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# Biochar enriched compost elevates mungbean (*Vigna radiata* L.) yield under different salt stresses

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## ABSTRACT

**Context.** Organic amendments including biochar can improve crop production under salt stress. However, it is still not clear whether biochar enriched compost would enhance legume performance under salt stress after fresh application and in succeeding crops. **Aim.** The aim of the study was to examine the effect of biochar enriched compost in reducing the salinity stress after fresh application at increasing rates and in the succeeding crop. **Methods.** In a pot trial, biochar–compost was applied at four different rates (0, 1, 2, and 3%) while mungbean was grown under five different salt stress conditions (0, 2, 4, 8, and 12 dS $m^{-1}$). In the field trial, the residual effect of different organic amendments (control, compost, cow urine, compost with cow urine, biochar–compost, and biochar–compost with cow urine) was evaluated under three different salt stress conditions (0, 3, and 6 dS $m^{-1}$). Soil properties, plant performance, and nutrient uptake were determined. **Key Results.** Results revealed a significant biochar × salt treatment interaction in our pot culture. Biochar–compost application can minimise salt effects at a higher application rate resulting in better plant performance; however, these effects are minimal when salt was added at higher rates. We also observed a significant residual effect of biochar compost on biomass production (51.03%), seed yield (79.48%), and $K^+$ uptake (77.95%) than the control treatment. We believe that biochar–compost buffered $Na^+$ while improved plant water, and nutrient availability and uptake. In addition, biochar–compost might have increased nitrogen acquisition through enhanced biological nitrogen fixation. **Conclusions.** Biochar enriched compost enhances the yield of legume grown under salt stress. **Implications.** Our results suggest that biochar–compost can be one of the sustainable means for alleviating soil salinity.

**Keywords:** pyrogenic carbon, biochar application rates, nutrient-enriched biochar, evapotranspiration, legume, Na:K ratio, residual effect, salt stress.

## Introduction

Salinity is one of the most stressing challenges across the globe while it has been predicted to increase in the future (Sahab *et al.* 2021). Due to natural salinity and human interferences, the arable land is continuously transforming into saline, that is expected to have overwhelming global effects, resulting in up to 50% land loss by 2050 (Saha *et al.* 2010; Hasanuzzaman *et al.* 2013). It is prevalent in Bangladesh across the coast. Specifically, the coastal areas of Bangladesh constitute 20% of the country, of which about 53% is affected by different levels of salinity (Islam 2004). Salinity affected land has been increasing over the years and increased from 102 million hectares in 2000 to 105.6 million hectares in 2009 (SRDI 2010). Increasing crop productivity in the saline area is of global concern, and will require the development of new technologies for sustainable crop production in saline soils.

Salinity stress is one of the most atrocious environmental factors restricting the productivity of crops including mungbean in arid and semiarid regions (Abd-Alla *et al.* 1998). Salt stress imposes substantial adverse effects on the physiology, and thus, on the performance of crop plants. In extreme cases, it can eventually lead to the death of the plant. However, the intensity of adverse and injurious effects of salinity stress depends upon nature, plant species, duration, growth stage, and salt concentration.

In the coastal areas of Bangladesh, mungbean is one of the most dominant crops covering 70% of agricultural lands during *Rabi* season (Mondol *et al.* 2013). Mungbean is grown as a rain-fed crop with minimal inputs in this area. Recently, seeds of mungbean are being exported to many countries including Japan. The yield of mungbean is and will be affected by soil salinity since both the area and severity of soil salinity are predicted to increase by 39% in the coastal areas of Bangladesh (Dasgupta *et al.* 2015). Therefore, management strategies are required for sustaining its yield.

Organic amendments to soil including biochar have been suggested as potential strategies for increasing crop yield in saline soils (Liu *et al.* 2021) and recent alluvial soils (Rahman *et al.* 2021). Like other organic amendments, biochar could alleviate salinity stress since it has a large surface area and carries functional groups that could counteract salt stress (Roy and Chowdhury 2021). Organic amendments such as compost and biochar, when applied together, could therefore be a useful tool for mitigating salinity stress and thus, conserving and enhancing soil fertility and crop yield (Liu *et al.* 2021). An increase in legume yield could contribute to the food and nutritional security of the coastal community while sustaining soil health.

Biochar is a carbon-rich material obtained from the thermochemical conversion of biomass in an oxygen-limited environment. Indeed, several studies have shown that biochar application to soil can (1) improve soil physical and chemical properties (Sohi *et al.* 2010; Mukherjee and Lal 2013) (2) enhance plant nutrient availability and correlated growth and yield (Jeffery *et al.* 2011; Biederman and Harpole 2013), (3) increase microbial population and activities (Quilliam *et al.* 2013; Jaafar *et al.* 2015), and (4) reduce greenhouse gas emission through carbon sequestration (Crombie and Mašek 2015). These beneficial effects of biochar on plant productivity and soil microbial population are related to the improvement of specific surface area, cation exchange capacity, bulk density, pH, water, and nutrients within the soil matrix (Thies and Rillig 2012). Besides the generally positive plant growth responses to biochar amendment, negligible or negative effects have also been reported due to feedstock quality and pyrolysis process, biochar application rate, plant species, and soil characteristics (Lentz and Ippolito 2012; Spokas *et al.* 2012). Furthermore, in most cases, biochar does not provide high amounts of nutrients (Glaser *et al.* 2002; Glaser and Birk 2012).

Biochar application changes soil properties of salt-affected soil (Saifullah *et al.* 2018). First, biochar's pores could contribute to increase the water-holding capacity and thus, increases the plant water availability although the effects can be diversified and specific to soil types (Saifullah *et al.* 2018). Another unique characteristic of biochar that makes it a suitable soil amendment for salt-affected soils is its high salt adsorption capacity (Thomas *et al.* 2013). Its high salt adsorption capacity is by its high surface area and cation exchange capacity (CEC). Thus, biochar can be used to mitigate the negative impact of salt stress by minimising the $Na^+$ uptake by plants (Akhtar *et al.* 2015*a*). For example, Akhtar *et al.* (2015*b*) found that biochar application was quite effective to mitigate the salinity stress in potatoes, resulting in higher potato yield. In another study on wheat, Akhtar *et al.* (2015*a*) observed that the biochar transiently binds to $Na^+$ to reduce its uptake by the plant. Also, biochar application enhanced the supply of $K^+$, $Ca^{2+}$, and $Mg^{2+}$ in the soil solution. It is also reported that biochar enhances the leaching of salts, thereby reducing the electrical conductivity (EC) of the soil solution in the root zone (Chaganti *et al.* 2015; Lashari *et al.* 2015; Yue *et al.* 2016).

