply of oxygen (i.e., pyrolysis) yields a series of energy products: bio-oil, syngas, and biochar.

Biochar is a carbon-enriched and porous material produced from a variety of biomass. Biochar can be used directly as a replacement for pulverized coal, but its application to soil exhibits much more value [1–3]. When used as a soil amendment, biochar can boost soil fertility and improve soil quality by raising soil pH, increasing moisture holding capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity, and helping soil retain nutrients [4,5]. A plot trial showed benefits of soil amendment with a greenwaste-derived biochar, including increased crop yield and improved soil quality [6]. Another benefit associated with the use of biochar as a soil amendment is that it can sequester

carbon from the atmosphere–biosphere pool and transfer it into soil [1–5]. Biochar may persist in soil for millennia because it is very recalcitrant to microbial decomposition and mineralization. The recalcitrance of biochar depends strongly on its properties, which are affected in turn by the type of feedstock and the pyrolytic conditions. Previous studies indicate that the bioenergy strategy involving biochar not only leads to a net sequestration of CO₂, but also that the use of biochar in soil may decrease emissions of other more potent greenhouse gases such as N₂O and CH₄ [7]. Therefore, modern biochar production from biomass (especially from waste biomass) and its use as a soil amendment may provide an attractive solution to alleviate the energy and environmental crises by decreasing dependence on fossil fuels and storing atmospheric carbon into soil.

The production of biochar by pyrolysis is a carbonization process in which the content of carbon increases with temperature accompanied by a simultaneous decrease in oxygen and hydrogen contents. The properties of biochar are different from activated carbon, though both of them are carbon-rich material. Generally, biochar is a not fully carbonized product because its production by pyrolysis is often operated under low temperatures (<500 °C) [5]. In contrast, the production of activated carbon from organic materials includes a two-step process: carbonization and activation

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[8]. After physical and chemical activation, the surface areas and internal pore structures of activated carbon are greatly enhanced and improved compared to biochar that only experiences the carbonization treatment [9]. Thus, biochar may act as a precursor to manufacture activated carbon.

Biochar is similar to activated carbon in some respects as a surface sorbent. Biochar usually possesses greater sorption ability than natural soil organic matter due to its greater surface area, greater negative surface charge, and greater charge density [10]. Biochar can not only strongly sorb many cationic chemicals such as ammonium ions and a variety of metal ions [11], but also efficiently remove anionic nutrients such as phosphate from aqueous solutions [5]. Thus, the addition of biochar into soil offers a potential environmental benefit by preventing the loss of nutrients and thus protecting the water quality. Also, previous studies have shown that the soils containing biochar have strong affinity for organic contaminants [12–14]. For example, the burning of crop residues has been reported to enhance the soil sorption for pesticides [12,13], which is attributed to the release of biochar-containing ashes to the soil. However, little is known about the environmental implications of direct application of unmodified biochar on the fate and transport of pesticides in soil [7]. Additionally, modified biochar (i.e., biochar through some specific physical and chemical activation treatments) has demonstrated its great potential to effectively remove a variety of organic contaminants from water as a sorbent [15,16]. The research field pertaining to the use of biochar as a cost-effective sorbent is rapidly emerging.

The primary objective of this study was to investigate sorption of atrazine and simazine by an unmodified biochar pyrolyzed from waste biomass and thereby evaluate the potential of biochar for removing pesticide residues from aqueous solution. These two triazine pesticides were chosen because they have been heavily applied for preemergence control of broadleaf weeds and annual grasses in corn and soybean crops in the United States. For example, atrazine was the most commonly used pesticide in the U.S. agriculture and its sale at present is still steadily maintained at 70–80 million pounds per year [17]. Accordingly, these pesticides are frequently detected in agricultural tile-drainage systems and surface water.

2. Materials and methods

2.1. Chemicals

Atrazine (99%) and simazine (99%) were purchased from Chem Service (West Chester, PA). Stock solutions of these two triazine herbicides were prepared in methanol. Deionized water ($>17.6 \text{ M}\Omega\text{-cm}$) was supplied by a Labconco Water Pro Plus system (Kansas City, MO). All chemicals were used as received.

2.2. Biochar production and characterization

The biochar feedstock was a greenwaste collected from Orchard Downs at the University of Illinois in Urbana, IL. The greenwaste from plant pruning was a mixture of maple, elm, and oak woodchips and barks. The collected samples were air dried for 7 days and subsequently oven-dried overnight at 80°C . The dry greenwaste was ground to less than 3 cm prior to use.

