Reduced Fertilization and Biochar Supplementation on Soil Fertility

Subjects: Soil Science

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Generally, the partial substitution of chemical fertilizer with palm silk biochar (PSB) at a low application rate may not substantially reduce plant-available NO3−-N and Olsen-P. It can also contribute to the sustainable availability of N and P in vegetable farmland soil via a variety of transformation processes, such as mineralization, immobilization, and loss.

biochar chemical fertilizer reduction co-application partial substitution nitrogen and phosphorus availability in situ incubation

1. Introduction

As the mainstay industry of agriculture in China, vegetable farming has become one major source of household income for many farmers [1]. Fertilization plays a decisive role in enhancing vegetable yields and profitability in southern China [2][3]. Based on the data of *2018 Guangdong Statistical Yearbook on Agriculture* [4], crop farming in Guangdong Province in 2017 consumed 9.10 × 10^5 t of nitrogen (N) fertilizer and 1.25 × 10^5 t of phosphorus (P) fertilizer (on N and P basis, respectively), over 29% of which were used to improve vegetable production. By comparing the annual change in chemical fertilizer consumption in Guangdong Province, the rate of N fertilizer applied in 2017 was only 4% lower than that in 2007, whereas the rate of P fertilizer applied between 2007 and 2017 increased dramatically by 36% [4][5]. Furthermore, with increasing amounts of chemical fertilizer input, the average annual input intensity of chemical fertilizer (chemical fertilizer use per unit area of planted land) has shown an increase of 12% during the past 10 years [4][5]. However, it has far exceeded the maximum safe ceiling of 225 kg hm^{-2}, which was determined by developed countries to prevent chemical fertilizer from polluting water bodies.

Long-term excessive fertilization has resulted in increased fertilizer nutrient surpluses in Guangdong Province [6]. In vegetable farmlands with different planting patterns, the overuse of fertilizers for vegetable production may not only decrease nutrient use efficiency, but also cause the risk of N and P losses via runoff or leaching from soils to adjacent waters [2][3]. According to the First National Pollution Source Census Bulletin in Guangdong Province, the total N and P losses from the planting industry in 2007 were 6.64 × 10^4 and 7.40 × 10^3 t, respectively [7], accounting for 3% and 0.3% of chemical fertilizer input during the same period, respectively. Therefore, soil N and P losses caused by long-term excessive fertilization cannot be ignored. Nowadays, the resulting agricultural non-point source pollution has become one important factor affecting ecological safety and human health. How to improve N and P availability in soils with minimal adverse environmental impacts has long been a hot topic for the research of nutrient management in agroecosystems.

Biochar is a solid product of biomass (e.g., crop residues, forestry wastes, animal feces), formed by pyrolysis at a relatively low temperature (<700 °C) within an anoxic environment [8]. Generally, it has a high porosity, large specific surface area, more surface charge, and strong stability [8]. In recent years, biochar has received more and more attention globally as a promising soil amendment for its role in emission mitigation and carbon (C) sequestration in agroecosystems. Biochar amendment can alter soil nutrient availability and its C:N:P stoichiometric ratios, which are critical in the regulation of nutrient transformation in the soil ecosystem [9][10]. Mineral N (i.e., NH_4^+-N and NO_3^--N) and available P (e.g., Olsen-P) are the two important indexes of soil nutrient availability, and their concentrations are greatly affected by biochar amendment [11][12]. Transformations (e.g., mineralization, immobilization, and loss) of N and P are the two most important aspects of nutrient cycling in biochar-amended soil [11]. The interaction of biochar with soil can directly or indirectly affect the mineralization, immobilization, and loss processes of N and P by altering the biotic (e.g., microbial and enzymatic) and abiotic (e.g., physical and chemical) drivers of N and P cycling [13][14]. Thus far, many scholars and researchers from domestic areas and abroad have studied the biochar effects on the mineralization, immobilization, and losses that influence the concentrations of NH_4^+-N, NO_3^--N, and Olsen-P in soil. Aiming at the elucidation of the availability and transformations of N and P in biochar-amended soil, several kinds of determination methods can be used and have been summarized, including (1) a soil incubation method to determine N and P mineralization [15][16], (2) an isotope tracer method to determine N immobilization [17][18], (3) an adsorption–desorption method to determine P immobilization [14][19], (4) a leachate collection method to determine N and P leaching [20][21], (5) an airflow enclosure method to determine NH_3 volatilization [22][23], and (6) a static chamber method to determine N_2O emission [24][25]. However, most of the studies on the availability and transformations of N and P in biochar-amended soil involve controlled experiments in a laboratory and are usually concentrated in a single process [13][14]. In addition, given the fact that a high degree of spatial variability exists under actual field conditions, the results of field pilot studies regarding the biochar effects on the availability and transformation processes of N and P in soil are confronted with uncertainties at different locations [14][24]. Presently, there is a need for in situ measurements of soil N and P dynamics under various field conditions, especially when considering the impact of the combined application of chemical fertilizer and biochar.