Based on this review of the literature, it can be inferred that biochar has the potential to mitigate salt stress by improving soil properties. However, all types of biochar are not equally effective in mitigating salt stress. Biochar effectiveness highly depends on the feedstock type, pyrolysis temperature and time, soil type and properties, and plant species (Saifullah *et al.* 2018). Consequently, it is vital to evaluate the effectiveness of different types of biochar to mitigate the salinity stress in a wide range of crop species (especially in salt stress-sensitive, high-value pulse crops) for making general recommendations for biochar as a soil amendment to mitigate the salinity stress in crops. One of the other important aspects of biochar/compost application is their rate of application. The application of organic amendments at a lower rate can be ineffective while a lager application can also be detrimental for the plant growth when grown under saline conditions.

Some recent studies have indicated that the combined applications of biochar with organic or inorganic fertilisers could lead to enhanced soil physical, chemical, and biological properties, as well as plant growth, possibly at a greater rate than sole application. In particular, several composted materials represent a sustainable source of available nutrients that could enhance plant growth, ameliorating soil physicochemical characteristics and microbiological properties (Fischer and Glaser 2012; Khan and Joergensen 2012; Liu *et al.* 2012; Schulz *et al.* 2013; Scotti *et al.* 2015). Liu *et al.* (2012) showed that the combined application of compost and biochar had a positive synergistic effect on soil nutrient content and water-holding capacity under field conditions and thus, it could be a reliable technique for salinity mitigation. In addition, the combination of biochar with compost has proved to be suitable, allowing the reduction of fertiliser input, stabilising the soil structure, and improving its nutrient content and water retention capacity (Agegnehu *et al.* 2015). These studies underline that compost and biochar combinations could enhance compost properties, leading to a higher added value and much better carbon sequestration potential due to the long-term stability of biochar (Guo *et al.* 2020). Since the effect of biochar-compost has been expected to last for more than a year, it is important to know how effective it would be to reduce salt stress in subsequent seasons. However, there are only a few studies that looked into the residual effects of the combined application of biochar and compost on crops while none of the studies examined the residual effect of biochar-compost on mungbean (Akhtar *et al.* 2015*a*; She *et al.* 2018; Alkhasha *et al.* 2019).

Considering all these together, a comprehensive study was conducted with the objectives to examine the effects of increasing rates of biochar-compost on the performance of mungbean and, to evaluate the residual effects of biochar-compost on the performance of mungbean grown under different levels of salinity.

## Materials and methods

### Biochar production and biological activation

Biochar was produced from sawdust in a slow pyrolysis biochar kiln for 10 h at ~400°C (Mia *et al.* 2015). The freshly prepared biochar was activated following a biological method using microorganisms collected from diverse soils after supplementation with nutrient solution and labile carbon sources (see Supplementary material, Table S1). The activation was for 15 days in a climate chamber (GC-300TL, Korea) at two different temperature cycles (40°C and 25°C for 12 h). The relative humidity of the chamber was at 90% while a 12 h light/dark period was also maintained. At the end of incubation, the pH of biochar was adjusted to the pH of freshly prepared biochar (6.50). Next, this biochar slurry was washed thoroughly with deionised water to remove excess salts and then dried at 105°C. The biochar properties are presented in Table 1.

### Composting and compost quality

Three different types of composts were prepared using organic waste, sawdust, and biochar at different ratios (2:1:1, dry basis). Kitchen waste, collected from student dormitories, was mixed with biochar and sawdust. Each drum was filled with 30 kg of dry biomass (equivalent to 64.7 kg wet biomass). The composting process was completed after 92 days. The compost quality is listed in Table 1. The details of composting process can be found elsewhere (M. Hasan *et al.*, unpubl. data). This biochar enriched compost is referred to as biochar-compost.

### Pot trial

A full factorial experiment was conducted at the farm site of Patuakhali Science and Technology University (22°27′52.6″N 90°23′10.6″E) with four different biochar-compost application rates (i.e. 0, 1, 2, and 3%). Soil was collected from the field where we had a field trial (discussed in the next section). The soil is clay loam in texture with sand, silt, and clay content of 35%, 38%, and 27%, respectively. The nutrient status of the soil was medium (total N – 0.071%, Olsen P – 8.49 μg $g^{-1}$ soil, K – 0.8 cmol (+) $kg^{-1}$ soil, available S – 13.40 μg $g^{-1}$ soil, B – 0.59 μg $g^{-1}$ soil) (Table S2). The pot was filled with 200 g soil after ground and passed them through a <2 mm sieve. Therefore, we applied 2 g for 1% rate, 4 g for 2%, and 6 g for 3% biochar-compost before sowing of mungbean seed (BARI Mung-6). After 30 days of growth, five different levels of salinity stress (0, 2, 4, 8, and 12 dS $m^{-1}$) were imposed by adding saline water. Each pot was considered as one experimental unit. The total plots were 80 (4 biochar rates × 5 salinity level × 4 replications). All plot numbers were arranged using Microsoft excel randomisation program. The amount of salt addition was determined with a pre-experiment. Specifically, the salt buffering capacity of the soil was determined by adding an incremental amount of salt (sodium chloride). The salinity development in soil was then calculated from regression analysis of the amount of

**Table 1.** Changes in compost properties with different biochar additions (mean ± s.e.) (S. Mia *et al.*, unpubl. data).