The production of biochar was conducted in a lab-scale pyrolysis unit developed at the Illinois Sustainable Technology Center. The pyrolysis system consists of a 4-L volume batch reactor equipped with a programmable temperature controller (up to $>900^\circ\text{C}$) and a cooling system (to collect gas and bio-oil). The batch reactor was filled up with greenwaste, covered with a fitting lid, and pyrolyzed under the oxygen-limited condition for 60 min at 450°C . The pyro-

Table 1

Physicochemical properties of the biochar with different particle sizes.

Biochar (mm)	SSA (m^2/g)	% C	% H	% N	% O ^a	% Moisture	% Ash
<0.250	6.74 ± 0.76	70.87	2.97	1.19	12.97	1.70	10.30
<0.125	7.29 ± 0.54	70.66	2.91	1.21	13.59	1.65	9.98
<0.075	7.57 ± 0.27	71.79	2.95	1.15	12.49	1.73	9.89
<0.053	7.56 ± 0.29	71.18	2.83	1.15	10.27	1.68	12.89

Abbreviations: SSA, specific surface area; C, carbon; H, hydrogen; N, nitrogen; O, oxygen.

^a By difference.

lysis temperature was chosen based on the previous reports on the production of biochar for soil amendment purposes [5,6]. Vapors generated during the pyrolysis were condensed to bio-oil by passing through the cooling system and collected in a quencher. After pyrolysis, biochar in the reactor was allowed to cool overnight to room temperature and then the sample mass was recorded. The yield of each bio-product was defined as the ratio of the weight of the product to that of the original greenwaste. Under these pyrolysis conditions, the yields of biochar, bio-oil, and syngas from the greenwaste were approximately 33%, 45%, and 22%, respectively. The biochar was sealed in a glass bottle and stored at room temperature until use.

The biochar was characterized for physical and chemical properties. Elemental analyses were conducted by the Microanalysis Laboratory at the University of Illinois using CE 440 CHN analyzer (Exeter Analytical). The N_2 -BET surface areas of the biochar samples were measured in static volumetric apparatus (Monosorb, Quantachrome Corporation) [8]. Ash content was measured by heating the samples at 800°C for 4 h. The physicochemical properties of the biochar with different particle sizes are shown in Table 1

2.3. Sorption experiments

Sorption of atrazine and simazine on the greenwaste biochar was determined using a batch equilibrium method. Briefly, 10 mL of pesticide solutions and the biochar were placed in conical glass vials. All sealed sample vials were agitated on a reciprocal shaker at 180 rpm and $22 \pm 0.5^\circ\text{C}$. At pre-determined times, sample vials were withdrawn from the shaker. Sample solutions from each vial were immediately filtered through a $0.45\text{-}\mu\text{m}$ membrane using a syringe. The filtrate was analyzed for pesticide concentrations using high pressure liquid chromatography (HPLC) techniques as described below. The amount of pesticide sorbed to the biochar was calculated from the difference between the initial and final concentrations of the pesticide in the solution phase. A preliminary experiment showed that no sorption occurred on the glass wall of the vials and loss due to volatilization was insignificant. Control experiments were concurrently performed in aqueous solutions containing only atrazine or simazine to determine the probable hydrolysis during the experimental period. All experiments were carried out in triplicate.

A variety of experimental factors affecting sorption of atrazine and simazine on the biochar were considered during the study. The experiment related to each factor is summarized below:

- Effect of particle size on sorption kinetics:* The greenwaste biochar was ground and then sieved through different size screens to obtain biochar subsamples with particle sizes <0.250, <0.125, <0.075, and <0.053 mm, respectively. Each particle size biochar (100 mg) was weighed into 10 mg/L atrazine solution. The procedure described above was used for shaking, sampling, and analysis of the residual pesticide in aqueous solutions.
- Sorption isotherm:* Stock solution containing 1000 mg/L atrazine in methanol was delivered to 10 mL of aqueous solutions, yielding an initial pesticide concentration ranging from 0.05 to