There have been many studies that have focused on the combined effects of chemical fertilizer and biochar on regulating the availability and losses of soil N and P under the influences of different soil properties (e.g., soil texture and pH), fertilizer types (e.g., urea and NH_4NO_3), biochar characteristics (e.g., biomass source and preparation condition), and experimental conditions (e.g., biochar application rate and residence time of biochar in soil). For example, applying both urea and biochar decreased NH_4^+-N but increased NO_3^--N, whereas the co-application of NH_4NO_3 and biochar reduced both forms of mineral N in soil [12]. In the presence of urea and monoammonium phosphate, biochar increased the concentrations of Olsen-P and labile P in two alkaline chernozemic soils [11]. Hangs et al. [26] observed that the combination of urea with added biochar mitigated the increased N_2O emission from two neutral agricultural soils; nevertheless, the accelerated urea hydrolysis in the presence of biochar may increase NH_3 volatilization associated with urea fertilization. Although the partial substitution of diammonium phosphate with biochar mitigated the fluxes of N and P outputs from paddy field water [27], there are still few reports on the in situ study of reduced chemical fertilization coupled with biochar supplementation to regulate the availability and transformation patterns of N and P in vegetable farmland soil. In particular, the mineralization, immobilization, and losses of N and P in biochar-amended soil remain unclear.

2. Soil pH

Compared with the non-fertilization treatment (Control), the soil pH decreased significantly ($p < 0.05$) in almost all fertilization treatments (except $CF_{90}B_{10}$ for the C-tube and CF_{100} for the O-tube), regardless of the type of tubes (**Figure 2**). Compared with the CF_{100} treatment, the soil pH also decreased significantly ($p < 0.05$) in the $CF_{80}B_{20}$ treatment for the C-tube.

