Regulating Environmental Factors of Nutrients Release from Wheat Straw Biochar for Sustainable Agriculture

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Short Communication

Regulating Environmental Factors of Nutrients Release from Wheat Straw Biochar for Sustainable Agriculture

One mechanism by which biochar application enhances soil nutrient availability is through direct nutrients release from biochar. However, factors controlling the release processes are poorly understood. In this study, the effects of pH, biochar to water ratio, temperature, ionic strength, and equilibration time on the release of PO₄³⁻, NO₃⁻, NH₄⁺, K⁺, Na⁺, Ca²⁺, and Mg²⁺ from biochar were evaluated in simulated experiments. The release of PO₄³⁻, K⁺, Ca²⁺, and Mg²⁺ was significantly affected by extraction pH, suggesting that their release from biochar was pH dependent or an H⁺-consuming process. Correlation analysis indicated that PO₄³⁻ and Ca²⁺, PO₄³⁻ and Mg²⁺, and Ca²⁺ and Mg²⁺ were co-solubilized with increasing soil acidity. To a lesser extent, the recovery of the nutrients was also affected by the ratio of biochar to water: more nutrients were soluble with more water supply. In contrast, the release of Na was not affected by pH while the concentration increased with decreasing biochar to water ratio. Meanwhile, other factors (temperature, ionic strength, and equilibration time) had less effect on nutrient release from biochar. Under the influence of pH, the patterns of NO₃⁻ and PO₄³⁻ release from biochar were different: extractable NO₃⁻ concentration was not affected by the pH but more PO₄³⁻ was released in strongly acidic conditions. Our data suggested that P was mainly retained in inorganic forms while N was in organic forms in biochar. We conclude that environmental factors have marked influences on nutrients release from biochar.

Keywords: Agricultural bioresource utilization; Environmental management; Equilibration time; Ionic strength; Soil fertility

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1 Introduction

In recent years, biochar production, focused on agricultural residues, has gained increasing interest [1–3]. Biochar is a recalcitrant organic compound and better environmental improvement additive, created when biomass (feedstock) is heated to temperatures between 300 and 1000°C under low oxygen concentrations [4–6]. Previous studies demonstrated that the application of biochar to soils could sequester carbon [7–9] and reduce soil emissions of greenhouse gases (e.g., NOₓ and CH₄) [10]. Some calculations suggested that a 250-ha farm could sequester approximately 1900 tons of CO₂ per year in the form of biochar applications [11–13]. Rondon et al. (2005) reported a 50% reduction in N₂O emissions from soybean plots and almost complete suppression of CH₄ emissions from biochar amended acidic soils in Eastern Colombian Plains [13–15].

In addition to benefits of biochar application on carbon sequestration and reduction of greenhouse gas emissions, biochar application has been shown to improve crop productivity by increasing nutrients availability and reducing nutrients loss. Increases in crop productivity were observed when biochar was applied concurrently with inorganic fertilizer as compared to applying inorganic fertilizer alone, as well as when biochar was applied to the soil without any fertilizer addition [16]. For example, grain and biomass yield of maize was found to increase by 91 and 44%, respectively, on soils with charcoal compared to adjacent field soils [17, 18]. Possible mechanisms for such yield improvement included stimulation of beneficial microbes such as mycorrhizal fungi [19, 20] in soils, neutralization of acidic soil pH [21, 22], increased water holding capacity [23, 24], and improved retention of soil nutrients [25]. Increases in soil pH have been found on active or historical charcoal-making areas in Ghana, Mexico, and Pennsylvania [26–28].

Apart from indirect mechanisms, the direct effect of biochar, such as the release of nutrients from biochar into soils, can also affect crop productivity. Nutrients released from biochar are important because biochar contain large amounts of nutrients. Wu et al. (2011) showed that biochar contained macro- and micronutrients required for plant growth [29]. Nutrient retention in biochar and the nutrient leach ability may be closely related to the properties of biochar.
which may be affected by the conditions used for biochar production such as temperature during pyrolysis [29] or the type of feedstock used for biochar making [30]. However, little is known about factors controlling and managing nutrients release from biochar [31]. Therefore, the objective of this study was to investigate the impact of pH, water to biochar ratio, temperature, ionic strength, and equilibration time on nutrients release from biochar.

2 Materials and methods

2.1 Biochar

The biochar was produced from wheat straw by pyrolysis at 350–550 °C. The biochar had C and N contents of 46.7 and 0.59%, respectively, an ash content of 20.8%, and a pH (H₂O) of 9.6. With respect to elemental content, the biochar contained 1% Ca, 0.6% Mg, 0.4% Fe, 2.6% K, and 0.3% P [13, 14]. For this study, the biochar was ground to pass through a 2-mm sieve, and mixed thoroughly.

