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Efficacies of biochar and biochar-based amendment on vegetable yield and nitrogen utilization in four consecutive planting seasons

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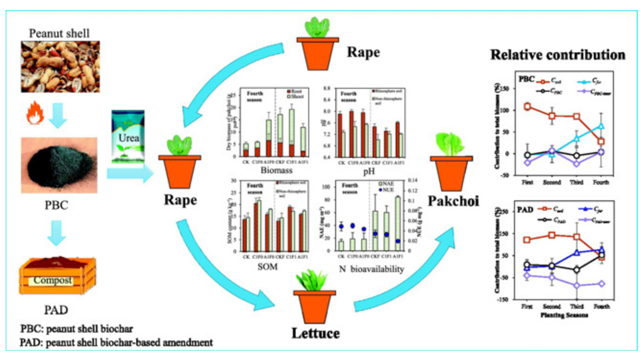
HIGHLIGHTS

- Efficacies of PBC and PAD on vegetable yield and N utilization were compared.
- PBC alone had little effect on vegetable yield, while PAD increased pakchoi yield.
- PAD co-application increased NH_4^+-N and NO_3^--N content due to its high N content.
- Ratio of biochar to additives should be optimized to avoid negative results.

GRAPHICAL ABSTRACT



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ABSTRACT

Biochar has been suggested as a potential tailored technology for mediating soil conditions and improving crop yields. However, the efficacies of biochar and biochar-based amendments (e.g., composted biochar) in agricultural soils under a rotation system remain uncertain. In this study, an arable soil was subjected to peanut shell biochar (PBC) and biochar-based amendment (PAD) combined with or without nitrogen (N) fertilizer to evaluate their effects on vegetable yield, N bioavailability, and their relative contribution to vegetable biomass in four consecutive planting seasons. PBC alone or in co-application with N fertilizer had little effect on vegetable yield, while PAD co-application with N fertilizer decreased vegetable biomass because of the inhibition of root morphology by excessive nutrient supply. PBC and PAD applications increased rhizosphere soil pH due to OH^- and HCO_3^- release and NO_3^--N uptake. Although the addition of PAD increased soil N contents due to its high contents in PAD, it had little effects on N utilization efficiency (NUE) in the four seasons. The relative contribution of PBC, PAD, and their interaction with N fertilizer to biomass yield was maintained at a low level. Our results indicated that a biochar-based amendment (e.g., PAD) was a potential alternative to N fertilizer, but the ratio of biochar to additives should be managed carefully to generate optimal benefits. Notably, the efficacy of PAD on plant growth was closely associated with plant species, and further related research on different plants is encouraged.

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1. Introduction

The huge challenge of limited arable soil in China forces farmers to use more and more synthetic nitrogen (N) fertilizer in the soils to increase cereal yields to meet the unprecedented demand of the increasing population (Foley et al., 2011; Godfray et al., 2010; Teng et al., 2014). However, N utilization efficiency (NUE) by crops in China is only 30–35%, which is much lower than that in developed countries (>50%). The overuse of N fertilizer and low NUE have resulted in a continuing vicious cycle. Excessive N fertilizer application not only results in huge economic losses and resource waste (Canfield et al., 2010; Tian and Niu, 2015) but also largely causes soil acidification and compaction (Ma et al., 2014). Additionally, N loss resulting from low NUE could induce serial environmental problems such as water eutrophication (Khan and Mohammad, 2014), underground water pollution (Marouane et al., 2015), and greenhouse gas emissions (Liu et al., 2016; Wang et al., 2013). Therefore, a sustainable and environmentally friendly agricultural strategy for improving NUE and decreasing synthetic N fertilizer inputs is greatly needed to ensure soil quality and reduce environmental risks.

Biochar, a carbonaceous material produced by the pyrogenic decomposition of biomass above 250 °C under limited oxygen content (Lehmann and Joseph, 2015), seems to be a promising and feasible solution to these soil problems (Atkinson et al., 2010; Kuppusamy et al., 2016). Studies have demonstrated that biochar with varied characteristics has multiple benefits to ameliorating soil degradation and enhancing crop yields (Dong et al., 2014; Herath et al., 2013; Ippolito et al., 2016; Lehmann and Joseph, 2015). As a fertilizer, biochar has the potential to provide N and phosphorus (P) and supplement soil organic carbon (Novak and Busscher, 2013; Zheng et al., 2013b). Moreover, as a soil conditioner, biochar is able to reduce soil density, enhance soil aeration (Case et al., 2012), and increase water holding capacity (WHC) and cation exchange capacity (Major et al., 2010; Zheng et al., 2013a). Meanwhile, biochar may facilitate soil microbial activity to regulate N cycle (e.g., leaching, mineralization, nitrification, denitrification, and NH_3 volatilization) in soils via the provision of niches for microorganisms and the sorption of signal molecules (Gul and Whalen, 2016; Jones et al., 2012; Wang et al., 2015). However, fresh biochar usually contains polycyclic aromatic hydrocarbons, volatile organic compounds and phenols. Those compounds are detrimental to nutrient bioavailability and plant growth, and may result in many uncertainties regarding the ameliorative effects of biochar in soils. Composted biochar is recommended as a practicable method for preparing biochar-based amendments to overcome these inherent deficiencies and reduce the needs for synthetic fertilizer (Dias et al., 2010; Doan et al., 2015; Kammann et al., 2015; Schmidt et al., 2014; Schulz et al., 2013). Moreover, one biochar amendment might present an inconsistent influence on plant growth in continuing cropping system (Major et al., 2010; Jones et al., 2012; Joseph et al., 2010; Sun et al., 2017). Once incorporated into a soil, biochar is almost impossible to be separated from the community of biochar and soil. Biochar can have negative effects on some plants and is not recommended as a soil amendment in some field rotation system. However, information regarding the effects of biochar amendment on different plants in a consecutive rotation system is particularly limited. Therefore, the objectives of this study were: (1) to investigate the effects of biochar and composted biochar-based amendment additions with or without N fertilizer on vegetable yield in four seasons of a consecutive rotation system, (2) to examine the effects of these amendments on soil properties, and (3) to evaluate N bioavailability in the soil and the contribution of biochar and composted biochar-based amendment to vegetable yield.