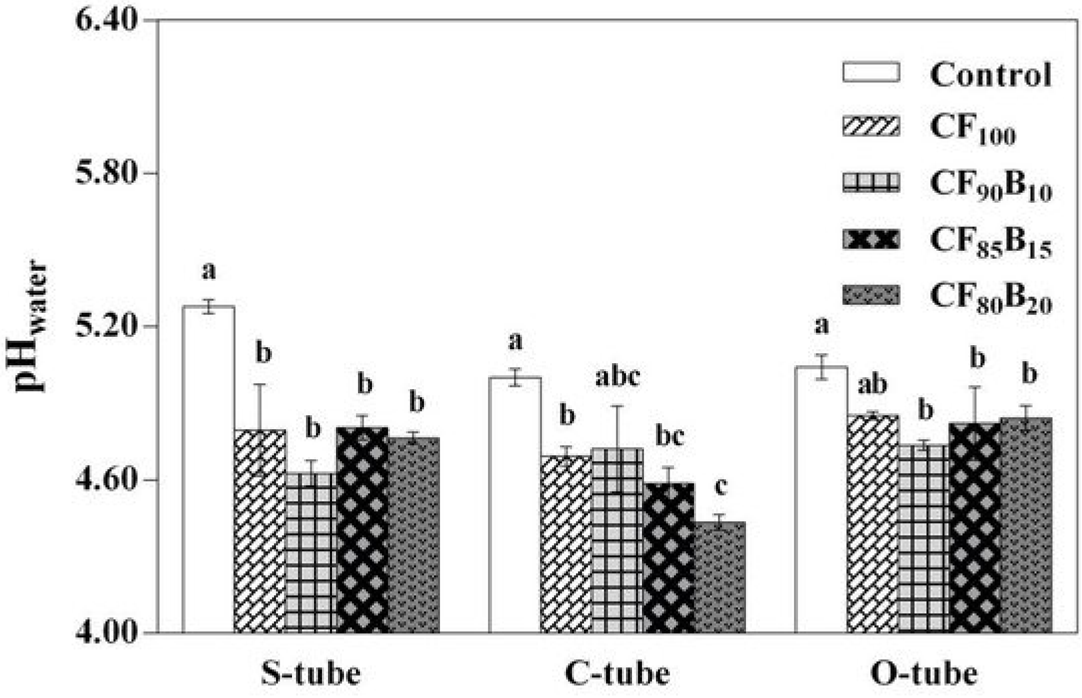

Figure 2. Coupled effect of reduced chemical fertilization and palm silk biochar (PSB) supplementation on pH_{water} in 0–40 cm soil layer. Abbreviations: S-tube, starting tube; C-tube, top-covered tube; O-tube, top-open tube. Treatments: Control, no fertilization; CF_{100}, 100% conventional fertilization; $CF_{90}B_{10}$, 90% conventional fertilization plus 10% PSB-based fertilization; $CF_{85}B_{15}$, 85% conventional fertilization plus 15% PSB-based fertilization; $CF_{80}B_{20}$, 80% conventional fertilization plus 20% PSB-based fertilization. Data are expressed as means ± SD (n = 3). For each tube type, bars labeled with different lowercase letters (e.g., a, b, c, etc.) indicate significant ($p < 0.05$) differences among the treatments based on the Tukey test or Games-Howell test.

3. Soil Mineral N and Available P

3.1. NH_4^+-N, NO_3^--N, and Mineral N Concentrations in Soil

Compared with the CF_{100} treatment, the soil NH_4^+-N concentration was decreased significantly ($p < 0.05$) in the non-fertilization (Control) and all PSB-based fertilization treatments (except $CF_{90}B_{10}$ for the S-tube), regardless of the type of tubes (**Table 4**). In addition, the higher reduction in chemical fertilization resulted in a greater percentage decrease in NH_4^+-N. For the S-tube, the percentage decreases in NH_4^+-N in the $CF_{90}B_{10}$, $CF_{85}B_{15}$, and $CF_{80}B_{20}$ treatments were −5%, −15%, and −20%, respectively—of which, the latter two were in good agreement with the chemical fertilizer reductions of 15% and 20%, respectively. Similar observations were obtained for the soil mineral N concentration and its percentage decrease in the $CF_{80}B_{20}$ relative to CF_{100} treatments.

Table 4. Concentrations of mineral N (NH_4^+-N and NO_3^--N) and available P (Olsen-P) (mg kg^{-1}) in 0–40 cm soil layer in three types of tubes and their percentage changes (±%) in the palm silk biochar (PSB)-based fertilization relative to 100% conventional fertilization treatments.

