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# Initial greenhouse observations on use of coal char as a soil amendment: Influences on plant growth and soil water holding capacity

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**A greenhouse study was conducted to begin testing the use of coal char (CC) as a soil amendment. CC is a solid, porous activated carbon material resulting from high-temperature pyrolysis of coal. The objectives of this preliminary trial were to evaluate the impacts of different concentrations of CC added to the soil (0% (control), 1, 5, and 10% (v/v)) on plant biomass yield and soil water holding capacity (WHC). The study was designed with ten replications using alfalfa as the test plant in two different soils: Uncultivated rangeland soil and cultivated agricultural soil. The application of 5% CC led to a significant increase ($p < 0.05$) in alfalfa mean dry biomass production of 1.54 ± 0.31 g in agricultural soil and 1.85 ± 0.25 g in rangeland soil compared to 1.05 ± 0.22 g and 1.20 ± 0.27 g mean biomass production in the controls of the respective soils. The growth of alfalfa plants was not significantly affected, positively or negatively, in any other treatments. A significant increase ($p < 0.05$) in soil WHC was observed at 5 and 10% CC concentrations in both soils compared to their respective controls. Therefore, adding coal char at optimal rates may increase plant growth and soil WHC in dryland soils.**

**Key words:** Coal char, plant growth, soil water holding capacity, soil amendment, alfalfa

## INTRODUCTION

Soil amendment involves adding materials to the soil to improve its physical properties, such as soil structure, water-holding capacity, and nutrient retention, providing a better environment for plant growth or seed germination (Davis and Whiting, 2013). Several agricultural and soil management practices, such as intensive tillage and cultivation, alter the soil environment and negatively impact soil health by reducing soil organic matter and soil structure, which can diminish soil nutrient and water-holding capacities as well as overall soil productivity (Al-Kaisi et al., 2014).

Reducing the negative impacts of intensive soil management and crop production, while meeting the world's food demands, is a critical challenge facing the global agricultural community (UNEPA, 2012). Adding organic materials to the soil, such as manure, crop residues, and green manure, has long been practiced to increase soil organic matter and improve soil productivity due to its beneficial effects on soil properties (Steiner, (Steiner, 2009). The use of low-ranked coal, such as

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and sub-bituminous coal, and its derivatives as a source of humic materials for agricultural soils has shown a wide range of benefits on soil physical, chemical, and biological functions (Akimbekov et al., 2021).

Indigenous peoples in parts of the Amazon Basin in South America have historically added charcoal and other materials to the soil to improve crop yields (Hunt et al., 2010). Soils heavily modified by anthropogenic inputs of charcoal, bone, and manure (Naves et al., 2004; Shu et al., 2015) are abundant in low, forested areas of Amazonia (covering up to 18,900 $km^2$ or more, Ruivo et al., 2003), where the intensely weathered tropical soils have very low inherent cation exchange capacity or nutrient holding potential.

Currently, in the United States, the use of biochar or pyrolyzed biomass as a soil amendment is growing rapidly due to claims that it can improve soil health, increase soil fertility, and enhance crop yields (Filiberto and Gaunt, 2013; Osei et al., 2020). A recent market analysis report (Research and Markets, 2021) revealed that the US biochar market size in 2020 was USD 125.3 million. Pyrolyzed coal or CC has many properties similar to biochar, such as extensive surface area, high porosity, low bulk density, good nutrient and water-holding properties, high carbon content, and alkaline pH.

Many studies have been conducted on the assessment of plant growth and soil properties using biochar as a soil amendment. However, the use of CC in agricultural soil amendment is a new concept that has recently emerged and has not been broadly tested. Therefore, this study aimed to determine the effects of different application rates of CC on cultivated agricultural clay loam (hereafter called Ag.soil) and uncultivated fine sandy loam soil (hereafter called Range soil). The objectives of this study were to examine the effects of CC added to the soil on alfalfa biomass production and to determine the influence of CC used as a soil amendment on WHC in two different semiarid dryland soils.

