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BIOCHAR APPLICATION IMPROVES SOIL BULK DENSITY, AGGREGATION AND MICROBIAL BIOMASS CARBON

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Abstract

Nitrogen (N) is an essential nutrient element for crop production, nevertheless too much or too little N is harmful for soil, environment and crops. Over the last century the reactive N (Nr) in the environment has become doubled from industrial and agricultural activities. Such Nr may impact soil physical, chemical and biological characteristics especially at farm level due to improper fertilizer management. Therefore, an experiment was conducted at the farmer's field of Tokenagar village of Kapasia upazila under Gazipur district to evaluate the effects of various N management practices including biochar application on bio-physicochemical properties of soils in the Boro-T. Aman rice pattern. The experiment consisted of five treatments: T_1-, control (zero nitrogen), T_2 - farmer's practice (FP) of N as prilled urea (PU), T_3- recommended dose of N (RDN) as PU, T_4 - biochar (2 t ha^{-1}) + RDN (BRDN), and T_5 - deep placement of urea super granule (USG). Soil samples were collected after each crop harvest s and analyzed for different physical and chemical parameters. Results indicated that biochar + RDN (T_4) treatment positively contributed to decreased soil bulk density and increased water-holding capacity. The same treatment increased soil pH by 4.9% and the USG treatment (T_5) did increase by 2.8% compared to the initial level. Compared to the control, water stable soil aggregates markedly increased in biochar (148-157%) and USG (54-111%) treatments. Smaller size soil particles (0.25 mm) were found more stable than larger sized particles (0.50 mm) size particles. Improvement of soil fertility is also evidenced, however, increment of 18% carbon for the biochar treatment is notable in terms of carbon-negative economy. Furthermore, the highest microbial biomass C and N due to biochar treatment confirms its effectiveness for sustained soil quality and environment.

Keywords: Biochar, Soil properties, Farmer field, Biomass carbon, Reactive nitrogen

1. Introduction

Rice (*Oryza sativa* L.) serves as the primary staple food for half of the global population. As the world's population is projected to reach 9.7 billion by 2050, meeting the rising demand for food will be a significant challenge (UN, 2015). The current population in Bangladesh is 173 million which is expected to reach 220 million in 2050 (UNFPA, 2024). It is crucial to produce food for the ever-burgeoning population from a limited land resource. Nitrogen (N) fertilization plays a vital role in fulfilling the growing food requirements of the rapidly expanding global population. It influences key physiological processes in plants, including photosynthesis, protein synthesis and grain yield (Ladha *et al.,* 2020). In many cropping systems, especially in tropical and subtropical climates, soil N is deficient which seriously limits crop yields (Rahman *et al.,* 2022a). Due to deficiency of N in agricultural land and cropping systems across the world, external supply of N as fertilizer is necessary to meet the increasing demand of food. However, the excessive use of synthetic N fertilizers adversely affects soil health and the environment. Despite the over application of chemical N fertilizers, a substantial portion is either lost or remains unavailable to plants, leading to issues such as groundwater contamination, increased greenhouse gas emissions, and soil fertility degradation (Islam *et al.,* 2024). Therefore, effective N management practices are crucial for improving soil health and maintaining soil fertility for future generations.

Alternatively, biochar application is an effective method for enhancing soil physico-chemical properties, such as soil porosity, bulk density, moisture content, soil organic carbon, total nitrogen, and other micronutrients (Islam *et al.,* 2024). Biochar, a carbon-rich material formed through the thermal decomposition of biomass and organic wastes, has demonstrated a significant improvement in soil quality (Rahman *et al.,* 2020). Its use benefits soil properties due to its high cation exchange capacity, large surface area, and rich nutrient composition. By increasing nutrient availability, improving soil chemical properties, and boosting soil microbial biomass carbon (C) and N, biochar can promote plant growth (Rahman, 2014). The slow decomposition rate of biochar allows it to have a lasting effect on soil properties and helps restore soil fertility (Rahman *et al.,* 2020). Research has shown that combining biochar with synthetic N fertilizers can enhance crop yields in acidic soils (Ullah *et al.,* 2021). Additionally, biochar can enhance plant growth by improving soil quality, increasing soil aggregate stability, increasing water retention, enhancing nutrient availability, promoting beneficial microbial activity, and reducing soil-borne diseases. Therefore, biochar is considered a valuable soil amendment for crop production (Glaser *et al.,* 2015). While recent studies suggest that using urea super granules (USG) through deep placement significantly improves N use efficiency (NUE) and rice yield but farm level adoption of this technology is low in Bangladesh (Rea *et al.,* 2019; Alam *et al.* 2023). Therefore, the present study was conducted in farmer’s fields in Bangladesh to investigate the impact of applying urea fertilizer along with biochar, or applying the N fertilizers by deep placement of USG on soil physico-chemical properties of rice field. The study aims to offer guidance on effective N management practices that improve soil health and preserve soil fertility for sustainable agriculture.