Tube Type	Treatment	NH_4^+-N		NO_3^--N		Mineral N		Olsen-P	
		mg kg^{-1}	±%	mg kg^{-1}	±%	mg kg^{-1}	±%	mg kg^{-1}	±%
S-tube	Control	2.40 ± 0.15 d	—	3.78 ± 0.58 c	—	6.18 ± 0.43 d	—	27.0 ± 2.4 c	—
	CF_{100}	122 ± 1 a	—	79.2 ± 9.3 ab	—	201 ± 10 a	—	227 ± 1 a	—
	$CF_{90}B_{10}$	116 ± 2 a	−4.92	89.9 ± 6.6 a	13.5	206 ± 6 a	2.69	221 ± 5 a	−2.64
	$CF_{85}B_{15}$	104 ± 4 b	−14.8	74.7 ± 8.1 ab	−5.68	178 ± 4 b	−11.2	224 ± 2 a	−1.32
	$CF_{80}B_{20}$	97.5 ± 2.1 c	−20.1	61.6 ± 7.8 b	−22.2	159 ± 9 c	−20.8	184 ± 1 b	−18.9
C-tube	Control	8.98 ± 2.38 e	—	7.13 ± 0.93 d	—	16.1 ± 1.5 d	—	37.2 ± 6.2 c	—
	CF_{100}	309 ± 16 a	—	106 ± 4 c	—	415 ± 18 a	—	209 ± 15 a	—
	$CF_{90}B_{10}$	231 ± 8 b	−25.2	116 ± 18 bc	9.43	347 ± 22 b	−16.4	196 ± 6 a	−6.22
	$CF_{85}B_{15}$	194 ± 18 c	−37.2	147 ± 15 a	38.7	340 ± 29 b	−18.1	183 ± 18 a	−12.4
	$CF_{80}B_{20}$	142 ± 12 d	−54.0	136 ± 4 ab	28.3	278 ± 14 c	−33.1	143 ± 4 b	−31.6
O-tube	Control	4.70 ± 1.35 c	—	10.4 ± 2.5 b	—	15.1 ± 3.9 c	—	39.9 ± 5.1 c	—
	CF_{100}	175 ± 31 a	—	58.3 ± 5.5 a	—	233 ± 28 a	—	172 ± 41 abc	—

Tube Type	Treatment	NH_4^+-N		NO_3^--N		Mineral N		Olsen-P	
		mg kg^{-1}	±%	mg kg^{-1}	±%	mg kg^{-1}	±%	mg kg^{-1}	±%
	CF$_{90}$B$_{10}$	114 ± 15 b	−34.9	49.2 ± 20.5 a	−15.6	163 ± 31 b	−30.0	176 ± 21 a	2.33
	CF$_{85}$B$_{15}$	90.5 ± 16.4 b	−48.3	40.2 ± 10.0 a	−31.0	131 ± 21 b	−43.9	140 ± 15 a	−18.6
	CF$_{80}$B$_{20}$	80.6 ± 12.1 b	−53.9	31.7 ± 6.4 ab	−45.6	112 ± 16 b	−51.8	129 ± 9 ab	−25.0

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3.2. Olsen-P Concentration in Soil

Compared with the CF$_{100}$ treatment, the soil Olsen-P concentration decreased significantly ($p < 0.05$) in the non-fertilization (Control) and CF$_{80}$B$_{20}$ treatments for both the S-tube and C-tube (**Table 4**). Furthermore, the soil Olsen-P concentration showed a decreasing trend with the reduction in chemical fertilization in most cases. For the S-tube, the percentage decrease in Olsen-P in the CF$_{80}$B$_{20}$ treatment (−19%) was close to the chemical fertilizer reduction of 20%, whereas, for the C-tube and O-tube, its percentage decreases in the CF$_{85}$B$_{15}$ and CF$_{80}$B$_{20}$ treatments (−12% and −19%, respectively) fluctuated around the chemical fertilizer reduction of 15%.