## MATERIALS AND METHODS

### Soil collection for the study

Two different regional soils were used in the greenhouse experiment to broaden the potential scope of the results. Both soils' surface samples (0-20 cm depth) were collected for the study. A local uncultivated prairie sandy loam soil (Borollic Haplargid, Fine sandy loam) was obtained from the rangeland of Laramie basin, WY, USA. Similarly, an agricultural cultivated clay loam soil (Typic Haplargid, Garland clay loam) was collected from the University of Wyoming Powell Research and Extension Center at Powell WY, USA, located 60 miles east of Yellowstone National Park. Both soils were air-dried by spreading on a tarp and homogenized. A rubber hammer was used to break down the larger soil aggregates to pass through a 3 mm sieve for use in plant growth experiments and a 2 mm sieve for use in the determination of soil WHC. Lab test results of both soils (Table 1) indicate some physical and chemical differences between the two soils.

### Soil amendment material CC used in the study

This study's CC (Figure 1) was obtained from Atlas Carbon LLC, Gillette, Wyoming, where the Powder River Basin (PRB) subbituminous coal was pyrolyzed up to a temperature of 800°C. Sub-bituminous coal of PRB Wyoming contains low Sulphur (0.5 wt.%) and ash (8%) with a low heating value of about 8000 BTU $lb^{-1}$ (French, 1990; Gibbins-Matham and Kandiyoti, 1988). A sieve test was performed to determine CC's particle size in the School of Energy Resources (SER) laboratory, University of Wyoming, USA. The particle size of the CC used for the experiment (Table 2) ranges from < 0.177 mm to > 0.40 mm, but coarse sand size dominated. Further analysis of coal and CC composition (Table 3) was performed by Energy Laboratories, Gillette, WY, USA. The fixed carbon on the CC was found to be 78.86%, while raw coal contains 40.17% fixed carbon.

### Experimental procedure and layout

This study was conducted at the Laramie Research and Extension Center, in the greenhouse complex of the College of Agriculture, Life Sciences, and Natural Resources, University of Wyoming, Laramie, USA. The temperature within the greenhouse was maintained relatively constant, ranging from 65 to 70°F. The concentrations of 1, 5, and 10% CC by volume (v/v) were mixed into both soils, along with a treatment with no CC added (control). All treatments were replicated ten times, resulting in 40 cone-tainers set up for each soil type. The CC-mixed soils were added to yellow cone-tainers (SC10U, Stuewe & Sons, Inc., Oregon, USA) and prepared for planting by filling them to within an inch from the top and moistening them. Alfalfa seeds were planted at a rate of 5 seeds in each cone-tainer initially, with each cone-tainer being limited to two plants after establishment (within seven days of emergence). A regular watering schedule of three times a week was maintained, allowing water to flow out of the soil from the bottom of the cone-tainers. No fertilizers were added to any treatments. These plants were allowed to grow for 60 days, rotated, and shifted within the greenhouse to account for potential environmental differences within the space. At the end of the growing period, plants were harvested with the root elutriator to separate soil from plant roots. Harvested alfalfa plants (roots and shoots) in each cone-tainer were dried (65 ± 5°C for a week) in the oven, and their dry weights were determined with an electronic analytical scale, accurate to ± 0.001g.

### Measurement of soil water holding capacity

The soil's WHC was determined in the University of Wyoming's soil lab. Collected soil samples from the two fields were sieved through a 2.0-mm sieve to ensure a uniform soil particle size. The method for measuring gravimetric soil water content was oven-dry soil weight versus saturated-drained (24 h) at field capacity (Yu et al., 2013). Soil samples (air dry) were prepared by mixing CC at 0, 1, 5, and 10% (v/v) to determine the WHC by mass. Each sample was then saturated with water for 24 h. After 24 h, wet soil was removed from filter paper and weighed immediately. Saturation period of 24

**Table 1.** Soil texture characteristics (0 – 20 cm depth) along with soil particle size distribution: pH (1:1), electrical conductivity (EC), organic matter (OM), nitrate nitrogen ($NO_3$-N), phosphorous (P), and potassium (K).

| **Properties** | **Ag. soil** | **Range soil** |
|---|---|---|
| pH | 7.9 (0.08) | 7.29 (0.01) |
| EC (mmhos $cm^{-1}$) | 1.2 (0.12) | 0.46 (0.01) |
| OM (%) | 2.04 (0.03) | 1.67 (0.05) |
| $NO_3$-N (mg $kg^{-1}$) | 0.01(0.00) | 6.09 (0.09) |
| P (mg $kg^{-1}$) | 0.04 (0.02) | 0.01 (0.00) |
| K (mg $kg^{-1}$) | 183.00 (8.19) | 142.67 (2.33) |
| **Soil texture** | **Sandy clay loam** | **Fine sandy loam** |
| Sand (%) | 53 (2.08) | 68.67 (0.88) |
| Silt (%) | 20.67 (1.86) | 18.67 (0.88) |
| Clay (%) | 22.33 (0.33) | 13.33 (0.33) |

Data indicates the mean values (n = 3) with the associated standard errors (SE) from the means in the parenthesis.