2. Materials and Methods

2.1 Site description

The study was conducted at Tokenagar village under Kapasia upazila of Gazipur district in Bangladesh. This village is located $24^0 02'$ and $24^0 16'$ N and in between $90^0 30'$ and $90^0 42'$ E. The village is under the agro-ecological zone (AEZ) of Old Brahmaputra Floodplain (AEZ 9). Rice is the main crop for the farmers in this village. Most of the farmers follow *Boro*-Fallow-*T. Aman* (Transplanted Aman) rice cropping system. The yield of rice in the study village is low because of dependency on only synthetic fertilizers without use of organic fertilizers, which has resulted in a decline in soil fertility.

2.2 Treatments, experimental design and fertilization

The study consisted of five treatments: T_1: zero N (control), T_2: normal farmer practice (FP), where prilled urea was used, T_3: soil test-based recommended dose of prilled urea (RDN), T_4: biochar 2 t ha^{-1} + RDN (BRDN), and T_5: deep placement of urea supper granules (USG). The experiment was laid out in a randomized complete block design with four replications. The size of individual plot was 16 m^2 (4 m × 4 m). A 0.5 m irrigation channel separated the blocks from each other, while each plot was separated by a 0.5 m wide levee to prevent horizontal seepage of water and fertilizer between the plots.

Prilled urea (PU) was used in all the N treatments except the USG. Soil samples at 0-15 cm were collected before the experiment was started and analyzed to determine soil test-based N rates which were 163 kg and 82 kg N ha^{-1} in *Boro* and *T. Aman* rice seasons, respectively while in normal farmer-practice, the application rates of prilled urea were 103 kg and 62 kg N ha^{-1}. For USG treatment, the rates were 104 kg and 69 kg N ha^{-1}, respectively. Rice husk biochar was used in the BRDN treatment at the rate of 3.2 kg plot^{-1} (air-dry basis) equivalent to a dose of 2 t ha^{-1}. This was applied 7 days before final land preparation and transplanting. Biochar was produced using rice husk in a burner developed by the Department of Soil Science, BSMRAU.

The study was conducted in the *Boro*-Fallow-*T. Aman* cropping system during 2022–2023. Boro is the dry season rice was grown with full irrigation, while *T. Aman* was grown under rainfed condition with supplementary irrigation, if needed. In the PU treatments, N was applied in three equal splits at 15, 35, and 55 days after transplantation (DAT). Urea super granules were applied as a single application at 15 DAT. Based on soil test results P, K and S were applied at 18 kg, 77 kg and 13 kg ha^{-1}, respectively for *Boro* rice as basal and mixed with soil on the day of transplanting in all the treatments including zero-N control.

For *T. Aman* rice (15 August–15 November 2023) variety Binadhan-17 was used. The soil test-based rates for P, K, and S were 6 kg, 52 kg, and 8 kg ha^{-1}, respectively. In the PU treatments, N was applied in three equal splits on 10, 25, and 40 DAT, while USG was applied at a single dose at 10 DAT. Triple super phosphate (TSP), muriate of potash (MoP), and gypsum served as sources for P, K, and S, respectively, in both the *Boro* and *T. Aman* seasons. Crop and plot management practices were uniform across all plots, encompassing consistent approaches to irrigation, weed control, and pest management.