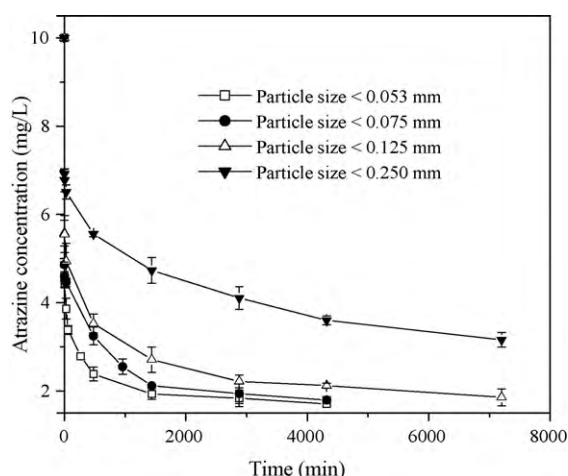


Fig. 1. Example time courses for sorption of atrazine on the biochar with different particle sizes at $22 \pm 0.5^\circ\text{C}$. Error bars represent standard deviation of triplicate samples.

30 mg/L. Similarly, simazine solutions with an initial concentration ranging from 0.05 to 5 mg/L were prepared using its stock solution (250 mg/L simazine in methanol). The biochar (100 mg) with a particle size at <0.075 mm was added into each solution sample. All samples were shaken 1 day to achieve the sorption equilibration.

- (c) *Solid/solution ratio*: Varied amounts of the biochar (10–200 mg) with a particle size at <0.075 mm were weighed into 10 mL of pesticide solutions to achieve a series of solid/solution ratios. The initial concentrations of atrazine and simazine were 10 and 5 mg/L, respectively.
- (d) *Effect of pH*: Aqueous buffer solutions (pH 3–10) were prepared, using KCl and HCl for pH 3, acetate buffer for pH 5, phosphate buffer for pH 7, and borate buffer for pH 9 and 10. The biochar (100 mg) with a particle size at <0.075 mm was weighed into glass vials containing 10 mL of buffer solutions with initial atrazine concentration at 10 mg/L or simazine at 5 mg/L.
- (e) *Competitive sorption experiment*: The experiment was performed in 10 mL of pesticide solutions with 100 mg of biochar (particle size at <0.075 mm). Two types of atrazine and simazine mixture solutions were tested: (1) solutions with a fixed concentration of atrazine (10 mg/L) and varied concentrations of simazine (0.05–5 mg/L) and (2) solutions with a fixed concentration of simazine (5 mg/L) and varied concentrations of atrazine (0.05–30 mg/L).

2.4. Analytical method

Concentrations of atrazine and simazine in samples were analyzed using a Water 2695 Separations Module HPLC equipped with a Waters 996 photodiode array detector (PDA). Separation was performed using a Supelcosil C_{18} analytical column (250 mm \times 4.0 mm i.d.; particle size, 5 μm). The mobile phase consisted of acetonitrile/water (50:50, v/v), the flow rate was 1.0 mL/min, and the detector wavelength was 223 nm. Under these conditions, the retention times for atrazine and simazine were 5.4 and 7.0 min, respectively.

3. Results and discussion

3.1. Effect of particle size on sorption kinetics

Example time courses for sorption of atrazine on the biochar with different particle sizes are shown in Fig. 1. Once biochar was

added into the aqueous solutions, the concentrations of the pesticide immediately decreased. Approximately 54%, 51%, 44%, and 31% of the amounts of atrazine during the first minute were removed by the biochar with particle sizes at <0.053 , <0.075 , <0.125 , and <0.250 mm, respectively. The concentration of atrazine in the aqueous solution then decreased gradually with increasing the contact time until the maximum sorption of the biochar was achieved. The initial rapid removal of atrazine from aqueous solution may be attributed to the highly hydrophobic surface of biochar, which may preferentially sorb hydrophobic solutes from water. However, the surface of biochar would be hydrated once contacting with water [18], which would alter its hydrophobic property. Thus, this sorption kinetic process (Fig. 1) distinguishes biochar from most of commonly used sorbents such as activated carbon or polymeric adsorbents. Before approaching equilibrium, sorption of organic contaminants onto activated carbon and polymeric sorbents is a gradual process and is controlled by intra-particle diffusion mechanism [19,20].

Although the biochar with different particle sizes have similar chemical compositions and surface areas (Table 1), their equilibrium time for atrazine sorption exhibits a significant difference. As shown in Fig. 1, the biochar with a small particle size needs less time to reach sorption equilibrium, indicating that the removal rate of atrazine from aqueous solution depends on the biochar particle size. For example, the biochar with particle size less than 0.075 mm needed 1 day to reach the sorption equilibrium. When the particle size of biochar increased to <0.125 and <0.250 mm, the sorption equilibrium time was lengthened to >2 and >5 days, respectively. These results indicate that the pesticide needs more time to reach the microporous region of the biochar with a large particle size. Previous kinetics studies also showed that the sorption by biochar or char always needed 1 day or several days to reach equilibrium [18,21].