4. Soil Net N and P Mineralization

4.1. Net Ammonification, Net Nitrification, and Net N Mineralization in Soil

As shown in **Figure 3**a, net ammonification in soil generally decreased with the reduction in chemical fertilization. Accordingly, soil net ammonification ranked in the order of CF$_{100}$ > CF$_{90}$B$_{10}$ and CF$_{85}$B$_{15}$ > CF$_{80}$B$_{20}$ > Control ($p < 0.05$). Differently, the CF$_{80}$B$_{20}$ and CF$_{85}$B$_{15}$ treatments had a significantly ($p < 0.05$) higher soil net nitrification than the other treatments. Hence, net nitrification in soil was increased dramatically when PSB was applied at 1840 or 2460 kg ha^{-1} (CF$_{80}$B$_{20}$ or CF$_{85}$B$_{15}$, respectively). Overall, net N mineralization in soil followed the order of (CF$_{100}$ > CF$_{90}$B$_{10}$ and CF$_{80}$B$_{20}$) ≈ CF$_{85}$B$_{15}$ > Control ($p < 0.05$). Unlike soil net ammonification and nitrification, no significant difference in net N mineralization was found among all PSB-based fertilization treatments. The relative nitrification index (RNI), which acts as an indicator of the prevalence of nitrification over ammonification during mineralization processes, generally showed increasing trends with the reduction in chemical fertilization (**Figure 3**b). The CF$_{80}$B$_{20}$ and CF$_{85}$B$_{15}$ treatments had a significantly ($p < 0.05$) higher RNI than the CF$_{90}$B$_{10}$ and CF$_{100}$ treatments.