2.2 Analysis of PO₄⁻³⁻, NO₃⁻, and NH₄⁺ concentrations

The effects of pH (from 2 to 9.6), temperature (5, 15, 25, and 35 °C), ionic strength (0.001, 0.01, 0.1, and 1 M KCl solution), biochar to water ratio (1:500, 1:200, 1:100, 1:50 w/v) and equilibration time (2, 5, 10, 24, 48, 96, 144 h) on PO₄⁻³⁻, NO₃⁻, and NH₄⁺ release from biochar were examined in this study. Every treatment combination was replicated three times. The extracts were centrifuged 4390 × g for 10 min, and the PO₄⁻³⁻ concentration in the supernatant was determined by a Tu-1810 spectrophotometer (PERSEE, China), using the ascorbic acid molybdenum blue method. The concentrations of NO₃⁻ and NH₄⁺ were analyzed by an auto analyzer (Auto Analyzer III, Germany).

2.3 Analysis of K⁺, Ca²⁺, Na⁺, and Mg²⁺ concentrations

The effects of pH, temperature, the ratio of biochar to water and equilibration time to the release of K⁺, Ca²⁺, Na⁺, and Mg²⁺ from biochar were studied. Different from the PO₄⁻³⁻ analysis, the extraction solution used was deionized water when testing the effect of pH on the release of K⁺, Ca²⁺, Na⁺, and Mg²⁺ from biochar, and 1 M (pH 7) ammonium acetate solution was used when testing the effects of temperature, biochar to water ratio and equilibration time. The K⁺, Ca²⁺, Na⁺, and Mg²⁺ concentrations were analyzed on an atomic absorption spectrophotometer (TAS-990, China).

2.4 Statistical analysis

All statistical analyses were performed using SPSS 17.0. The effect of each factor on element release from biochar was tested by one-way ANOVA. The significance level was \( p < 0.05 \).

Figure 1. Effects of pH, temperature, ionic strength, the biochar/water ratio, and equilibration time on the release of P from biochar. Different letters indicate significant difference at \( p < 0.05 \).
3 Results and discussions

3.1 The release PO₄³⁻ from biochar

The pH and the ratio of biochar to water significantly affected the PO₄³⁻ release from biochar \((p < 0.01)\), while temperature, ionic strength, equilibration time showed less effects (Fig. 1). The amount of PO₄³⁻ released from biochar was 1137.0 mg kg⁻¹ at pH 3 while it was reduced to 123.3 mg kg⁻¹ as the pH increased to 9.6. The response of PO₄³⁻ release to pH was more apparent in acidic conditions (pH < 7) than that in alkaline conditions (pH > 7). Under acidic conditions, approximately 210 mg kg⁻¹ of PO₄³⁻ per unit of pH was released from biochar while the value was 71 mg kg⁻¹ under alkaline conditions. It has been shown that the release of PO₄³⁻ from sediments was affected by pH through ion-exchange and sorption-desorption [9, 12, 15, 20]. Under acidic conditions, the desorption of metal ions increases because of competitive adsorption; meanwhile, mineral elements can form poorly soluble complex compounds with PO₄³⁻, and the dissolution of sparingly soluble phosphate can also lead to PO₄³⁻ release [7, 8]. Our result and the literature indicate that PO₄³⁻ release rates are higher at lower pH or the PO₄³⁻ release is more apparent under acidic conditions [22, 25, 29].

To a lesser extent, biochar to water ratio also affected the release of PO₄³⁻ from biochar. In this study, the amount of PO₄³⁻ release increased by a factor of 2.8 as the biochar to water ratio decreased from 1:50 to 1:500. This indicates that a smaller biochar to water ratio is beneficial to the desorption of PO₄³⁻ from biochar [14, 23]. There were no obvious change in PO₄³⁻ release \((p = 0.489)\) when the temperature varied among 15, 25, and 35°C. However, PO₄³⁻ release increased by about 20.4 mg kg⁻¹ when the temperature increased from 5 to 15°C. The result suggested that low temperature (<10°C) may inhibit PO₄³⁻ release from biochar or the desorption of PO₄³⁻ was an energy-consuming process [26, 27]. The effect of equilibration time on PO₄³⁻ desorption was not noticeable when the equilibration time was <10 h \((p = 0.226)\), while between 10 and 24 h, the amount of PO₄³⁻ released increased from 101.3 to 123.3 mg kg⁻¹, and then the amount of PO₄³⁻ released reached steady state after 24 h. In addition, no significant effect of ionic strength on PO₄³⁻ release was observed in this study.