Similar sorption kinetics was also observed for simazine (data not shown). Decreasing biochar particle size shortened the time for the pesticide to reach the sorption equilibrium. Biochar with particle size <0.075 mm was selected for the further experiments and thereby the sorption equilibrium time was set up at 1 day.

3.2. Sorption isotherm

The sorption isotherms of atrazine and simazine on the biochar are displayed in Fig. 2. It can be clearly seen that sorption isotherms of these two pesticides by biochar are nonlinear with a concave-downward shape. Fig. 2 shows that the affinity of the biochar for atrazine and simazine decreased progressively with increasing pesticide concentration. Biochar usually comprises of carbonized and noncarbonized fractions, which indicates that the surface of biochar is heterogeneous [15,16]. A previous study using scanning electron micrograph revealed that the unmodified biochar has a rudimentary pore structure and its partial surface is accumulated with tar-like deposits [9].

In such systems, the experimental sorption data are often analyzed using the Freundlich and Langmuir models, which correspond to the heterogeneous and homogenous sorbent surfaces, respectively. Considering the heterogeneous surface of biochar, the Freundlich expression was used in the study to model sorption of two pesticides on the biochar:

$$\log C_s = \log K_f + \frac{1}{n} \log C_e$$

where C_s is the sorbed concentration of pesticide (mg/kg) on the biochar, C_e is the equilibrium concentration of pesticide in aqueous solution (mg/L), and K_f and $1/n$ are adjustable parameters used to fit the model to experimental data. The coefficient K_f (mg/kg)(mg/L) $^{-n}$ represents the relative sorption capacity of

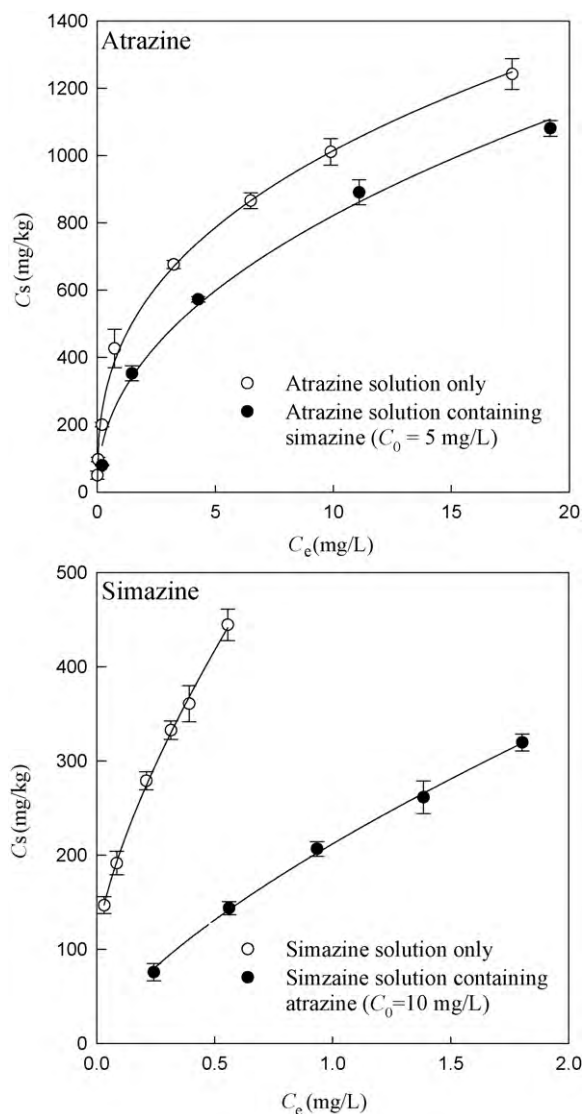


Fig. 2. Sorption isotherms of atrazine and simazine on the biochar at $22 \pm 0.5^\circ\text{C}$. Error bars represent standard deviation of triplicate samples.

the sorbent, and $1/n$ (dimensionless) reflects the curvature in the isotherm.