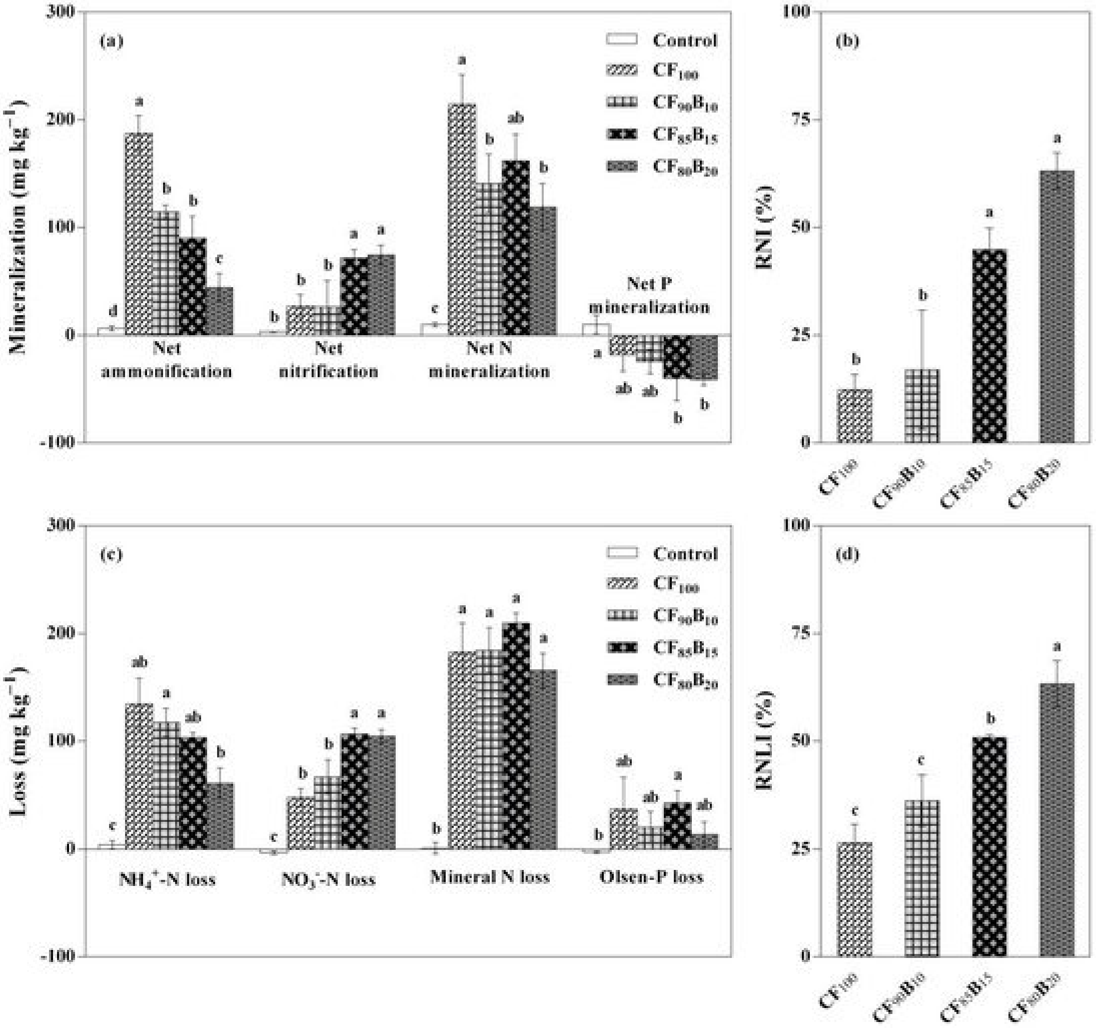

Figure 3. Coupled effects of reduced chemical fertilization and palm silk biochar (PSB) supplementation on net N and P mineralization (**a**), relative nitrification index (RNI) (**b**), mineral N and available P losses (**c**), and relative NO_3^--N loss index (RNLI) (**d**) in 0–40 cm soil layer. Treatments: Control, no fertilization; CF_{100}, 100% conventional fertilization; $CF_{90}B_{10}$, 90% conventional fertilization plus 10% PSB-based fertilization; $CF_{85}B_{15}$, 85% conventional fertilization plus 15% PSB-based fertilization; $CF_{80}B_{20}$, 80% conventional fertilization plus 20% PSB-based fertilization. Data are expressed as means ± SD ($n = 3$). For each parameter, bars labeled with different lowercase letters (e.g., a, b, c, etc.) indicate significant ($p < 0.05$) differences among the treatments based on the Tukey test or Games–Howell test.

4.2. Net P Mineralization in Soil

Unlike soil net N mineralization, net P mineralization was positive in the non-fertilization (Control) and negative in all fertilization treatments (**Figure 3**a). In the latter case, soil net P mineralization did not change significantly, regardless of chemical fertilizer reduction.

5. Soil Mineral N and Available P Losses

5.1. NH_4^+-N, NO_3^--N, and Mineral N Losses from Soil

Compared with the CF_{100} treatment, the NH_4^+-N loss from soil generally showed decreasing trends with the reduction in chemical fertilizer application; reversely, the loss of soil NO_3^--N increased significantly ($p < 0.05$) in almost all PSB-based fertilization treatments (except $CF_{90}B_{10}$; **Figure 3**c). However, the loss of soil mineral N did not change significantly, regardless of chemical fertilizer reduction. The relative NO_3^--N loss index (RNLI), which is based on the NO_3^--N loss as a percentage of the mineral N loss from soil, showed a general increasing trend with the reduction in chemical fertilization (**Figure 3**d). Statistically speaking, the $CF_{80}B_{20}$ treatment had the highest RNLI, followed by $CF_{85}B_{15}$, and the $CF_{90}B_{10}$ and CF_{100} treatments had the lowest ($p < 0.05$).

5.2. Olsen-P Loss from Soil

The Olsen-P loss from soil was negative in the non-fertilization (Control) and positive in all fertilization treatments, which was contrary to the results of net P mineralization in soil (**Figure 3**c). Compared with the CF_{100} treatment, all PSB-based fertilization treatments did not significantly affect the loss of soil Olsen-P.

6. Conclusions

Despite chemical fertilizer reduction, the partial substitution of chemical fertilizer with PSB at a relatively low application rate (e.g., 1840 kg ha−1) may not substantially reduce the soil available NO3−-N and Olsen-P for the plant to some degree, and could contribute to the sustainable availability of N and P in vegetable farmland soil via a variety of transformation processes, such as mineralization, immobilization, and loss. It provides an effective approach to understanding the availability and transformations of N and P in subtropical acid soils. There is a need for long-term studies evaluating the potential of the partial substitution of chemical fertilizer with PSB, especially in fields under continuous application.

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