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ARTICLE

Biochar can Increase Chinese Cabbage (*Brassica oleracea* L.) Yield, Decrease Nitrogen and Phosphorus Leaching Losses in Intensive Vegetable Soil

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ABSTRACT

There are few evidences on the effect of biochar on vegetable yield, nitrogen (N) and phosphorus (P) leaching losses under intensive vegetable production soil. The current field plot scale study evaluated responses of Chinese cabbage (*Brassica oleracea* L.) yield, N and P leaching losses using five N treatments of common N application rate according to local farmers' practice (N100%), reducing 20% or 40% N fertilizer (N80% and N60%), and reducing 40% N fertilizer but incorporating 10 or 20 t/ha biochar (N60% + BC10 and N60% + BC20). Results showed that N80% and N60% decreased both the cabbage economic and leaf yields by 6.8%–36.3% and 27.4%–37.7%, respectively. Incorporation of biochar with reduced N fertilizer rates improved the cabbage yield, in particular the N60% + BC20 matched the yield that observed in N100% treatment. Enhanced N and P uptake capacities of cabbage shoot probably contributed the higher vegetable production under both biochar amendment schemes. Biochar application mitigated the NH_4^+-N and total P leaching losses by 20%–30% and 29%–32%, respectively, compared with their counterpart treatment N60%. Nevertheless, biochar exerted no influence on the NO_3^--N leaching. In addition, soil organic matter content was recorded with 7.4%–28.7% higher following 10–20 t/ha biochar application. In conclusion, biochar application can increase economic yield of cabbage via increasing N and P use efficiency, decrease N and P leaching losses, and improve soil quality in an intensive vegetable production system.

KEYWORDS

Biochar; leachate; non-point source pollution; vegetable yield; soil quality

1 Introduction

In China, the intensive use of inorganic nitrogen (N) and phosphorus (P) fertilizers for vegetable production systems is higher than that of the world average [1]. These intense fertilizer applications in croplands may lead to lowering the fertilizer use efficiency. For example, intensive vegetable production systems in some places reported with only a maximum of 40% of the N use efficiency (NUE) [2]. In addition to increase in cost of production, these inefficient use of organic N and P fertilizers lead to soil degradation and contamination of hydrosphere and atmosphere environments [3,4]. In particular, rapid accumulation of nitrate, phosphorus, and salinity in soils were found under intensive vegetable production systems in southern China, as results of high amount of fertilizer application [5–7]. Therefore, it is of great concern to mitigate leaching N and P losses from vegetable production systems to enhance soil and water quality in the agriculture environment.

Biochar, a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment, has attained extensive attention due to its agronomical and environmental benefits in agro-ecosystems [8–11]. Regarding to the effects of biochar on N cycling in vegetable production system, many literatures reported its influences on NH_3 volatilization and N_2O emission from both stable crop and vegetable production systems [12–15]. Further, Dong et al. [16] observed the effect of biochar amendment on N release to percolation water in paddy soil. However, there have been relatively less evidences on the effect of biochar incorporation on the leaching N and P losses from vegetable soils. Well known, leaching is one of the main N and P losses pathway in vegetable production, which can be controlled by different mitigation practices such as improved fertilizer management, reduced water management, and catch crops [2,3,6]. Yang et al. [17] recently reported that the positive effects of different biochar amendments on leachate characterization of an agricultural soil.

At present, both the researchers and policy makers suggested that the N application rate is far higher than the actual demand of vegetable [18]. However, it is not practicable to reduce the N requirement in vegetable production systems as vegetable biomass is one of the major factors of the vegetable growers during the production processes. Therefore, it is important to pinpoint to mitigate the N and P leaching losses and increase the vegetable yield production at optimum rate of inorganic N and P application. Therefore, it is suggested to amend biochar with soil to improve N and P use efficiency in a vegetable production system.

The objectives of the current plot-scale field experiment were: 1) to assess the market yield of vegetable, N and P leaching losses at reduced chemical N application rate by 20%–40% of common N application rate according to local farmers' practice, 2) to measure the efficiency of biochar on enhancing vegetable yield and mitigating N and P leaching losses in soil system receiving reduced N fertilizer, and 3) to observe the changes in soil properties following N reduction and biochar application.