The Freundlich constants K_f and $1/n$ together with the correlation coefficient (R^2) are summarized in Table 2. The high R^2 values suggested that the Freundlich model may well simulate the sorption of two pesticides on the biochar. All values of $1/n$ were less than 1, indicating a favorable sorption of two pesticides on the biochar [22]. As shown in Table 2, the sorption capacity (K_f) of the biochar for simazine is higher than that of atrazine. This suggests that simazine may be more favorable for sorption on the biochar than atrazine, although these two pesticides have similar molecular structures.

Table 2

Freundlich parameters (K_f and $1/n$) and correlation coefficients (R^2) for sorption isotherms of atrazine and simazine on the biochar.

	Atrazine		Simazine	
	Single-solute	Co-solute (simazine at 5 mg/L)	Single-solute	Co-solute (atrazine at 10 mg/L)
K_f (mg/kg) (mg/L) ⁻ⁿ	435 ± 15	286 ± 26	514 ± 12	212 ± 2
$1/n$	0.368 ± 0.015	0.458 ± 0.035	0.687 ± 0.063	0.693 ± 0.019
R^2	0.997	0.992	0.993	0.999

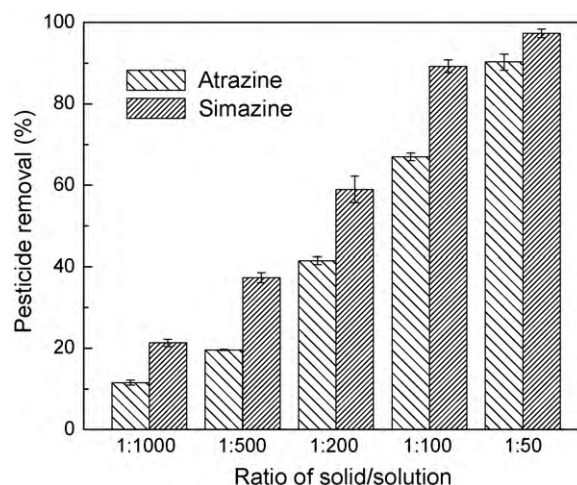


Fig. 3. Effect of biochar application amounts on removal of atrazine and simazine. The volume of each pesticide solution was 10 mL. Error bars represent standard deviation of triplicate samples.

3.3. Effect of solid/solution ratio

The solid/solution ratio is an important factor determining the capacity of a sorbent in a batch sorption study. The effect of solid/solution ratio on sorption of atrazine and simazine is shown in Fig. 3. It can be clearly seen that the removal of these two pesticides increased with increasing the amount of biochar. For example, the percentage removal of atrazine and simazine from the aqueous solutions increased from about 10% to 90% and 20% to 95% when the solid/solution ratio increased from 1:1000 to 1:50 (g/mL), respectively. However, the amounts of these two pesticides sorbed per unit weight of the biochar decreased with increasing the solid/solution ratio. For example, the sorption capacity (C_s) of atrazine and simazine decreased from 1158 to 451 mg/kg and 1066 to 243 mg/kg when the solid/solution ratio increased from 1:1000 to 1:50 (g/mL), respectively.

3.4. Effect of pH

The sorption coefficients K_d (C_s/C_e) of atrazine and simazine were plotted against the solution pH (Fig. 4). The effect of pH on the sorption of two pesticides on the biochar exhibits a similar tendency in the studied pH range (pH 3–10). At pH < 7, the K_d values of two pesticides decreased with an increase in the pH, suggesting that the sorption of the biochar for atrazine and simazine was favored by low pH. At pH ≥ 7 , the sorption of these two pesticides on the biochar had little influence by pH. Atrazine and simazine are weak base pesticides with pK_a at 1.7 and 1.6, respectively. These weak base molecules can be sorbed on soils as both protonated and neutral species depending on the pH of solutions [23]. The neutral species of two pesticides are usually predominated in the environment (pH 5–9), but very low pH solutions will facilitate the formation of their triazine cations [23]. Therefore, the occurrence of triazine cations in acidic media would enhance the pesticide interaction with the negatively charged surface of the biochar via