| Biochar | Elemental composition (%) | | | | | H/C | O/C | TGI | CEC (cmol$_c$ kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | C | H | O | N | S | | | | |
| Fresh biochar | 66.7 ± 0.0a | 2.3 ± 0.1 | 30.2 ± 0.1b | 0.8 ± 0.0b | 0.02 ± 0.01b | 0.42 ± 0.02 | 0.34 ± 0.0b | 1.76 | 18.2 ± 2.5b |
| Biologically activate biochar | 65.8 ± 0.0b | 2.0 ± 0.0 | 30.5 ± 0.2b | 1.5 ± 0.0a | 0.23 ± 0.0a | 0.37 ± 0.00 | 0.35 ± 0.0b | 2.03 | 20.9 ± 1.6b |
| *P* value | <0.05 | n.s. | n.s. | <0.05 | <0.05 | n.s. | n.s. | – | n.s. |
| Compost | 27.5 ± 0.1c | 2.4 ± 0.1b | 67.8 ± 0.0a | 2.1 ± 0.0ab | 0.15 ± 0.00 | 1.07 ± 0.02a | 1.85 ± 0.00a | 0.70 | 32.5 ± 1.9b |
| FBC compost | 44.9 ± 0.0a | 3.0 ± 0.1a | 50.1 ± 0.1c | 1.9 ± 0.1b | 0.13 ± 0.02 | 0.81 ± 0.03b | 0.84 ± 0.0 0b | 0.91 | 38.2 ± 1.1b |
| BBC compost | 43.4 ± 0.0b | 2.8 ± 0.0ab | 51.4 ± 0.1b | 2.2 ± 0.0a | 0.16 ± 0.01 | 0.78 ± 0.02b | 0.89 ± 0.00c | 1.27 | 39.8 ± 2.1a |
| *P* value | <0.01 | <0.01 | <0.01 | <0.01 | 0.39 | <0.01 | <0.01 | – | 0.04 |

TGI represent thermo-gravimetric index. Within columns, means followed by different letters indicate significant differences at Tukey's SHD at 5% level of probability.

salt addition per gram of soil and the EC determined with water (1:5, w/v) (see Fig. S1). Next, the EC at field capacity was calculated using a standard conversion factor of 5 for this particular soil (Hossain *et al.* 2020). The amounts of salt were 0.6 g, 1.3 g, 3 g, and 4.9 g per 100 g soil for 2, 4, 8, and 12 dS $m^{-1}$ levels of salinity, respectively. This amount of salt was added in three instalments with irrigation water that completely moisturised the soil up to the field capacity. Plant height and the number of leaves per plant were measured at the vegetative growth stage while dry weight of the plant was also recorded.

## Field trial

A field trial was conducted with different soil amendments (control, cow urine, compost, compost with cow urine, biochar-compost, biochar-compost–cow urine) at the farm site of Patuakhali Science and Technology University (22°27′52.2″N 90°23′15.4″E) for two consecutive seasons. The properties of biochar were discussed in Table 1 while the available nitrogen ($NH_4^+$, and $NO_3^-$) concentrations of cow urine were 5.2 and 3.2 g N $L^{-1}$. Biochar was applied at 2 t $ha^{-1}$ on the dry basis. After the application of the treatment, rice was grown during *Aman* season. Post-harvest soil properties were determined and presented in Table S3. After harvesting of the rice, mungbean (BARI Mung-6) was sown on the 3 February 2020 at the same experimental field and let grow for 30 days. Next, we imposed salinity to a plant by encircling the plants with polyvinyl chloride (PVC) pipe (10 cm diameter and 30 cm length). There were three different salinity treatments (0, 3, and 6 dS $m^{-1}$). Specifically, 1 g and 2.2 g of salt per 100 g soil were added for imposing 3 and 6 dS $m^{-1}$ levels of salinity. The salt was applied following the methods stated above. Two sets of experimental units were used for this study where half of the pots were used for yield determination and the rest of the pots were harvested for nodule collection.

## Data collection

The chlorophyll content of leaves was measured by Single Photon Avalanche Diodes (SPAD) meter (SPAD-502 plus). SPAD readings were taken from five randomly selected leaves of each plant. Nodules were collected from pots through destructive harvesting at the flowering stage (i.e. 55 DAS). Soil pH and EC (1:5, m/w in $H_2O$) were determined at the final harvest taking representative samples. Yield and yield contributing characters were recorded including the number of pods per plant, number of seeds per pod, biomass production and seed yield per plant. After harvest, the shoot biomass was analysed for P, Na and K concentrations. In brief, biomass was ground and ashed at 550°C for 4 h and next, the ash was dissolved in 6 N HCl in a heating hot plate. The near to dry solution was volumed up to 25 mL. The plant P was determined using a colorimetric method using a spectrophotometer (T60U, United Kingdom) (Jackson 1958) and the concentration of Na and K was determined using a flame photometer (BK-FP640, China) (Rowan *et al.* 1982).

## Statistical analysis

A two-way analysis of variance (ANOVA) was performed for the response variables collected in both of the experiments while the means were separated using Tukey's HSD. Moreover, a principal component analysis was done using the soil properties, plant parameters, and nutrient concentrations in plants. All statistical analyses were performed using JMP pro 11 (SAS, USA) while the graphs were prepared using Sigmaplot 11.0 (Systat Software Inc., USA).

# Results

## Pot trial

Compost application at different rates significantly influenced soil properties, evapotranspiration, and plant performance ($P < 0.05$, Table S4). Average across all salt addition rates, soil pH was higher (8.07) in pots receiving a larger amount of biochar-compost with the largest value at 3% biochar-compost application. In contrast to soil pH, the highest soil EC was recorded in the control treatment (1.82 dS $m^{-1}$). The evapotranspiration rate was significantly influenced due to the application of biochar-compost. The evapotranspiration was higher in the control treatment (16.6 mL) while it was reduced with the increase of biochar application. The plant performance (plant height, No. of leaves, and dry weight of plant) was highest when biochar was applied at 3%, which were followed by 2% and 1%, respectively.

Salt addition negatively affected the plant performance with the largest negative effect with the highest salt application rate. Similarly, the evapotranspiration was reduced with increasing salt addition. Soil salinity was the highest (2.87 dS $m^{-1}$) with 12 dS $m^{-1}$ salinity treatment, which reduced when salt was applied at lower rates. Likewise, the soil pH was increased with increased salinity treatment (Table S5).