2.3 Soil sampling and analysis

Before setting up the experiment and after completion of two-season rice harvesting, random composite soil samples (3 per plot) from 0-15 cm depth were taken using an auger. The soil samples were left to dry naturally in a shaded area and then pulverized with a mortar and ground to attain a particle size capable of passing through a 2 mm sieve. Nitrogen concentration in soil was determined by Kjeldahl method (Douglas *et al.,* 1980). Soil samples were analysed for pH by glass electrode pH meter using a soil and water ratio of 1: 2.5 (Jackson, 1958), organic carbon by wet oxidation method (Walkley and Black 1934), available P by Olsen method (Olsen and Sommers, 1982), S by turbidimetric method (Chesnin and Yien, 1950) and K by ammonium acetate extraction method (Barker and Surh, 1982). The fumigation extraction procedure was used to measure soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN) in the soil as previously described by Brookes *et al.* (1985). Soil bulk density (Bd) and water holding capacity (WHC) were measured according to methods described by Page *et al.* (1982). For water stable soil aggregates (WSA), collected soil was air dried and divided into 0.50 mm and 0.25 mm aggregates and water stable soil aggregates were determined by wet sieving method (Castellanos-Navarrete, 2013).

2.4 Statistical analysis

Statistix version 10.0 statistical software was used for the statistical analysis of the data. ANOVA and univariate analyses were conducted to assess all parameters, and the separation of treatment means was accomplished through the least significant difference (LSD) method. Various graphs were generated using Microsoft Excel (Office 2007).

3. Results and Discussion

Effects of different treatments on soil properties are presented in table and graphs, and discussed below.

3.1 Bulk density

Effects of different treatments on bulk density (Bd) of post-harvest soil are summarized in Fig. 1(a). Significant interactive effect was found from the combination of biochar and N fertilizer on soil bulk density. The biochar treatments recorded the lowest soil Bd value (1.32 g cm^{-3}) which was probably due to the less dense and highly porous nature of rice husk biochar. When applied as a soil conditioner, biochar supports proliferation of soil faunas under these treatments, which in turn helps in maintaining the soil structure with proper soil aeration and water movement contributing to lowering of soil Bd (Burrell *et al.,* 2016). Celik *et al.* (2010) found alike information that compared to mineral fertilization, different organic amendment reduced the bulk density at 0-15 cm soil depth.

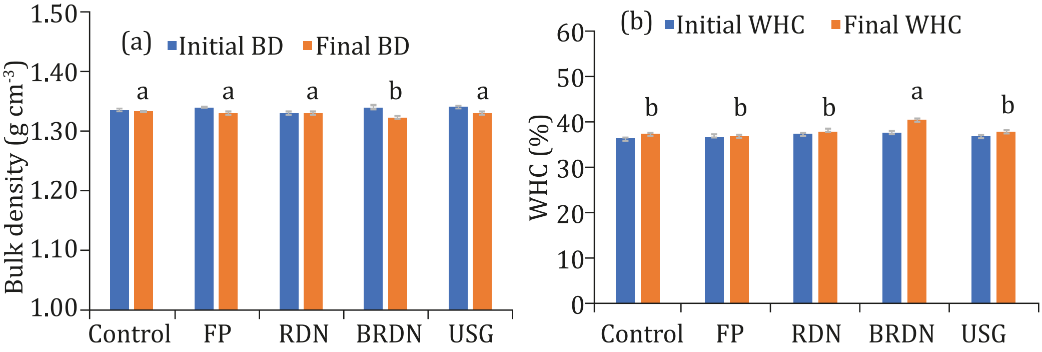

Fig. 1 *Effects of different treatments on (a) bulk density and (b) water holding capacity of post-harvest soil; Vertical bar on the column indicates standard error. (Different letters on the bar of respective parameter indicate significant difference)*

3.2 Water holding capacity

Similar to bulk density, a significant effect was observed from the combined application of biochar and N fertilizer on soil water-holding capacity (WHC) of post-harvest soil, as shown in Fig. 1(b). The treatment demonstrated the highest WHC of 41%, the reason can be attributed to the large surface area and macro- and micropores structure on the external and internal surface of rice husk biochar which possibly helped water storing in the pore network. Also, the less hydrophobicity and polarity of rice husk biochar due to its conditioning after pyrolysis possibly influenced soil aggregation (Busscher *et al.,* 2010), which could have potentially contributed to the enhanced WHC. On the other hand, the N-treated plot exhibited an inconsistent change in water-holding capacity, might be due to N increased microbial activity and accelerated the decomposition rate. Findings from our study are corroborated by Burrell *et al.* (2016) who reported similar results with an increase in WHC upon wood residue biochar application.