3.2 The release of NO₃⁻ and NH₄⁺ from biochar

The pH and biochar to water ratio did not affect NO₃⁻ desorption from biochar, but more NH₄⁺ was released in the strong acidic and with small biochar to water ratio extractions (Fig. 2). The release of NO₃⁻ and NH₄⁺...
from biochar was sensitive to ionic strength. As ionic strength decreased, more NO₃⁻ and NH₄⁺ were released. With respect to temperature, it did not affect NO₃⁻ and NH₄⁺ release when the temperature increased from 5 to 35°C. The effect of equilibration time was more apparent for NO₃⁻ desorption from biochar. After 24 h of desorption, the release of NO₃⁻ from biochar reached a steady state level.

Unlike the desorption of PO₄³⁻ from biochar, NO₃⁻ desorption was not sensitive to changes in pH although acidic condition may be more favorable for NH₄⁺ release. In this study, almost half of the total-P was released from biochar. After 24 h of desorption, PO₄³⁻ release was at a steady state level after 96 h.

Table 1. Correlation analysis among P, NO₃⁻–N, NH₄⁺–N, Na, K, Ca, and Mg under the influence of extraction pH

<table>
<thead>
<tr>
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<th>NO₃⁻–N</th>
<th>NH₄⁺–N</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>–0.24</td>
<td>0.99</td>
<td>0.22</td>
<td>0.98*</td>
<td>0.98*</td>
<td>0.96*</td>
</tr>
<tr>
<td>NO₃⁻–N</td>
<td>–0.39</td>
<td>–0.61</td>
<td>–0.33</td>
<td>–0.50</td>
<td>–0.33</td>
<td></td>
</tr>
<tr>
<td>NH₄⁺–N</td>
<td>0.17</td>
<td>0.98*</td>
<td>0.98*</td>
<td>0.96*</td>
<td></td>
<td></td>
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<tr>
<td>Na</td>
<td>0.29</td>
<td>0.34</td>
<td>0.37</td>
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<td></td>
<td></td>
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<tr>
<td>K</td>
<td>0.97**</td>
<td>0.99**</td>
<td></td>
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<td>Ca</td>
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<td>Mg</td>
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* p < 0.05.  ** p < 0.01.

3.4 Relationships between nutrients

There were positive correlations among the studied elements, except for NO₃⁻ and Na⁺ (Tab. 1). The PO₄³⁻ was positively related to NH₄⁺, K⁺, Ca²⁺, and Mg²⁺ (p < 0.05, 0.01, 0.01, and 0.05, respectively), likely because those nutrients came from the same source or they were controlled by the same reaction such as the dissolution of sparingly soluble compounds. The linear regression equation for the relationship between Ca (y) and P (x) was y = 12.3x + 2797.6. The slope (k = 12.3) showed that the amount of Ca²⁺ released from biochar was much greater than that of PO₄³⁻, which indicated that apart from sparingly soluble Ca–P compounds, other Ca compounds (e.g., CaCO₃) had contributed to the release of Ca²⁺ from the biochar. Correlation analysis confirmed that P and N were retained in different forms in biochar [30, 31].

4 Conclusions

We conclude that environmental factors have important impacts on the release of nutrients from biochar. Our data showed that the

**Figure 3.** Effects of pH, temperature, the biochar:water ratio, and equilibration time on the release of K, Ca, Na, Mg from biochar (Na; K; Ca; Mg). Different letters indicate significant difference for each parameter at p < 0.05.
releases of \( \text{PO}_4^{3-}, \text{NH}_4^+, \text{K}^+, \text{Ca}^{2+}, \text{and Mg}^{2+} \) were sensitive to pH and biochar to water ratio. The release of \( \text{Na}^+ \) was affected by the ratio of biochar to water but not by pH. To a lesser extent, temperature and equilibration time were also important to the release of nutrients from biochar. Ionic strength and equilibration time affected \( \text{NO}_3^- \) and \( \text{NH}_4^+ \) release from biochar. However, we only tested one biochar and testing different types of biochar in the future would help us understand the applicability of those data to other biochar types. Among the nutrients studied, other than between \( \text{NO}_3^- \) and \( \text{Na}^+ \), there were obvious positive correlations, indicating that these nutrients were from the same source or were controlled by similar reactions. The comparison of \( N \) and \( P \) under the influence of \( \text{pH} \) and correlation analysis suggested different forms of \( N \) and \( P \) in biochar which \( P \) was mainly retained in inorganic forms while \( N \) was mainly in organic forms.

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The authors have declared no conflict of interest.

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