2 Materials and Methods

2.1 Site Description and Soil Characteristics

The field experiment was conducted in Datang Town, Foshan City, Guangdong Province (23° 34′ N, 113° 02′ E), located at Pearl River Delta region, Southern China. This location belongs to a subtropical maritime monsoon climate, with a mean annual precipitation and temperature of 1690 mm and 22.2°C, respectively. The experiment was conducted from November 20, 2018 to March 30, 2019, to assess the responses of vegetable (Chinese cabbage, *Brassica oleracea* L.) yield, leaching N and P losses, and soil properties to reduced application rates of organic N fertilizer and two rates of biochar. Before the establishment of the experiment, the site was evenly maintained under a typical open-field vegetable production managements for more than ten years. A bulk topsoil (0–20 cm) sample was collected from the experimental site and analyzed for soil characteristics. The topsoil was classified as Orthic Ferralsol, and showed following properties:pH (soil:water = 1:5) 6.56, available N 139.6 mg/kg, total N 0.5 g/kg, available P 154.7 mg/kg, total P 0.48 g/kg, and organic matter 13.0 g/kg. Biochar used in this study was derived from canola (*Brassica campestris* L.) straw at 400°C and had a pH (biochar:water = 1:5) of 7.5, and contained 62.5% of C and 0.19% of N. These selected properties of soil and biochar were measured according to that described in Lu [19].

2.2 Treatments and Management

Five treatments were established in the field with different biochar and N application rates consisting: local farmers' practice N rate (N100%, 130 kg ha^{-1} N), 80% and 60% of practice N rate (N80% and N60%), and N60% with 10 and 20 t/ha biochar (N60% + BC10 and N60% + BC20). Each treatment was triplicated, and total fifteen plots (each plot was measured 15 m × 2 m) were arranged in a randomized complete block design (RCBD). The cabbage seeds were evenly sown at a rate of 200 g per plot and mixed with top 3–5 cm soil on November 20, 2018, and harvested on March 30, 2019. Due to the high nutrient demand of cabbage, P and potassium (K) fertilizers were applied at the equal rates (90 kg P_2O_5/ha, and 120 kg K_2O/ha) to all treatments. The fertilizer N was split-applied on November 20, 2018 and December 21, 2018 with 50% and 50% as basal and supplementary fertilizer, respectively. All P and K fertilizer were applied as one-time basal fertilizer. Nitrogen, P and K fertilizers were in the forms of urea (N, 46%), calcium superphosphate (P_2O_5, 12%), and potassium chloride (K_2O, 60%), respectively. Agronomic managements such as irrigation, weed and pest controls were conducted according to local farmers' traditional practice.

2.3 Measurements

2.3.1 Yield, N and P Uptakes of Cabbage

The cabbage yields were determined by measuring the quantity of fresh market value shoot biomass from each whole plot. Approximately 1 kg of fresh leafy vegetables samples from each plot were separately collected, washed with deionized water, and dried at 70°C in an oven to a constant weight. The dry leafy vegetable samples were digested with H_2SO_4 and H_2O_2 and used for the determination of total N and P concentrations by Kjeldahl and Molybdenum antimony colorimetric methods, respectively. The N and P concentrations were multiplied by the dry biomass weight to get the N and P uptake capacity of the cabbages.

2.3.2 Soil Available N and P, and Organic Matter

Available N and P were extracted from five topsoil samples which randomly collected from each plot. Briefly, 100 g of soil was shaken with 200 mL of a KCl solution (1 M) for 24 h and determined by continuous-flow colorimetric. Soil C content was measured by the external heating potassium dichromate oxidation-capacity method. Soil organic matter content was calculated by multiplying soil C content with a constant number of 1.724.

2.3.3 Leachate N and P

One year prior to the experiment, a lysimeter (0.50 m × 0.50 m) was installed in each plot at a 0.50 m depth [6]. Each plot was separated with natural soil ditch in 0.5 m width to prevent cross movement of runoff water and nutrients. Leachate samples from lysimeters were collected on January 25, February 24, and March 20, 2019, respectively. After the volumes of leachate were recorded, 200 mL leachate was subsampled and frozen for the analysis of pH, NO_3^--N, NH_4^+-N, and total P using the Continuous Flow Injection Analyzer (Skalar San^{++}, the Netherlands).