The interaction of biochar-compost and salt addition had significant effects on the evapotranspiration rate. The highest evapotranspiration rate was recorded from 0 dS $m^{-1}$ at 0% biochar-compost rate and the lowest (3.3 mL) from 12 dS $m^{-1}$ salt addition at 3% of biochar-compost rate ($P < 0.01$, Table 2). In the case of soil EC, the application of salt caused an increase in soil EC, but the application of biochar-compost decreased soil EC. On the other hand, plant performance (plant height, no. of leaves, and dry weight of plant) was higher when biochar was applied at

**Table 2.** Changes in soil properties and performance of mungbean after different biochar-compost application rates (mean ± s.e., $N = 4$).

| Salt addition (dS m$^{-1}$) | biochar-compost (%) | Plant height (cm) | No. of leaf plant$^{-1}$ | Dry weight of plant (g) | Soil pH | Soil EC (dS m$^{-1}$) | Evapotranspiration rate day$^{-1}$ (mL) |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 10.6 ± 0.4cd | 8.3 ± 0.3cd | 1.79 ± 0.07cd | 6.72 ± 0.04o | 0.61 ± 0.12m | 23.3 ± 0.6a |
| | 1 | 11.5 ± 0.1bc | 9.3 ± 0.3bc | 1.95 ± 0.02bc | 6.91 ± 0.04n | 0.98 ± 0.03l | 17.0 ± 0.4c |
| | 2 | 12.2 ± 0.2b | 9.8 ± 0.3b | 2.07 ± 0.04b | 7.12 ± 0.03m | 1.06 ± 0.01kl | 13.5 ± 0.3de |
| | 3 | 14.9 ± 0.8a | 12.3 ± 0.6a | 2.53 ± 0.14a | 7.19 ± 0.01lm | 1.09 ± 0.00kl | 9.5 ± 0.3ghi |
| 2 | 0 | 8.5 ± 0.2efg | 6.5 ± 0.3efg | 1.44 ± 0.03ef | 7.29 ± 0.04l | 1.16 ± 0.01jkl | 20.8 ± 0.9b |
| | 1 | 8.3 ± 0.1efg | 6.8 ± 0.3ef | 1.42 ± 0.01ef | 7.55 ± 0.08k | 1.19 ± 0.00jkl | 15.3 ± 0.5cd |
| | 2 | 8.9 ± 0.2ef | 7.3 ± 0.3de | 1.50 ± 0.04e | 7.79 ± 0.02j | 1.25 ± 0.01ijk | 12.0 ± 0.4ef |
| | 3 | 9.4 ± 0.1de | 7.5 ± 0.3de | 1.60 ± 0.02de | 7.93 ± 0.02i | 1.31 ± 0.01ij | 8.3 ± 0.3hi |
| 4 | 0 | 6.5 ± 0.0hij | 5.0 ± 0.0hij | 1.10 ± 0.00ghi | 7.97 ± 0.00hi | 1.33 ± 0.00ij | 16.5 ± 0.6c |
| | 1 | 7.0 ± 0.1hi | 5.5 ± 0.3ghi | 1.19 ± 0.01gh | 8.01 ± 0.01ghi | 1.36 ± 0.00hij | 13.3 ± 0.9e |
| | 2 | 7.3 ± 0.1ghi | 6.0 ± 0.0fgh | 1.24 ± 0.01fgh | 8.05 ± 0.01fgh | 1.40 ± 0.01hi | 10.0 ± 0.4gh |
| | 3 | 7.6 ± 0.0fgh | 6.0 ± 0.0fgh | 1.29 ± 0.01fg | 8.08 ± 0.00fg | 1.46 ± 0.02ghi | 7.8 ± 0.3i |
| 8 | 0 | 5.6 ± 0.1jk | 4.3 ± 0.3jk | 0.95 ± 0.02ij | 8.10 ± 0.00fg | 2.00 ± 0.03de | 12.5 ± 0.6ef |
| | 1 | 5.5 ± 0.1jkl | 4.0 ± 0.0jkl | 0.93 ± 0.02ij | 8.15 ± 0.02ef | 1.81 ± 0.01ef | 10.8 ± 0.5fg |
| | 2 | 6.2 ± 0.3ij | 4.8 ± 0.3ij | 1.06 ± 0.05hi | 8.25 ± 0.03e | 1.67 ± 0.03fg | 8.5 ± 0.3hi |
| | 3 | 6.2 ± 0.0ij | 5.0 ± 0.0hij | 1.05 ± 0.00hi | 8.42 ± 0.02d | 1.55 ± 0.02gh | 5.0 ± 0.4j |
| 12 | 0 | 3.4 ± 0.2m | 2.3 ± 0.3m | 0.58 ± 0.03k | 8.50 ± 0.01cd | 4.00 ± 0.11a | 10.0 ± 0.4gh |
| | 1 | 3.7 ± 0.2m | 2.3 ± 0.3m | 0.62 ± 0.03k | 8.59 ± 0.01bc | 2.87 ± 0.07b | 8.8 ± 0.3hi |
| | 2 | 4.2 ± 0.0lm | 3.0 ± 0.0lm | 0.72 ± 0.01k | 8.66 ± 0.01ab | 2.44 ± 0.07c | 8.0 ± 0.0i |
| | 3 | 4.6 ± 0.1klm | 3.3 ± 0.3klm | 0.78 ± 0.02jk | 8.74 ± 0.02a | 2.16 ± 0.04d | 3.3 ± 0.3j |
| Organic amendments (OA) | | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Salinity (S) | | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| OA × S | | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |

higher rates while these increments were reduced with increased salt addition providing a significant interaction between biochar and salt addition.

## Field trial

### Soil properties

Soil amendments significantly affected soil pH and EC ($P < 0.05$, Fig. 1). The highest soil pH was observed in the biochar-compost and cow urine treatment while the same treatments had the lowest soil EC. On the other hand, salinity treatment significantly increased soil pH and EC. Therefore, there were significant interactive effects of salinity and soil amendment treatments ($P < 0.01$, Fig. 1). The highest soil pH (8.23) was obtained from the combined application on biochar and compost with cow urine ($T_6$) at 6 dS m$^{-1}$ salinity level followed by $T_5$ (biochar-compost) at 6 dS m$^{-1}$ while the minimum pH (7.29) was recorded from the control treatment ($T_1$) at 3 dS m$^{-1}$ salinity level. The soil EC (0.38 dS m$^{-1}$) was lower in the biochar and compost amendment treatments when they received relatively less amount of salt.