3.3 Water stable soil aggregates (WSA)

Treatments exhibited significant effects on soil aggregate stability (Fig. 2). The significantly highest WSA were attributed in the biochar treatment for both 0.50 mm (318%) and 0.25 mm (348%) sized soil particles. It is evident that smaller sized soil particles are more stable than that of the larger particles. Roy *et al.* (2019) also found that smaller sized soil particles contributed to a higher degree of aggregate stability. Soil aggregate stability largely depends on different agronomic management practices which may affect and breakdown larger aggregates, while the smaller aggregates may exist in high percentage (Simansky, 2013).

In terms of WSA, the treatments followed the order BRDN>USG>RDN>FP>Control (Fig. 2). Biochar is efficient in increasing soil aggregate stability of its larger surface area, and being organic materials, it acts as glue in binding soil particles together and makes soil aggregates stronger. Thus, the improved soil structure might contribute to nutrient and water retention, and also it becomes stronger to resist disruptive force and control soil erosion.

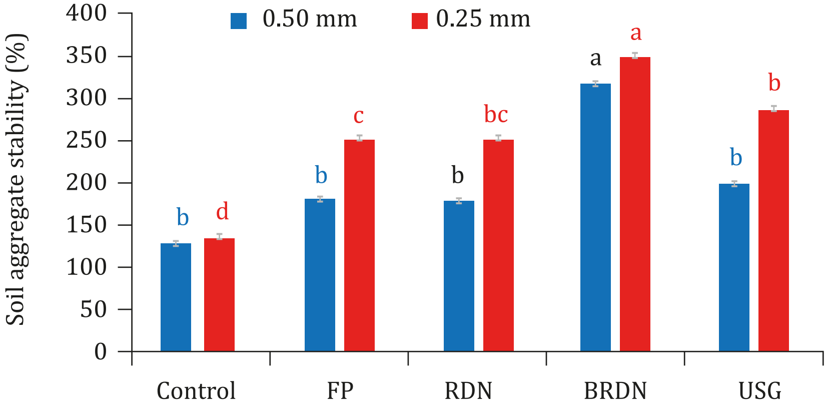

Fig. 2 *Soil aggregate stability (SAS) as affected by different N management practices (Different letters on the bar of respective parameter indicate significant difference)*

3.4 Soil pH

Nitrogen management practices significantly influence the chemical properties of post-harvest soil. After two consecutive rice growing seasons, soil pH was found significantly increased compared to initial soil status (Table 1). A significant difference ($p < 0.05$) was identified in the pH of initial and post-harvest soil in BRDN, USG, and FP treatments in a paired T-test (Table 1). Non-significant difference was found in pH of initial soil. Whereas, the pH value was significantly highest in the BRDN treatment (6.41) followed by USG (6.32), RDN (6.27), FP (6.25) and control (6.17) treatment in post-harvest soil. Application of biochar resulted in a significant increase in soil pH, which was in agreement with He *et al.* (2017). As the total basic content was higher in biochar, it increased the pH of post-harvest soil (Chintala *et al.,* 2014).

Table 1. Effects of different treatments on soil pH, organic C and total N contents of post-harvest soil

Treatments	Soil pH		Organic C (%)		Total N (%)	
	Initial	Final	Initial	Final	Initial	Final
Control	6.12	6.17_{c}	0.80	0.81_{b}	0.078	0.079_{d}
FP	6.13^{B}	6.25^{A}_{bc}	0.83	0.84_{b}	0.081^{B}	0.093^{A}_{c}
RDN	6.16	6.27_{bc}	0.80	0.85_{b}	0.083^{B}	0.102^{A}_{b}
BRDN	6.11^{B}	6.41^{A}_{a}	0.82^{B}	0.97^{A}_{a}	0.078^{B}	0.106^{A}_{b}
USG	6.15^{B}	6.32^{A}_{ab}	0.81	0.83_{b}	0.082^{B}	0.136^{A}_{a}
LSD (5%)	NS	0.11	NS	0.11	NS	0.008