2.4 Statistical Analysis

The difference among the five treatments was analyzed with a one-way analysis of variance (ANOVA). All tests of significance between pair treatments were conducted with Duncan's multiple-comparison tests ($P < 0.05$). All statistics and analyses were performed using Excel 2010 and the SPSS 16.0 for Windows.

3 Results and Discussion

3.1 Vegetable Production

The impacts of fertilizer reduction and biochar application on cabbage economic yield and leaf biomass are presented in Fig. 1. The head yield and leaf biomass of cabbage among treatments were ranged from 25.0 to 42.2 t/ha and from 10.2 to 14.1 t/ha, respectively. Reduced application of chemical N fertilizer by 20%–40% lowered both the head yield and leaf biomass by 6.8%–36.3% and 27.4%–37.7%, respectively. This observation indicates that N is as the major nutrient for high production. The loss of the yield with reducing urea N fertilizer application by 20%–40%, is in agreement with the previous studies [2,20,21]. This also suggests that local farmers had not over-applied N fertilizer for their vegetable production. However, the results showed that addition of biochar increased both the economic and leaf yield losses even when we reduced the chemical N inputs by 40%. In particular, N60% + BC10 and N60% + BC20 treatments increased the cabbage economic yield by 58.7%–68.8% compared with N60%, which were equivalent to that observed under N100% treatment (Fig. 1). Similarly, the leaf biomass of cabbage also increased with the addition of biochar treatments. Biochar amendment had been widely shown to increase plant productivity via improving soil physical properties [10], enhancing soil fertility [22], and providing nutrients contained in biochar itself [23]. Thus, the current study demonstrated that the vegetable production could be increased by biochar application at a10–20 t/ha rate, under reduced (60%) N input treatments.

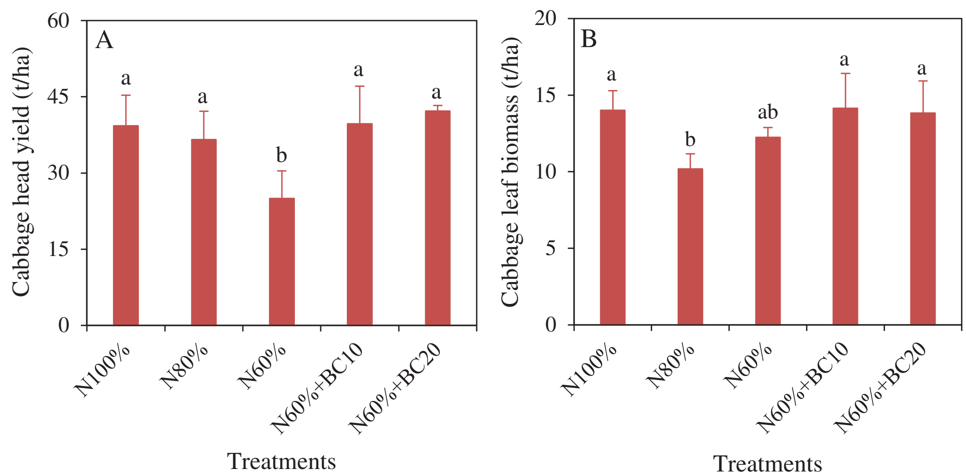

Figure 1: Impacts of N reduction and biochar application on cabbage head yield (A) and leaf biomass (B). Error bars were the standard variation (SD) for the three replicates, and different lowercase letters indicate the significant difference between each treatment according to the Duncan multiple-comparison test at $P < 0.05$

The reduction of N input (particularly under N60% treatments) lowered the total N concentrations of both the cabbage head and leaf compared to the N100% treatment (Tab. 1). Further, the addition of biochar also did not show any impact on the cabbage total N concentration in all treatments, except for N60% + BC20 treatment where it significantly ($P < 0.05$) increased the leaf total N concentration by 17.5% and 13.1%, compared to N60% and N60% + BC10, respectively.