### Plant performance

The residual effect of soil amendment significantly influenced the mungbean performance ($P < 0.01$, Table 3). Plant performance in terms of plant height, number of pods per plant, number of seeds per plant, seed weight per plant, and biomass production were higher in the $T_6$ compared to all other treatments including control (Table S6). However, salinity treatment reduced plant performance with the largest reduction at higher levels of salt addition. For instance, seed yield per plant was reduced by 39.51% at 6 dS m$^{-1}$ treatment whereas the biomass production was reduced by 41.37% ($P < 0.01$, Table S7). In addition, nodulation rate was reduced from 5.12 to 2.66 per plant ($P < 0.01$, Table S7). The interactive effect of soil amendments and salinity treatments were not significant except for the number of seeds and seed weight per plant (Table 3).

### Plant nutrient concentration

The chlorophyll concentration (i.e. SPAD) value was relatively higher when the plant received organic amendments, while it was reduced with salt addition ($P < 0.01$, Fig. 2).

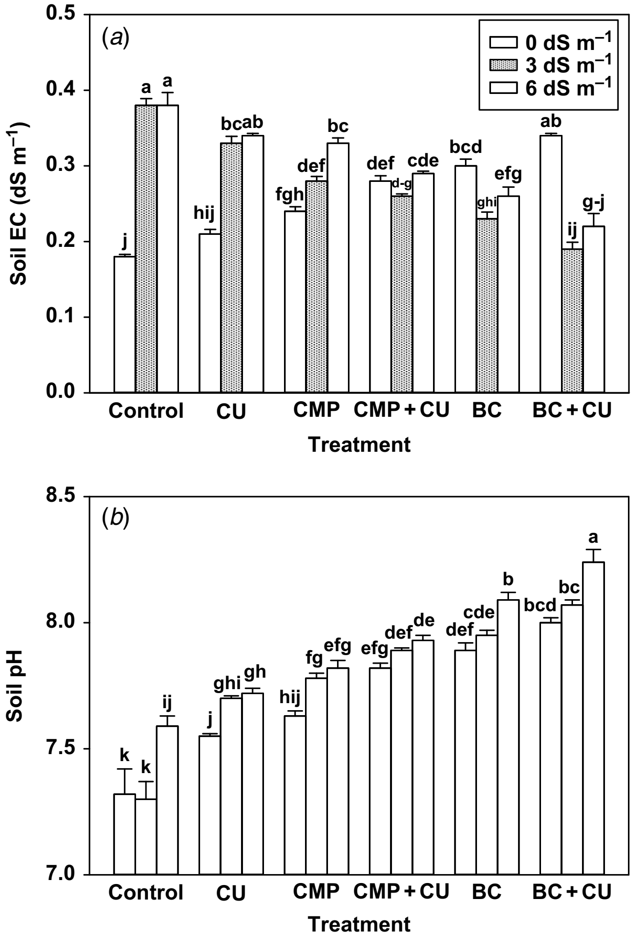

**Fig. 1.** Changes in soil EC (panel *a*) and soil pH (panel *b*) in mungbean under different salt and soil organic amendment treatments. Different letters above bars indicate differences among treatment combinations (*post hoc* Tukey's HSD, $P < 0.05$).

The highest SPAD value (53.63) was obtained from the application of biochar-compost with cow urine ($T_6$) at 0 dS $m^{-1}$ salinity while the minimum SPAD value (37) was recorded from the control treatment ($T_1$) at 6 dS $m^{-1}$ salinity level. Similarly, the P and K concentrations in plants were increased significantly in the biochar-compost addition than only cow urine and control treatments (Table 4). However, the salt addition reduced their concentration in shoot. In contrast, Na uptake was lower in the same treatment although it increased with salt addition providing a significant organic amendment × salt addition treatment. Therefore, the relative concentration of Na:K was lower when the soil received biochar-compost and cow urine in the previous season but at lower magnitude when incremental salt was added.

### Relationships and principal component analysis

There were significant positive relationships between nodule number and SPAD value with seed yield (Fig. 3). The bi-plot of the first two principal components (PCs) and the loading of variables in the field study are presented in Fig. 4. The first and second PC explained 68.1% and 11.1% of the variations of different variables. In PC1, the loading was relatively higher for seed yield, plant P, plant K, and SPAD value variables while it was lower for soil EC, plant Na, and plant Na:K ratio variables. In the second PC, soil pH, plant Na, SPAD value, and plant p variables had relatively larger loading while dry biomass, plant height, and nodule variables had lower loading. The seed yield was positively correlated with soil pH, plant K, and SPAD value while it was negatively correlated with plant Na, soil EC, and plant Na:K ratio. The relative position of the biochar-compost and cow urine treatments were in the direction of seed yield and its associated variables while control and control treatments were placed in the direction of soil salinity.

## Discussion

### Biochar-compost application rates affect plant performance

Organic amendments including biochar are shown to alleviate soil salinity (Saifullah *et al.* 2018). In our study, application of biochar-compost significantly improved crop performance including biomass production with the largest increment in the 3% biochar-compost amendment compared to control treatment. The increment might have occurred due to several reasons. These were (a) biochar-compost might have buffered added salt in their reactive surfaces (e.g. in the CEC) and thus, reduced the salt stress (Akhtar *et al.* 2015*a*, 2015*b*), (b) biochar-compost could have increased plant water status by diluting salt concentration since biochar retained more water than control treatment (Chaganti *et al.* 2015; Ferdous *et al.* 2018; Rahman *et al.* 2021), and (c) biochar might have increased plant nutrition since it contains some nutrients while it might have helped to make the nutrient available for the plant uptake through stimulation of soil biological activities and alteration of soil physical and chemical properties (e.g. pH and CEC) (Sun *et al.* 2017; Chávez-García and Siebe 2019). For instance, we observed a significant reduction in soil EC and ET with higher biochar application rates, indicating that the biochar adsorbed a substantial amount of ions and water (Table 2). Our biochar-compost contained some basic cations of $Ca^{2+}$, $Mg^{2+}$, and $K^{+}$ that might have helped in remediation of salt stress. Similar results have been reported in previous studies (Rekaby *et al.* 2020). For instance, the application of biochar-compost at different rates in saline soils significantly reduced salt stress and improved the performance of different crops including legumes (Usman *et al.* 2016; She *et al.* 2018; Rekaby *et al.* 2020). However, the application at higher rates (i.e. 10%) has been shown to negatively affect the crop performance (Luo *et al.* 2017; Hussien Ibrahim *et al.* 2020) In this case, an additive effect of biochar-compost application