2. Materials and methods

2.1. Soil sampling

The surface soil (0–20 cm) was sampled using a spade from seven random sites on a farm (37.43°N, 120.33°E) in Zhaoyuan, Shandong Province, China, where the soil suffered recurrent over-fertilization. The soil was air-dried, ground, sieved to pass through a 2-mm sieve and then mixed homogeneously. The soil was classified as a sandy loam containing 43.0% sand, 43.1% silt, and 13.9% clay. The soil pH was 7.61 (1:2.5 w/v ratio H_2O). Soil organic matter (SOM) content was 13.5 mg kg^{-1}. The concentration of total N (TN), total P (TP), NH_4^+-N, and NO_3^--N in the soil was 1080, 1050, 0.63, and 15.8 mg kg^{-1}, respectively.

2.2. Biochar and biochar-based amendment preparation

Peanut shells were pyrolyzed at 350 °C for 3 h using a self-designed pyrolytic reactor, which consisted of a heating tank and a cooling tank. After charring, the peanut shell biochar (PBC) samples were naturally cooled to room temperature in the cooling tank, milled to pass a 2-mm sieve, and mixed evenly. Peanut shell composted biochar-based amendment (PAD) was prepared from a mixture of PBC, seafood shell powder, peanut shell, commercial humate and inorganic nutrients at a certain ratio, followed by a 30-day composting process. The properties of PBC and PAD are shown in Table S1.

2.3. Pot experiments

The pot experiments were performed in a greenhouse for four consecutive planting seasons. PBC and PAD were added to the soil at rates of 0% and 1.5% (w/w), which was equivalent to 31.5 t ha^{-1}. N fertilizer (urea) was incorporated into the soil at a rate of 0.02% (w/w), which was equivalent to 0.42 t ha^{-1}. Thus, the following six treatments were included in the study: (i) soil without any amendments (CK); (ii) soil + PBC (C1F0); (iii) soil + PAD (A1F0); (iv) soil + N fertilizer (CKF); (v) soil + PBC + N fertilizer (C1F1); and (vi) soil + PAD + N fertilizer (A1F1). These treatments were divided into two subgroups, i.e., no fertilizer subgroup (CK, C1F0 and A1F0) and plus fertilizer subgroup (CKF, C1F1 and A1F1). Each polyethylene plastic pot (25 cm in diameter and 20 cm in depth) was filled with 12.5 kg of soil or a mixture of soil with PBC or PAD. All treatments were replicated three times, and all the pots were randomly placed in the greenhouse. In the second, third and fourth seasons, N fertilizer was added at rates of 75%, 50% and 25% of that in the first season (0.42 t ha^{-1}) to evaluate N efficiency with the co-application of PBC or PAD. After fertilization in each growing season, the pots were equilibrated for three days in the greenhouse before sowing.

Rape (*Brassica napus* L.), rape (*Brassica napus* L.), lettuce (*Lactuca sativa* var. *longifolia* L.) and pakchoi (*Brassica chinensis* L.) were chosen as the tested plants in the pot experiments for the four consecutive planting seasons, respectively (Fig. S1). In each season, ten healthy seeds were sowed in each pot, and then thinned to the best three after germination. Soil moisture was kept at 60% of the maximum WHC during the growing season. After 45–50 days of cultivation, the vegetable roots were gently lifted and the rhizosphere soil was collected using a hand shaking method (Zheng et al., 2013a). The rhizosphere and non-rhizosphere soil samples were air-dried for analysis. The vegetables were divided into shoot and root, and then cleaned with deionized water to remove the attached soils. Then, the roots were scanned, and root morphology including length, surface area (SA), tips and volume were analyzed using an Epson Scanner (Expression 10000XL, Epson, Japan) and WinRhizo Pro.2005 (Zheng et al., 2013a). After root scanning, the roots and shoots were dried at 105 °C for 30 min to deactivate enzymes and then dried at 65 °C to a constant weight; the roots and shoots were ground into powders for further analysis.

2.4. Sample analysis

Soil pH was determined at a 1:2.5 (w/v) soil/distilled water ratio with a pH meter (AB150, Fisher Scientific, USA). SOM was determined by using the potassium dichromate oxidation method. TN content was