**Figure 1.** The physical appearance of coal char used as a soil amendment.

h will provide homogenization of water content throughout the soil samples (Péron et al., 2007). A standard soil drying oven temperature of 110 ± 5°C was used as defined by the American Society for Testing and Materials (ASTM) Standard D 2216-10 (ASTM Standard D2216, 1998). Finally, the amount of water held in samples was calculated by subtracting the oven-dry weight of soil from the weight of saturated soil after removal from the filter paper. The available water content of each sample was determined by calculating the difference in weight of saturated drained soil and oven dry soil. Weight difference between oven-dry and saturated wet soil was divided by oven-dry soil weight, and the result was multiplied by 100% to find the soil WHC. Soil WHC (%) (Equation 1):

$$\text{Water holding capacity (\%)} = \frac{\text{weight of saturated drained soil (24 h)} - \text{weight of oven dry soil}}{\text{weight of oven dry soil}} \times 100\% \quad (1)$$

Average soil WHC was determined for the CC mixed soil samples with three replications from each treatment. Standard deviation (SD) was computed from the three replicate samples for each treatment, and SD was used to compute SE.

### Statistical analysis

The experimental data were analyzed using Microsoft Excel 2016 to

**Table 2.** Coal char sieve analysis results (average particle size).

| Particle size (mm) | Texture | Mesh | Percent |
|---|---|---|---|
| >0.400 | Coarse sand | < 40 | 19.1 |
| 0.250 - 0.400 | Coarse sand | 60-40 | 36.3 |
| 0.219 - 0.250 | Medium sand | 70-60 | 7.9 |
| 0.177 - 0.219 | Silt + sand | 80-70 | 8.7 |
| <0.177 | Silt +clay | >80 | 27.8 |
| Total | | | 99.8 |

**Table 3.** Lab test results for trace elements, including fixed carbon %, and volatile matter in raw coal and coal char (Energy laboratories, Gillette, WY, USA).

| Parameters | Coal | Coal char |
|---|---|---|
| Ash % | 5.96 | 16.72 |
| Volatile matter % | 36.26 | 14.06 |
| Fixed carbon % | 40.17 | 78.86 |
| Arsenic (mg $kg^{-1}$) | 1 | 1.2 |
| Cadmium (mg $kg^{-1}$) | ND | ND |
| Chromium (mg $kg^{-1}$) | 3 | 5 |
| Copper (mg $kg^{-1}$) | 6 | 14 |
| Lead (mg $kg^{-1}$) | 2 | 2 |
| Mercury (mg $kg^{-1}$) | ND | ND |
| Selenium (mg $kg^{-1}$) | ND | ND |

ND = Not detected at the reporting level.

examine the significant difference between treatment means in alfalfa plant biomass and soil WHC in no CC control and CC treatments within the soil types. Statistical significance of treatment effects was identified using criteria of $p < 0.05$ from the t-test. All results were stated as the mean value and presented along with SE in tables and figures (Dangi et al., 2020; Joardar et al., 2020). Regression analysis was performed in R (64 4.1.2) statistical software.

## RESULTS AND DISCUSSION

### Plant growth

In this study, alfalfa dry biomass production (Table 4) significantly increased ($p < 0.05$) at 5% CC application rate in both Ag. soil (1.54 ± 0.098 g) and range soil (1.85 ± 0.08 g) compared to their controls (1.05 ± 0.068 g) and (1.20 ± 0.086 g), respectively. However, there were no significant differences in alfalfa biomass production in soils with 1 and 10% CC application over controls. In Ag. soil, the 1 and 10% CC treatments resulted in similar growth, 1.13 ± 0.067 g and 1.13 ± 0.071 g, respectively, compared to 1.05 ± 0.068 g yield of its control, and the difference was not significant ($p > 0.05$). Outcomes from this greenhouse pilot trial indicate that the lower application rate (1%) of CC in the two soils tested does not result in increased alfalfa growth. There may need to be more than a small amount of CC mixed into the soil to enhance soil properties significantly. Also, the high application rate (10%) does not improve alfalfa growth, possibly due to a lack of plant essential nutrients in CC. Moreover, Due to its high porosity and surface area, a large quantity of CC in soil may adsorb more nutrients from the soil solution. Granatstein et al., (2009) documented a decline in plant biomass with a high application rate of biochar, which they speculated was due to biochar's surface area and adsorption reducing nutrient availability. Jha et al. (2010) reported a negative effect on plant development when there is more than 9% (by mass 90g/kg soil) biochar in loamy sandy soil.