**Table 3.** Performance of mung bean after different soil organic amendments (mean ± s.e., *N* = 4).

| Salinity (dS m$^{-1}$) | Organic amendments | Plant height (cm) | No. of leaves plant$^{-1}$ | No. of pods plant$^{-1}$ | No. of seed pod$^{-1}$ | No. of seeds plant$^{-1}$ | Wt. of seeds plant$^{-1}$ (g) | Dry wt. of plant (g) | No. of nodules plant$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0 | $T_1$ | 31.36 ± 0.64 | 15.66 ± 0.33 | 12.67 ± 0.88 | 5.33 ± 0.33 | 67.00 ± 1.52def | 2.47 ± 0.06fg | 3.97 ± 0.24 | 12.67 ± 2.60 |
| | $T_2$ | 38.40 ± 0.95 | 16.00 ± 0.57 | 13.33 ± 0.88 | 5.67 ± 0.33 | 75.00 ± 1.73bcde | 2.89 ± 0.05def | 6.60 ± 0.36 | 5.67 ± 0.67 |
| | $T_3$ | 35.60 ± 1.87 | 17.33 ± 0.88 | 14.33 ± 0.33 | 5.67 ± 0.33 | 81.00 ± 3.00abcd | 3.25 ± 0.12bcde | 5.55 ± 0.70 | 12.67 ± 1.76 |
| | $T_4$ | 29.66 ± 1.33 | 18.00 ± 0.57 | 15.00 ± 0.57 | 5.67 ± 0.33 | 84.67 ± 2.90abc | 3.52 ± 0.11abc | 3.33 ± 0.50 | 11.33 ± 1.20 |
| | $T_5$ | 35.76 ± 2.70 | 18.33 ± 0.66 | 15.33 ± 0.88 | 5.67 ± 0.33 | 86.33 ± 1.85ab | 3.70 ± 0.08ab | 5.61 ± 1.01 | 16.33 ± 0.88 |
| | $T_6$ | 35.90 ± 2.45 | 20.00 ± 0.57 | 16.00 ± 0.57 | 5.67 ± 0.33 | 90.33 ± 3.17a | 3.91 ± 0.14a | 5.67 ± 0.92 | 13.00 ± 1.73 |
| 3 | $T_1$ | 30.06 ± 1.46 | 15.00 ± 0.57 | 12.67 ± 0.88 | 5.33 ± 0.33 | 67.00 ± 1.52def | 2.46 ± 0.09fg | 3.48 ± 0.55 | 12.67 ± 1.45 |
| | $T_2$ | 35.33 ± 0.88 | 16.00 ± 0.57 | 13.00 ± 0.57 | 5.33 ± 0.33 | 69.00 ± 2.08def | 2.66 ± 0.09efg | 5.45 ± 0.33 | 8.67 ± 2.19 |
| | $T_3$ | 32.20 ± 1.56 | 16.00 ± 0.57 | 13.67 ± 1.66 | 5.33 ± 0.67 | 70.66 ± 1.33cde | 2.83 ± 0.04defg | 4.28 ± 0.59 | 17.33 ± 3.76 |
| | $T_4$ | 31.33 ± 1.58 | 17.67 ± 1.76 | 13.67 ± 0.88 | 5.33 ± 0.33 | 72.33 ± 1.45bcde | 3.01 ± 0.06cdef | 3.95 ± 0.60 | 11.33 ± 3.71 |
| | $T_5$ | 35.63 ± 0.63 | 19.00 ± 1.15 | 14.33 ± 1.20 | 5.67 ± 0.33 | 80.67 ± 5.20abcd | 3.43 ± 0.22abcd | 5.57 ± 0.24 | 9.33 ± 1.76 |
| | $T_6$ | 37.10 ± 1.53 | 19.00 ± 1.15 | 15.00 ± 0.57 | 5.67 ± 0.33 | 84.67 ± 2.90abc | 3.64 ± 0.12ab | 6.11 ± 0.58 | 10.67 ± 2.85 |
| 6 | $T_1$ | 27.90 ± 1.74 | 13.67 ± 0.88 | 8.000 ± 0.57 | 3.33 ± 0.33 | 26.67 ± 3.17i | 0.94 ± 0.11j | 2.67 ± 0.65 | 8.33 ± 1.45 |
| | $T_2$ | 25.43 ± 3.71 | 15.00 ± 0.57 | 9.330 ± 0.88 | 4.00 ± 0.00 | 37.33 ± 3.52hi | 1.39 ± 0.10ij | 2.44 ± 0.70 | 7.00 ± 2.08 |
| | $T_3$ | 26.03 ± 1.73 | 15.33 ± 0.33 | 11.00 ± 0.57 | 4.33 ± 0.33 | 47.33 ± 1.76gh | 1.85 ± 0.06hi | 1.97 ± 0.65 | 5.33 ± 1.86 |
| | $T_4$ | 26.00 ± 1.25 | 15.67 ± 0.33 | 13.00 ± 1.00 | 4.33 ± 0.33 | 55.67 ± 0.33fg | 2.25 ± 0.02gh | 1.96 ± 0.47 | 7.33 ± 0.88 |
| | $T_5$ | 31.66 ± 0.83 | 16.33 ± 1.20 | 13.33 ± 0.33 | 4.67 ± 0.33 | 62.00 ± 3.00efg | 2.58 ± 0.13fg | 4.08 ± 0.31 | 7.33 ± 0.88 |
| | $T_6$ | 28.33 ± 0.66 | 16.67 ± 0.88 | 14.00 ± 0.57 | 5.00 ± 0.57 | 69.33 ± 5.20def | 2.94 ± 0.22cdef | 2.83 ± 0.25 | 6.67 ± 1.20 |
| Organic amendments (OA) | | 0.0024 | <0.01 | <0.01 | 0.19 | <0.01 | <0.01 | 0.03 | 0.11 |
| Salinity (S) | | <0.01 | <0.04 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| OA × S | | 0.18 | 0.94 | 0.45 | 0.84 | 0.01 | 0.03 | 0.11 | 0.20 |

$T_1$, control; $T_2$, cow urine; $T_3$, compost; $T_4$, compost with cow urine; $T_5$, biochar-compost; $T_6$, biochar-compost with cow urine.