Table 1: Total N and P concentrations of tested vegetable shoot biomass

Treatments	Total N (g/kg)		Total P (g/kg)	
	Cabbage head	Cabbage leaf	Cabbage head	Cabbage leaf
N100%	21.2 ± 2.1 a	12.3 ± 0.1 a	2.56 ± 0.28 a	1.78 ± 0.03 bc
N80%	15.5 ± 1.1 b	11.6 ± 0.5 ab	2.35 ± 0.09 a	1.74 ± 0.07 cd
N60%	14.4 ± 0.4 b	10.3 ± 0.8 c	2.23 ± 0.04 a	1.66 ± 0.01 d
N60% + BC10	14.2 ± 1.3 b	10.7 ± 0.8 bc	2.36 ± 0.26 a	1.85 ± 0.09 b
N60% + BC20	15.5 ± 2.1 b	12.1 ± 0.3 a	2.40 ± 0.27 a	2.12 ± 0.04 a

Note: Data was mean ± SD (n = 3), and different lowercase letters in same column indicate the significant difference between each treatment according to the Duncan multiple-comparison test at $P < 0.05$.

There was no significant ($P > 0.05$) difference observed in the total P concentration of cabbage head among all treatments. However, leaf total P concentration under N60% treatment significantly ($P < 0.05$) lowered by 6.7% than that under N100% treatment. In contrast, soil amendment with biochar at a rate of 10–20 t/ha significantly ($P < 0.05$) increased the leaf total P concentration by 11.4%–27.7% compared to N60%. Overall, the results suggest that addition of biochar to soil enhanced the N and P uptake capacities of vegetable shoot, which contributed the higher cabbage yield (Fig. 1 and Tab. 1).

3.2 N and P Leaching Losses

Significant losses of N and P could occur after heavy chemical fertilization under open-field conditions which combined with high precipitation in the vegetable production systems in Eastern China [2,6]. In the current study, the NH_4^+-N, NO_3^--N and total P leaching losses from cabbage growth cycle under N100% treatment were 0.20 ± 0.02 kg/ha, 20.9 ± 1.3 kg/ha, and 0.38 ± 0.02 kg/ha, respectively (Tab. 2). This is in agreement with previous studies, where the NO_3^--N leaching loss was also the major concern under vegetable soil system [20,24]. Data in Tab. 2 suggested that reduced chemical N fertilizer application by 20% significantly ($P < 0.05$) decreased 25.0% of NH_4^+-N and 10.5% of total P leaching losses compared to N100%. Further, there was a significantly ($P < 0.05$) higher reduction of NH_4^+-N, NO_3^--N and total P losses by 50%, 22.5%, and 26.3%, respectively, when organic N input rate was decreased from N100% to N60%. This implied that reduction of N input decreased its leaching losses [6,25]. However, data in Tab. 1 shows that the N and P uptake capacities have not been lowered under two reduced rates of N treatments. The change of P leaching loss is probably the result of the mismatch between N:P stoichiometry and more studies should be conducted to confirm the related mechanisms in future.

Table 2: The NH_4^+-N, NO_3^--N and total P leaching losses under cabbage growth cycle

Treatments	N and P leaching losses (kg/ha)		
	NH_4^+-N	NO_3^--N	Total P
N100%	0.20 ± 0.02 a	20.9 ± 1.3 a	0.38 ± 0.02 a
N80%	0.15 ± 0.02 b	21.1 ± 1.7 a	0.34 ± 0.01 b
N60%	0.10 ± 0.01 c	16.2 ± 2.0 b	0.28 ± 0.01 c
N60% + BC10	0.08 ± 0.01 d	14.6 ± 0.8 b	0.20 ± 0.01 d
N60% + BC20	0.07 ± 0.02 d	14.3 ± 0.7 b	0.19 ± 0.01 d

Note: Data was mean ± SD (n = 3), and different lowercase letters in same column indicate the significant difference between each treatment according to the Duncan multiple-comparison test at $P < 0.05$.