A field study results (Thapa et al., 2024) also indicated no significant increase in grass biomass yield with the CC

**Table 4.** Effect of CC application rate on Alfalfa dry weight (g cone$^{-1}$).

| Soil types | CC application rate (%) | Alfalfa biomass dry weight (g) |
|---|---|---|
| | 0 | 1.05 (0.068) |
| Ag. Soil | 1 | 1.13 (0.067) |
| (Sandy clay loam) | 5 | 1.54* (0.098) |
| | 10 | 1.13 (0.071) |
| | | |
| | 0 | 1.20 (0.086) |
| Range Soil | 1 | 1.14 (0.039) |
| (Fine sandy loam) | 5 | 1.85*(0.080) |
| | 10 | 1.18 (0.022) |

Data indicates the mean weight values (n = 10) with the associated standard errors from the means in the parenthesis. Statistically significant differences from control ($p < 0.05$) are indicated by an asterisk (*).

application rate of 10% (v/v) in sandy loam soil, however, found significantly increased grass biomass yield in the treatment when the same quantity of CC co-applied with manure in the same field.

Results of this study in two dissimilar soils indicate the addition of 5% CC resulted in improved alfalfa growth in both clay loam and sandy loam soils, resulting in a significant increase in alfalfa biomass production. Logical reasoning for this significant increase in plant growth could be the amelioration in soil physical properties, such as less soil compaction due to the addition of CC which may help the expansion of plant roots to reach more nutrients and water in the soil. A similar biochar study (Adekiya et al., 2020) reported improved in soil physical properties: soil porosity, bulk density and moisture content in the biochar amended field soil in southwest Nigeria. Biochar applied in heavy clay soil (Obia et al., 2018) also resulted in higher maize yields due to decreased soil bulk density compared to control. Weight dilution due to CC addition in the soil could have affected soil bulk density and porosity. However, result from this study also indicated that CC application rate greater than 5% could be not beneficial for plant growth. Several factors may contribute to decreasing plant growth with higher concentration of CC in soils. First of all, greater concentration of CC added to soil could have reduced soil bulk density significantly, which might cause a greater soil porosity leading to greater water infiltration rate. That might have leached out more water-soluble nutrients from the soil, resulting less nutrients available for plant growth. A recent study (Jílková, 2023) in biochar application with low rate (20 t ha$^{-1}$) and high rate (40 t ha$^{-1}$) in coarse-textured temperate soil indicated that high application rate of biochar resulted in greater leaching amount of dissolved nitrogen and dissolved phosphorous than low application rate. Lower application rate of biochar produced from organic residues also resulted in increase in plant available nutrients and crop yield on sandy soil (Knoblauch et al., 2021).

As a soil amendment, CC probably have similar mechanisms of benefit for plant growth (Cooper et al., 2022). Reviews and meta-analysis show biochar generally lowers soil acidity and increases soil buffering capacity; increases dissolved and total organic carbon, cation exchange capacity, available nutrients, water retention, aggregate stability, and reduces bulk density(Joseph et al., 2021; Lehmann and Joseph, 2009). Biochar can increase microbial activity, accelerate nutrient cycling and reduce the leaching and volatilization of nitrogen(Joseph et al., 2021).