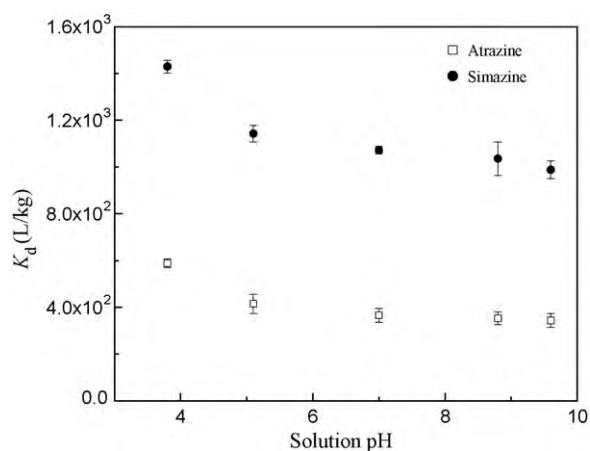


Fig. 4. Effect of solution pH on the sorption affinity of the biochar for atrazine and simazine measured as the linear distribution coefficient K_d (C_s/C_e). The initial concentrations of atrazine and simazine were 10 and 5 mg/L, respectively. Error bars represent standard deviation of triplicate samples.

electrostatic attraction, which would significantly improve sorption affinity of the biochar for atrazine and simazine.

3.5. Competitive sorption

Since atrazine and simazine are often present concurrently in the aqueous environment, their co-existence may impact their sorption behavior on sorbents. The effect of the presence of simazine on the amount of atrazine sorbed by the biochar is shown in Fig. 5A. In the co-solute system, the sorption affinity of atrazine on the biochar decreased in the presence of simazine. Moreover, the sorption capacity of the biochar for atrazine decreased with increasing simazine concentration in the co-solute solutions. A similar result was observed for simazine sorption in the presence of atrazine (Fig. 5B), indicating that the occurrence of competitive sorption between two pesticides on the biochar.

The sorption isotherms of atrazine and simazine on the biochar in the co-solute system are shown in Fig. 2. When the co-solutes existed, both sorption isotherms of atrazine and simazine shifted lower compared to their corresponding isotherms in the single-solute system. For example, the sorption capacity of atrazine on the biochar decreased around 34% in the presence of 5 mg/L simazine, reflecting by a decrease in K_f from 435 to 286. Similarly, the sorption capacity of simazine decreased approximately 59% in the co-solute solutions with the initial concentration of atrazine at 10 mg/L (Table 2). This further implies that the sorption ability of the biochar for atrazine and simazine is expected to decrease when they co-existed in the aqueous environment.

3.6. Sorption mechanisms

A number of conceptual model and mechanisms have been postulated to account for the sorption of organic contaminants in soils and sediments, including competitive sorption [24–26]. Natural sorbents such as soil organic matter (SOM) are considered as a heterogeneous sorbent, which consists of two principal types of sorption domains: a “soft” carbon domain analogous to rubbery polymers and a “hard” carbon domain analogous to glassy polymers [26–29]. These two different types of domains exhibit different sorption mechanisms. The sorption in the rubbery domain would be characterized by a partition mechanism to exhibit a linear and noncompetitive sorption behavior, whereas the sorp-

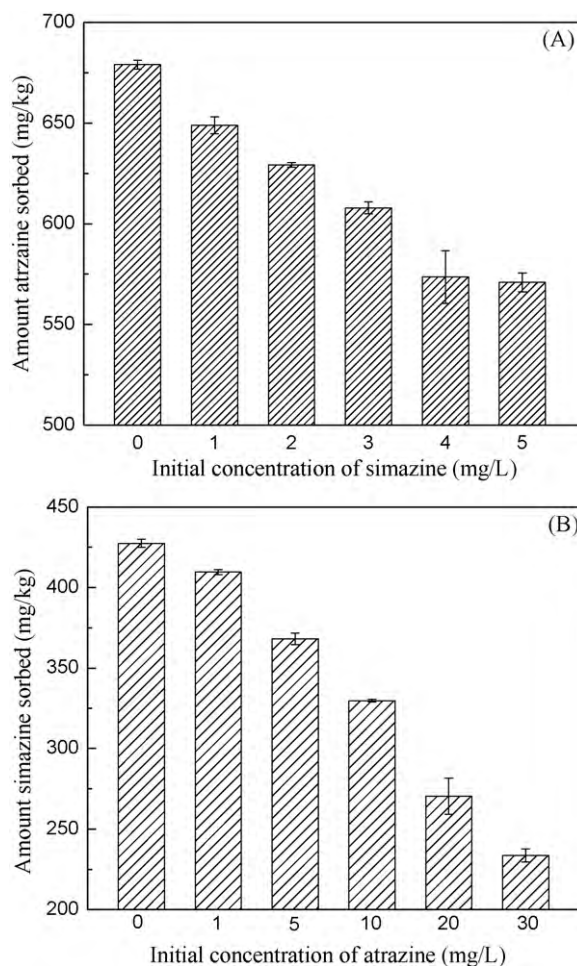


Fig. 5. Competitive sorption between atrazine and simazine on the biochar: (A) the initial concentration of atrazine was 10 mg/L and (B) the initial concentration of simazine was 5 mg/L. Error bars represent standard deviation of triplicate samples.