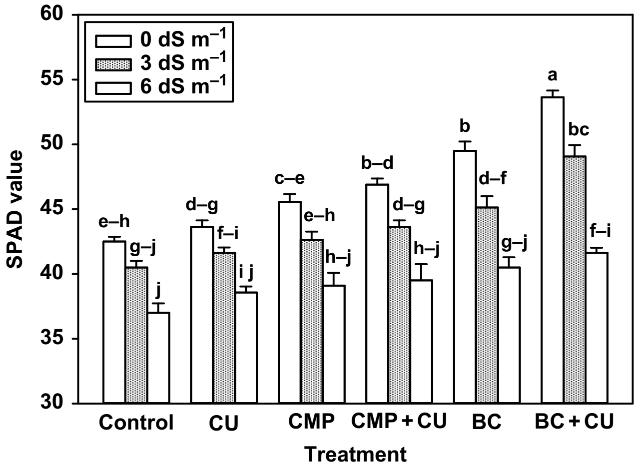

**Fig. 2.** Effect of salinity and different soil organic amendments on chlorophyll content of leaves (SPAD value). CU, cow urine; CMP, compost; CMP + CU, compost with cow urine; BC, biochar-compost; BC + CU, biochar-compost with cow urine. The error bars indicate the standard error of means ($N = 3$) while different letters above the bars indicate significant differences at Tukey's HSD ($\alpha = 5\%$). Different letters above bars indicate differences among treatment combinations (*post hoc* Tukey's HSD, $P < 0.05$).

was not observed although in many previous studies reported negative, neutral, additive, and even synergistic effects (Gunarathne *et al.* 2020; Phuong *et al.* 2020). These diversities in effects of biochar and compost on the plant performance under salinity stress underscore the specificity of biochar-compost and soil types where the interactions are taking place.

Application of salt reduced plant growth as well as reduced evapotranspiration indicate that the plant was under higher stress when salt was added in an incremental rate. This is in agreement with the previous studies (Lin *et al.* 2015; Luo *et al.* 2017; Sun *et al.* 2017; Zheng *et al.* 2018) that also reported reduced plant performance with increasing salt stress. The soil EC of different treatments was low (<4.0 dS m$^{-1}$) since the electrical conductivity was measured in water (1:5 w/v). It is usual that the soil salinity measured in water is usually lower than EC measured at saturated soil paste (ECe) (Hossain *et al.* 2020). However, the plant might have experienced sufficient salt stress, although the values were low. For instance, an EC of <1.45 dS m$^{-1}$ was considered as highly saline when the EC was measured with water at 1:5 (w/v) (Das *et al.* 2020).

**Table 4.** Phosphorus, sodium, and potassium concentrations in mung bean under different salt and soil organic amendment treatments (mean ± s.e., $N = 3$).

| Salinity (dS m$^{-1}$) | Organic amendments | P (mg g$^{-1}$) | Na (mg g$^{-1}$) | K (mg g$^{-1}$) | Na:K |
|---|---|---|---|---|---|
| 0 | $T_1$ | 3.19 ± 0.06 | 3.11 ± 0.09lm | 20.97 ± 0.55hi | 0.14 ± 0.0026hij |
| | $T_2$ | 3.46 ± 0.02 | 2.67 ± 0.16mn | 22.98 ± 0.56gh | 0.11 ± 0.0043jk |
| | $T_3$ | 3.57 ± 0.04 | 2.17 ± 0.08no | 29.52 ± 0.13ef | 0.07 ± 0.0027klm |
| | $T_4$ | 3.79 ± 0.18 | 1.63 ± 0.08o | 34.66 ± 1.80cd | 0.04 ± 0.0050lmn |
| | $T_5$ | 4.31 ± 0.11 | 1.35 ± 0.06op | 41.51 ± 0.46a | 0.03 ± 0.0018mn |
| | $T_6$ | 4.57 ± 0.13 | 0.74 ± 0.14p | 42.59 ± 0.52a | 0.01 ± 0.0033n |
| 3 | $T_1$ | 2.78 ± 0.05 | 6.30 ± 0.09fg | 20.82 ± 0.80hi | 0.30 ± 0.0085d |
| | $T_2$ | 2.87 ± 0.09 | 5.89 ± 0.14gh | 23.04 ± 0.63gh | 0.25 ± 0.0110de |
| | $T_3$ | 3.16 ± 0.04 | 5.40 ± 0.10hi | 26.79 ± 0.74f | 0.20 ± 0.0091fg |
| | $T_4$ | 3.48 ± 0.10 | 4.81 ± 0.20ij | 28.24 ± 0.69ef | 0.17 ± 0.0034ghi |
| | $T_5$ | 3.77 ± 0.06 | 4.15 ± 0.14jk | 33.73 ± 0.55cd | 0.12 ± 0.0022ijk |
| | $T_6$ | 4.05 ± 0.19 | 3.60 ± 0.13kl | 39.59 ± 0.42b | 0.09 ± 0.0025kl |
| 6 | $T_1$ | 2.11 ± 0.10 | 14.20 ± 0.33a | 18.32 ± 0.43i | 0.77 ± 0.0148a |
| | $T_2$ | 2.43 ± 0.08 | 11.88 ± 0.49b | 20.10 ± 0.41hi | 0.59 ± 0.0164b |
| | $T_3$ | 2.45 ± 0.12 | 9.42 ± 0.41c | 22.48 ± 0.94h | 0.42 ± 0.0307c |
| | $T_4$ | 2.72 ± 0.01 | 8.09 ± 0.28d | 26.38 ± 0.48fg | 0.30 ± 0.0060d |
| | $T_5$ | 2.86 ± 0.03 | 7.41 ± 0.04de | 31.80 ± 0.25de | 0.23 ± 0.0006ef |
| | $T_6$ | 3.39 ± 0.09 | 6.82 ± 0.19ef | 36.58 ± 0.25bc | 0.18 ± 0.0063fgh |
| Organic amendments (OA) | | <0.01 | <0.01 | <0.01 | <0.01 |
| Salinity (S) | | <0.01 | <0.01 | <0.01 | <0.01 |
| OA × S | | 0.51 | <0.01 | <0.01 | <0.01 |

$T_1$, control; $T_2$, cow urine; $T_3$, compost; $T_4$, compost with cow urine; $T_5$, biochar-compost; $T_6$, biochar-compost with cow urine.