## Soil water holding capacity

A significant increase ($p < 0.05$) in gravimetric WHC occurred in the CC concentrations of 5 and 10% in both sandy clay loam and fine sandy loam soil (Table 4). In the fine sandy loam range soil, WHC at 5 and 10% CC concentrations were found to be 21.33 ± 0.61 and 22.50 ± 0.21%, respectively, that was 12.67 and 18.85% greater than no CC soil of 18.92 ±0.22% WHC. Furthermore, in sandy clay loam Ag. Soil also, soil WHC increased by 10.53 and 20.91% at 5% (26.40 ± 0.60) and 10% (29.42 ± 0.33) CC concentrations, respectively, compared to 23.90 ±0.53% soil WHC at 0% CC concentration. A lower concentration of CC (1%) did not cause a significant increase in soil WHC ($p > 0.05$) in either soil. The highest error was noticed at 5% mixtures, and the lowest was found at 1% mixtures of both soils. The average gravimetric water holding capacities are

**Table 5.** Experimental results for soil WHC (%) on two soils in different treatments

| Soil types | CC concentrations (%) | WHC (%) | % increase |
|---|---|---|---|
| | 0 | 23.90 (0.53) | - |
| Ag. Soil | 1 | 23.77 (0.21) | -0.54 |
| (sandy clay loam) | 5 | 26.40* (0.60) | 10.53 |
| | 10 | 29.42* (0.33) | 20.91 |
| | 0 | 18.92 (0.22) | - |
| Range soil | 1 | 19.60 (0.19) | 3.54 |
| (fine sandy loam) | 5 | 21.33* (0.61) | 12.67 |
| | 10 | 22.50* (0.21) | 18.85 |

Data indicates the mean values (n = 3) with the associated standard errors from the means in the parenthesis. Statistical differences from control ($p < 0.05$) are indicated by an asterisk (*).

shown in Table 5.

Among all treatments, the most increase in soil WHC (29.42 ± 0.33%) was observed in the CC application rate of 10% (Table 5) in the Ag. soil, which is a 20.91% increase over the control (23.90 ±0.53%) of the same soil. Increasing CC concentration in both soils increased soil gravimetric WHC. Studies on biochar addition to soil demonstrate it can also increase soil WHC and, as a result, support temperate agroecosystem functioning. This change could result from the combined effect of alteration on physical, chemical and biotic soil properties (Jones et al., 2012). The particle size of biochar can influence on soil WHC due to alteration in pore characteristics. Pores inside of biochar may provide additional spaces for water storage in soil (Liu et al., 2017). Biochar pore spaces with diameters between 0.5 and 50 µm are classified for capable to holding plant available water (Batista et al., 2018).

Preliminary results from this greenhouse study on soil WHC indicated that the CC appeared to improve soil WHC of sandy loam soil and sandy clay loam soil compared to no CC control soils. More water content in CC treated soil compared to non-treated soil could be explained by the micro-pore space of added CC that could have retained more water. High carbon content in CC could improve the soil's physical, chemical, and biotic properties and can be the emerging soil amendment product in future. Dryland agricultural system like Wyoming can benefit by using CC due to its promising soil WHC, which can improve soil health by retaining soil moisture for a more extended period. Increased soil carbon and moisture may foster soil microbial diversity and population, positively impacting nutrient cycling. Non-biodegradable nature of CC can remain in soil for decades or centuries, thus, providing sustainable soil health benefits. Moreover, CC seems economically feasible to farmers (< 100 U.S. dollars ton$^{-1}$) based on PRB sub-bituminous coal current price of USD 16.20 (USEIA, 2022). However, biochar market price varies according to geographic locations and the feedstock used to make biochar.

### Correlation between CC concentration and soil WHC

Figure 2 indicate a clear positive correlation between CC concentrations and soil WHC in both soils included in this study. Changes in soil WHC were regressed with changes in CC concentrations. The Ag. soil had a stronger relationship between soil WHC and CC concentrations with a slope of 0.5808 and a better goodness of fit ($R^2$ =0.9185) compared to the range soil which had slope 0.3516 and goodness of fit ($R^2$ =0.8596). Higher CC concentration provides more significant WHC enhancement in either soil. The reason may be that more remarkable pore space available in the soil amended with a high concentration of CC. Furthermore, higher amount of CC may have provided greater micro pores in soils to hold a greater amount of water. Previous biochar study on bulk density and soil WHC (Verheijen et al., 2019) mentioned that higher biochar concentration (20% v/v) reduced soil bulk density by 19.3% in sandy soil. Decreasing soil bulk density might enhance soil porosity, providing space for soil water storage.