The application of biochar either 10 or 20 t/ha rates did not show any influence on NO_3^--N leaching losses. However, the biochar applications wiht 10–20 t/ha significantly (P < 0.05) mitigated the NH_4^+-N and total P leaching losses by 20%–30% and 29%–32%, respectively, compared with their counterpart treatment N60%. Previous studies have found that biochar can absorb NH_4^+-N, NO_3^--N and phosphate [26,27]. For example, Sika et al. [28] found that pine wood biochar effectively reduced both NH_4^+-N and NO_3^--N leaching losses by 12%–86% and 26%–96%, respectively. Further, Ke et al. [29] found that biochar reduced P leaching by 11.4%–16.0% in Mollisol eggplant field in Northeast China.

In the current study, biochar application with 10–20 t/ha reduced only the NH_4^+-N and total P leaching losses (except NO_3^--N leaching losses) under intensive vegetable system. The results showed that both N reduction and biochar application had no significant (P > 0.05) influence on leachate volumes over the Chinese cabbage growth cycle (Fig. 2A). This suggests that the mitigation effect of biochar on NH_4^+-N and total P leaching could not be explained by the changes of leachate volumes.

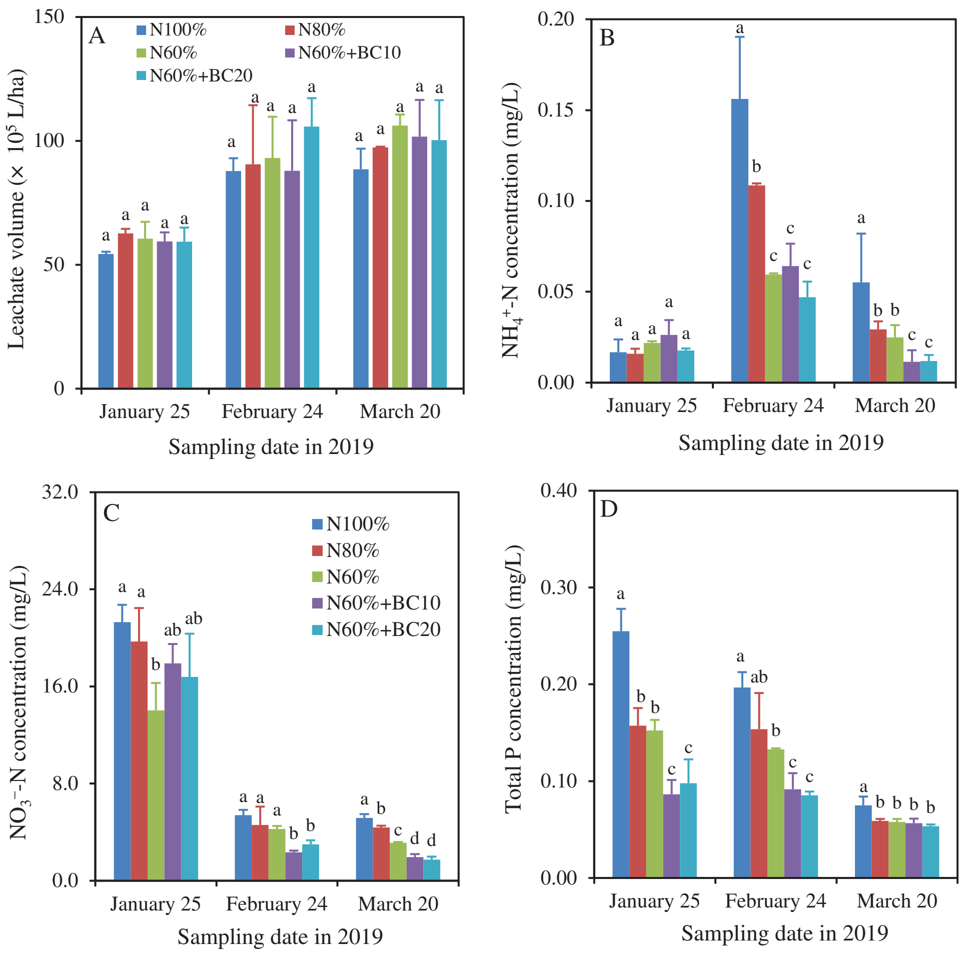

Figure 2: Impacts of fertilizer N reduction and biochar application on volume (A), NH_4^+-N (B), NO_3^--N (C), and total P (D) concentrations of leachates sampled on January 25, February 24, and March 20, 2019, respectively. Error bars were the standard variation (SD) for the three replicates, and different lowercase letters indicate the significant difference between each treatment according to the Duncan multiple-comparison test at P < 0.05