Control: zero nitrogen, FP: prilled urea used as farmer's practice, RDN: recommended dose of N, BRDN: RDN + biochar 2 tha^{-1} *and USG: deep placement of urea supper granules. Different superscript capital letters in the rows under each parameter differ significantly, while different subscript small letters in the column under each parameter differ significantly.* $^{A\ and\ B}$ *Indicate significant difference between the initial and final properties*

3.5 Organic Carbon

Soil organic carbon increased significantly only in the BRDN (0.82% to 0.97%) treatment in post-harvest soil compared to the initial soil carbon (Table 1). Non-significant difference was found in organic carbon of initial soil. Whereas, the significantly highest organic carbon was estimated in the BRDN treatment (0.97%) compared to other treatments in post-harvest soil. In the present investigation, 2 t ha^{-1} biochar was added in both Boro and Aman rice seasons in the biochar-treated plots, so the significantly highest soil organic C (%) was observed on that treatment. Lorenz and Lal (2014) and Bromm and Glaser (2021) also reported that the application of biochar increased soil organic carbon status.

3.6 Soil nutrients

A significant difference ($p < 0.05$) was identified in the total N (%) of initial and post-harvest soil (Table 1). Total N (%) increased in all the treatments in post-harvest soil except the control treatment. No significant difference was found in the total N (%) of the initial soil. However, the significantly highest total N (%) was recorded in the USG treatment (0.136%), while the lowest was in the control treatment (0.079%) in the post-harvest soil. Husan *et al.* (2014) also reported that deep placement of USG increases total N % of paddy soil.

A significant difference in available P (Olsen-P) levels between the initial and post-harvest soil was observed (Table 2). The available P content in the post-harvest soil significantly increased in the USG, BRDN, and FP treatments compared to the initial soil P levels. Non-significant difference in this element level was found initial soil. However, the highest available soil P (15.8 mg kg^{-1}) was recorded in the RDN treated plot, while the lowest was in the control (12.2 mg kg^{-1}) treatment.

Table 2. Effects of different treatments on available P, exchangeable K and available S contents of post- harvest soil

Treatments	Available P (mg kg^{-1})		Exchangeable K (c-mol kg^{-1})		Available S (mg kg^{-1})	
	Initial	Final	Initial	Final	Initial	Final
Control	12.1	12.2_{d}	0.17	0.17_{b}	20.3	21.3_{b}
FP	12.2^{B}	14.0^{A}_{c}	0.17	0.18_{b}	20.3^{B}	21.2^{A}_{b}
RDN	12.1	15.8_{a}	0.16	0.18_{b}	21.1	23.8_{a}
BRDN	12.0^{B}	15.3^{A}_{b}	0.15^{B}	0.21^{A}_{a}	22.2	22.2_{b}
USG	12.1^{B}	15.1^{A}_{b}	0.17	0.19_{ab}	21.3^{B}	24.2^{A}_{a}
LSD (5%)	NS	0.2	NS	0.02	01.4	1.1

Control: zero nitrogen, FP: prilled urea used as farmer's practice, RDN: recommended dose of N, BRDN: RDN + biochar 2 tha^{-1} and USG: deep placement of urea supper granules. Different superscript capital letters in the rows under each parameter differ significantly, while different subscript small letters in the column under each parameter differ significantly. $^{A\ and\ B}$ Indicate significance between the initial and post-harvest chemical properties.

After two consecutive rice growing seasons, exchangeable K in the post-harvest (0.21 c-mol kg^{-1}) soil increased significantly than that of the initial soil (0.15 c-mol kg^{-1}) only in the BRDN treatment (Table 2). There was no significant difference in exchangeable K content of initial soil. Exchangeable K content in the post-harvest soils was found significantly higher in the BRDN (0.21 c-mol kg^{-1}) and USG (0.19 c-mol kg^{-1}) treated plots. Application of biochar treatment also led to a notable rise in the exchangeable K content which is in line with the findings of He *et al.* (2017). The process of pyrolyzing plant biomass resulted in the majority of K from the plants being transferred to the biochar component, as noted by Lehmann and Joseph (2009). Consequently, the direct incorporation of biochar into the soil had a positive impact on certain nutrient levels.