tion in the glassy domain is a pore-filling mechanism and its adsorption behavior is nonlinear and solute–solute competitive. A previous study demonstrated that nonlinearity and competitive sorption in soils were attributed to the presence of glassy domain carbonaceous materials such as black carbon (soot and charcoal) [29].

The unmodified biochar produced in this study is not fully carbonized. The carbonized and noncarbonized phases of biochar generally represent different sorption mechanisms [15,16]. In contrast to SOM, carbonized fraction on biochar is akin to the glassy domain. Correspondingly, noncarbonized fraction is semblable to the rubbery domain of SOM. Sorption on carbonized phase of biochar is characterized by nonlinear adsorption, whereas sorption on noncarbonized phase follows a partition mechanism which can be described by a linear isotherm. The sorption of atrazine and simazine on the biochar is a combined mechanism with adsorption and partition representing the sorption occurring on carbonized and noncarbonized fractions of the biochar. The nonlinearity of sorption isotherms of atrazine and simazine on the biochar (Fig. 2) is a characteristic of sorption processes arising from site-specific interactions occurring on the carbonized phase of the biochar. In the co-solute system, atrazine and simazine would compete for finite adsorption sites on the carbonized phase of the biochar, which results in a significant decrease in the sorption affinity of the biochar for both pesticides compared to the single-solute solution (Fig. 2 and Table 2).

3.7. Environmental significance

It is known that biochar produced from waste biomass can provide four valuable streams: energy production, waste reduction, carbon sequestration, and soil fertilization. This study suggests that the unmodified biochar can effectively remove atrazine and simazine from aqueous solutions. Compared to previous reports, the sorption capacities of two pesticides on the biochar are much higher than that in agricultural soils [26,30] or compost [8]. A previous study showed that the sorption of atrazine in amended soil is significantly enhanced when biochar is used as a soil amendment [7]. Thus, the addition of biochar to soil may readily hold pesticide active ingredients in soil, effectively prevent their leaching, and ultimately minimize the adverse environmental effects related to pesticide use in agricultural production.

In addition to agricultural application, activated biochar is being developed as an effective sorbent for environmental remediation [15,16]. In contrast to unmodified biochar, the production of activated biochar needs higher temperature and additional treatment processing. Although this activation process requires more energy and higher production cost, the conversion of waste biomass into biochar as a sorbent is a “win-win” solution via improving waste management and protecting the environment [16]. Moreover, some biochar generated from some special waste such as dairy manure can remove both organic contaminants and toxic metals [16]. Therefore, activated biochar as a sorbent akin to activated carbon could be widely applied for a variety of cleansing processes such as water filtration, wastewater treatment, and sorption of gas and solid contaminants.

4. Conclusions

In this study, the biochar produced from waste biomass exhibited a high sorption affinity for two agricultural pesticides – atrazine and simazine. The sorption kinetics showed that that removal rate of the pesticides from aqueous solution depended on the biochar particle size. The biochar with the particle size <0.075 mm needed 1 day for the sorption process to approach equilibrium. When the particle size of the biochar increased to <0.125 and <0.250 mm, the sorption equilibrium time was extended to 2 and 5 days, respectively. The sorption affinity of the biochar for the pesticides increased with decreasing solid/solution ratio. At pH < 7, the sorption affinity of the biochar for atrazine and simazine decreased with increasing the solution pH. At pH ≥ 7, the sorption of these two pesticides on the biochar was little influenced by solution pH changes. The sorption isotherm and competitive sorption studies of the two pesticides in the single-solute and co-solute systems indicate that the biochar is a heterogeneous sorbent with a combined adsorption and partition mechanism, occurring on carbonized and noncarbonized fractions of the biochar. This study suggests that biochar may effectively remove pesticide residues from aquatic environment and thus mitigate pesticide pollution.

Acknowledgments

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