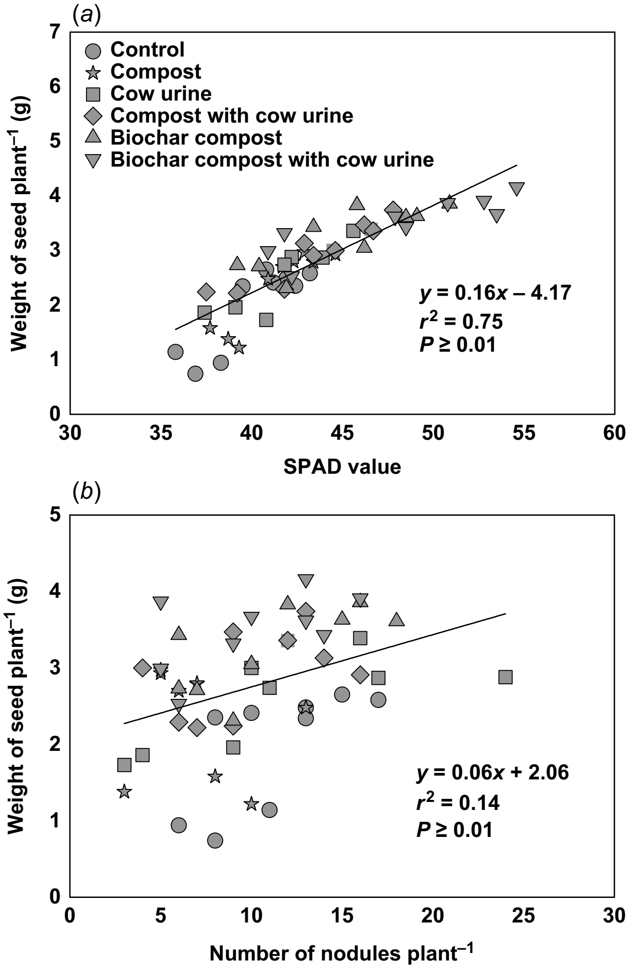

**Fig. 3.** Relationship between seed weight and chlorophyll content (SPAD value, panel *a*) and number of nodules (panel *b*).

## Residual effect of soil amendments

The residual effect of organic amendments on the plant performance under saline conditions might be minimal (Akhtar *et al.* 2015*b*). In our study, there wasa significant improvement in plant performance including 79.48% increase in seed yield in mungbean. This may have occurred due to a decrease in soil salinity since there was a reduction of soil EC when biochar-compost was applied. Secondly, biochar-compost promoted plant N acquisition either by enhanced biological nitrogen fixation or by soil nitrogen availability. A significant increase in SPAD value and nodule number was observed in this treatment while there were significant positive relationships between seed yield and nodulation/SPAD value (Figs 3 and 4). There is a possibility to increase N and P use efficiency by application of biochar-compost since there was a significant improvement of these nutrient statuses in the soil before start of the experiment. Moreover, biochar-compost addition increased $K^+$ uptake which is one of the potential means to reduce salt stress (Table 4). In addition, biochar-compost application significantly increased soil organic matter in our previous study, and thus, it could have increased water retention and nutrients in the soil for plants (Rahman *et al.* 2021). These might have contributed to alleviating the negative effects of salinity (Wong *et al.* 2010). Biochar-compost might have changed soil microbial community, soil structure and water availability (Chaganti *et al.* 2015). These parameters were not measured in this study. There are only a few studies to compare our results (Akhtar *et al.* 2015*b*; Lashari *et al.* 2015). However, in these studies, alleviation of salt stress was reported due to an enhancement of plant water and nutrients (basic cations – $K^+$, $Ca^{2+}$, $Mg^{2+}$) uptake.

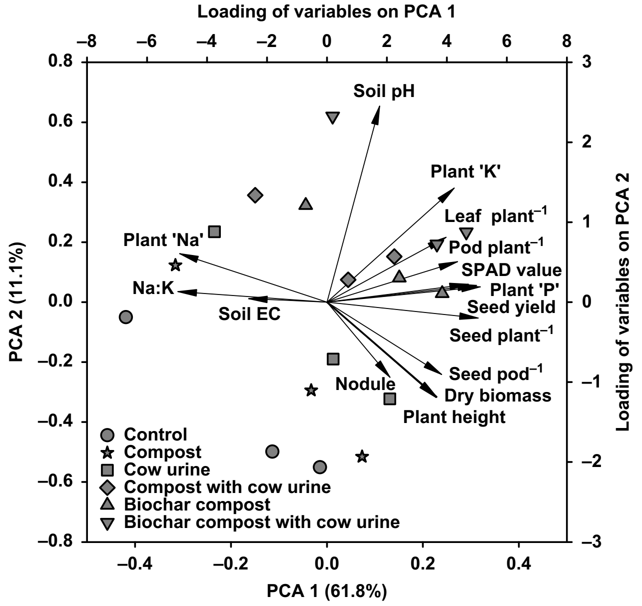

**Fig. 4.** Bi-plot of PCA analysis showing the first two principal components (PCA1 and PCA2). For PCA analysis, data included were soil properties, plant parameters, and nutrient concentrations.

## Conclusions

Organic amendments including biochar and compost can alleviate soil salinity. We observed a significant biochar × salt treatments interaction in our pot study indicating that biochar-compost can reduce salt stress with larger effects at higher application rates but these effects were reduced with the increased levels of salinity. We also observed a significant residual effect of biochar-compost on biomass production, seed yield, and $K^+$ uptake of mungbean under salt stress. A significant increase in plant N acquisition through biological nitrogen fixation was observed while this enhanced N contributed to the seed yield (a positive correlation between seed yield and nodulation). The enhanced performance of biochar-compost can also be explained by $Na^+$ buffering and improved plant water and nutrient availability. Our results suggest that biochar-compost could be one of the sustainable means to alleviate soil salinity.

## Supplementary material

Supplementary material is available online.

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**Data availability.** The data of this study will be shared upon reasonable request to the corresponding author.

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