Available sulphur (S) content significantly increased in the BRDN and FP treatments in post-harvest soil compared to the initial soil (Table 2). Non-significant difference was found in available S levels of initial soil. However, soil S content was observed the significantly higher in the USG (24.2 mg kg^{-1}) and RDN (23.8 mg kg^{-1}) treated plots. While the lowest S content was observed in the FP (21.2 mg kg^{-1}) treated plot which was statically similar to the control (21.3 mg kg^{-1}) and BRDN (22.2 mg kg^{-1}) treated plot.

3.7 Soil microbial biomass carbon and nitrogen

Different treatments had a notable effect on soil microbial biomass carbon (MBC) in both initial and post-harvest soils (Fig. 3a). The highest soil MBC was observed in BRDN (320 mg kg^{-1}) followed by USG (291 mg kg^{-1}), RDN (270 mg kg^{-1}) and FP (251 mg kg^{-1}) treatments while the lowest was noted in the control treatment (201 mg kg^{-1}). It was observed that the combined application of biochar and RDN significantly increased SMBC compared to the use of RDN alone. So, combined application of biochar and inorganic fertilizer had a positive effect of increasing MBC. Similar results were found by Ali *et al.* (2021). Biochar addition to soil alters soil organic carbon, soil organic matter (Bruun and EL-Zehery 2012), and soil enzymatic activities i.e., catalase, invertase, alkaline phosphates and urease (Oladele, 2019), which consequently might have influenced microbial biomass in paddy soil.

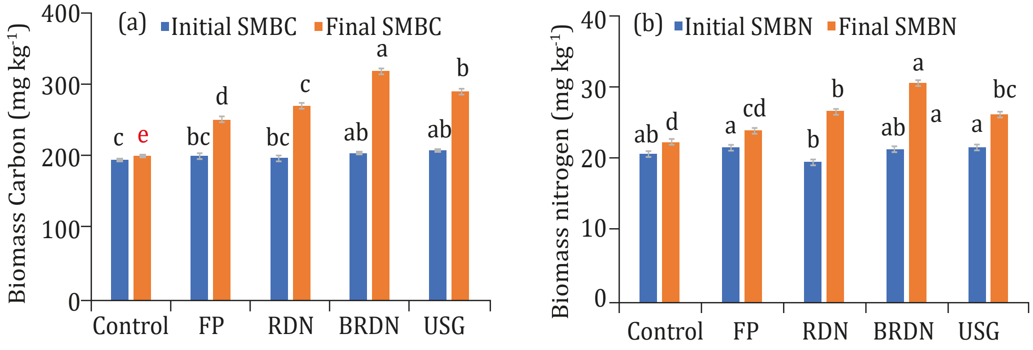

Fig. 3 Effects of different treatments on (a) soil microbial biomass carbon (SMBC) and (b) soil microbial biomass nitrogen (SMBN) of post-harvest soil. *Vertical bar on the column indicates standard error. (Different letters on the bar of respective parameter indicate significant different)*

Similar to soil MBC, the imposed treatments had a notable impact on soil microbial biomass nitrogen (MBN) in both initial and post-harvest soils (Fig. 3b). The highest soil MBN was observed in BRDN treatment (31 mg kg^{-1}) while the lowest was observed in the control treatment (22 mg kg^{-1}) which was statistically similar to FP treatment (24 mg kg^{-1}). It was also observed that the combined application of biochar and RDN significantly increased MBN compared to the use of RDN alone. So, combined application of biochar and inorganic fertilizer had a positive effect of increasing MBN. On the other hand, nitrogen is an essential element for microbial growth and development. So, MBN increased in all treatments compared to control. Similar results were found by Ali *et al.* (2021).

4. Conclusions

Different nitrogen management practices had a notable impact on the physico-chemical properties of post-harvest soil. After two consecutive rice-growing seasons, SOC, pH, total N, available P, and exchangeable K contents of the post-harvest soils were found to have significantly increased compared to their initial status in soil. The combined application of biochar and recommended dose of urea-N fertilizer decreased bulk density and significantly increased water-holding capacity compared to other treatments. Significant improvement was also observed in soil pH, organic C, total N, available P, and exchangeable K in the biochar plus RDN treatment. The highest soil microbial biomass carbon and nitrogen were also observed in the biochar containing-treatment. Therefore, the combination of biochar and the recommended dose of urea-N is likely to be the most efficient management practice for improving soil health and maintaining soil fertility.

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Conflicts of Interest

The authors declare no conflicts of interest regarding publication of this paper.

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