High application rate of CC (10%) in Ag. soil seemed more responsive with a 20.91% increase in soil WHC compared to 18.85% increase in range soil at same level of CC concentration comparing the control of the respective soils. The greater slope of a fitted line (Figure 2) in Ag. soil indicated more response with greater CC concentration. This increase in soil WHC can be due to the mechanism of dilution of soil clay particles by low

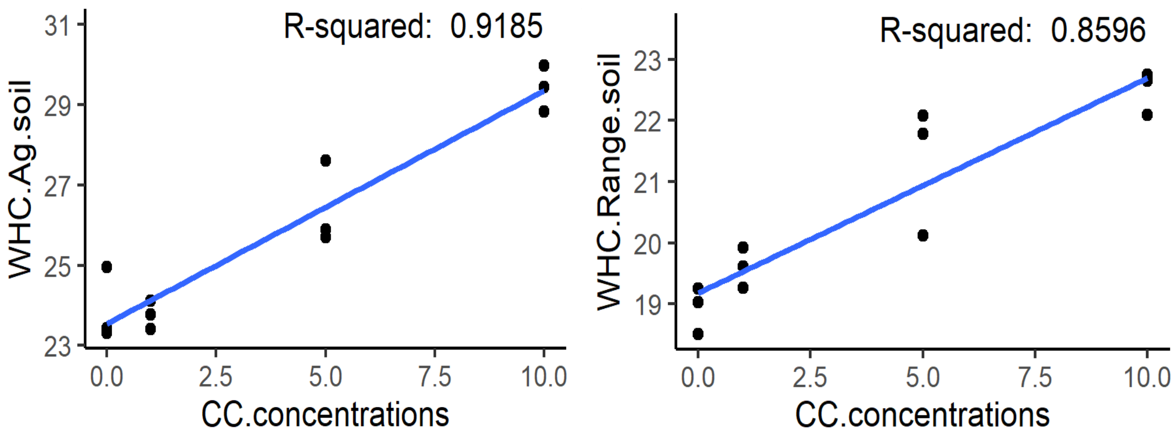


**Figure 2.** Soil WHC (%) at 0, 1, 5, and 10% CC concentrations in sandy clay loam (left) and fine sandy loam (right) soils. WHC refers to Water Holding Capacity and CC refers to coal char.

density CC and providing appropriate pore size and improved soil aggregation in sandy clay loam soil. A recent meta-analysis study (Islam et al., 2021) indicated that soil aggregation significantly improved by 16.4 ± 2.5% with biochar application. Another study (Du et al., 2017) in a site of typical monsoon climate in China found a significant increase in soil macro aggregate (250-2000 µm) in the biochar application rate of 4.5 and 9 t $ha^{-1}$ $year^{-1}$.

## Conclusion

Results of this study demonstrate that CC added to two aridisols resulted in statistically significant improvements in growth of alfalfa plants and significantly increased soil WHC. Low and high application rates of CC are ineffective for increasing plant growth in sandy loam and clay loam soils. However, a moderate application rate (5% CC) resulted in a significantly high plant dry biomass yield in both soils, with the highest yield recorded in the fine sandy loam soil. Another interesting result is that the high application rate of CC resulted in no significant difference on plant biomass production in both soil types. It could be associated with the great adsorbent nature of CC with significant high porosity, and nutrients could have been adsorbed from the soil solution leading to fewer nutrients available for plant uptake and growth. Loading essential plant nutrients from conventional materials like manure, compost or fertilizers into CC can compensate for the adsorbed nutrients by the char materials. It was noticed from this study that impact of CC on WHC varies according to soil textures, meaning CC interacts differently according to soil types. CC used in this study increased soil WHC significantly at 5, and 10% application rates in both soils, and the relationship was found to be linear. A low application rate (1% CC concentration) was found not to increase soil WHC in both soils. Sandy clay loam soil holds more water than fine sandy loam soil in all treatments, which can be explained by higher surface area and pore spaces. Greater CC concentration in soils could increase soil volume due to decrease in soil bulk density which can be associated with increased soil water storage. This can be linked to irrigation effectiveness where multipliers effect such as increase in soil microbial population and diversity due to an increase in soil moisture and soil carbon can positively impact on nutrient cycling and nutrient availability for plant growth and yield. However, further evaluation on effect of CC on plant growth and soil properties is warranted to confirm appropriateness of CC use as a soil amendment. Long term field experiments are required for understanding interactions of CC in soils.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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