The dynamics of leachate NH_4^+-N, NO_3^--N, and total P concentrations were summarized in Fig. 2. The reduction of N application by 20%–40% lowered the NH_4^+-N, NO_3^--N and total P concentrations in soil, which contributing to the lower NH_4^+-N, NO_3^--N and total P leaching losses under 60%–80% N added treatments (Tab. 2). Further, data in Figs. 2B and 2D showed that biochar amendment reduced the leachate NH_4^+-N and total P concentrations in most cases because of biochar's absorb functions as reported in previous literatures [26,27,30].

3.3 Soil Properties

Data in Tab. 3 showed that the lowering N inputs by 20%–40% increased the soil pH by 0.58–1.06 units, which was observed under both with and without biochar added treatments. This result is in agreement with previous studies where they showed that the reduction of N application could relieve the soil acidification process in vegetable production system [4,5]. In general, biochar has the ability to increase the soil pH due to its alkaline properties [31,32]. However, the results showed that there was no significant (P > 0.05) changes in soil pH of 60% N input treatments with or without biochar in the vegetable production system receiving 60% of common N input (Tab. 3). This may be attributing to the aging effect of biochar itself [33,34] and the buffer capacity of soil [35,36]. Similarly, the soil total N and P concentrations, also did not show any difference under reduced N treatments whether received biochar or not in a short-term. However, both fertilizer N reduction and biochar application affected the soil organic matter content. In particular, 60%N treatment decreased the soil organic matter by 9.6%. In contrast, 60%N + BC20 significantly (P < 0.05) increased the soil organic matter by 16.3%. Biochar derived organic matter (BDOM) plays an important role in determining biochar's impacts in soil characteristics [37,38], such as increasing the soil organic matter content in the current study (Tab. 3). Of course, the long-term effect of reducing N fertilizer and applying biochar on properties of intensive vegetable soil should be investigated in future.

Table 3: Responses of selected soil properties to fertilizer N reduction and biochar application

Treatments	pH	Total N (mg/kg)	Total P (g/kg)	Organic matter (%)
100%	6.12 ± 0.10 b	1.22 ± 0.12 a	0.59 ± 0.03 a	1.35 ± 0.03 bc
N80%	6.70 ± 0.48 a	1.08 ± 0.18 a	0.60 ± 0.01 a	1.44 ± 0.02 b
N60%	7.18 ± 0.02 a	1.13 ± 0.12 a	0.60 ± 0.02 a	1.22 ± 0.02 d
N60% + BC10	6.72 ± 0.04 a	1.14 ± 0.12 a	0.58 ± 0.03 a	1.31 ± 0.07 cd
N60% + BC20	6.98 ± 0.35 a	1.09 ± 0.17 a	0.67 ± 0.14 a	1.57 ± 0.09 a

Note: Data was mean ± SD (n = 3), and different lowercase letters in same column indicate the significant difference between each treatment according to the Duncan multiple-comparison test at P < 0.05.

4 Conclusions

Current field study demonstrated that there is a loss in vegetable yield when the N fertilizers were reduced by 20%–40% from farmers' common fertilizer management. However, the application of biochar with 10–20 t/ha could increase the cabbage production even under 60% of common practiced N treatments and matched with the yield performed with full rate of N applied treatments. Further, biochar addition at a rate of 10–20 t/ha effectively mitigated the NH_4^+-N and total P leaching losses by 20%–30% and 29%–32%, respectively, which was mainly due to the lower NH_4^+-N and total P concentrations of leachate. No response was observed in soil pH, total N and P contents following the biochar application to vegetable soil in short-term. However, biochar amendments increased the soil organic matter content, particularly when being applied at a higher rate (20 t/ha in current work).

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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