Carbon dioxide nanobubbles and biochar integration: A climate smart agricultural strategy for a resilient future

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Abstract

This study investigates the synergistic role of carbon dioxide nanobubbles (CNBs) and biochar (BC) on seed germination, plant growth, and soil quality, employing *Solanum lycopersicum* (tomato) and *Phaseolus vulgaris* (beans) as test plant species. CNBs, generated and dispersed in both distilled water (DW) and tap water (TW), exhibited distinct characteristics, with TW-CNBs being larger and more stable (sizes ranging from 18.17-299.5 nm, zeta potential (ZP) of -5.91), while DW-CNBs have sizes 1.63-216.1 nm, ZP of -3.23. The results show that CNBs increased seed germination by 8-20%. CNBs in BC amended soil further promoted plant height and leaf number. CNBs increased dissolved CO_2 levels to 2-24 ppm within 40 minutes, while BC enriched soil organic carbon from 19.20-24.96 ppm in beans and 18.33-22.35 ppm in tomatoes. The pH levels decreased from 7.68 to 3.78 for TW-CNBs and from 7.41 to 2.13 for DW-CNBs. Additionally, the electrical conductivity (EC) decreased from 112.1 to 99.6 for TW-CNBs, while it increased from 4.15 to 32.1 for DW-CNBs. Together they significantly increased soil available phosphorus and potassium to 4.03-8.06 and 3.58-7.16 kg ha^{-1} and 5.67-55.74 and 17.57-43.79 kg ha^{-1} in bean and tomato, respectively. Variations in nutrient concentrations were observed, with substantial increase in Na (16.27% and 6.58%), Zn (3.39% and 0.46%), and Mg (5.05% and 1.44%) content for beans and tomatoes, respectively. Structural equation model and principal component analysis revealed differences between CNB and BC treated soils, highlighting positive impact on soil quality and plant growth compared to control. Integration of CNBs and BC presents a multifaceted approach to enhance soil quality and promote plant growth, offering promising solutions for sustainable agriculture and environmental management.

Materials and Methods

Production of BC and CNBs

Waste biomass from the NTU farm was used as feedstock for preparing BC by pyrolysis at 550 °C. NBs were generated by injecting compressed air through a tubular membrane into TW and DW. This process was carried out continuously for 40 min under a pressure of 512 kPa and a flow rate of 0.5 L m^{-1}. It was performed in order to reach a stable bubble size distribution and a saturation point.

Pot trial set-up and soil characterization

Solanum lycopersicum (Tomato) and *Phaseolus vulgaris* (Beans) were used as model plant in this pot trial. Plant height and root length were quantified in both the control and NB-treated groups. Leaf samples were collected from all treatment groups, and their chlorophyll content was determined using an ethanol extraction technique. At the end of the study, soil samples were gathered from all the containers and subjected to comprehensive physico-chemical analyses.

Results and Discussion

Characterization of CNBs

The bubble size distribution of CNBs dispersed in both TW and DW is shown in Fig. 1a. The size distribution profiles for CNBs-TW ranged from 18.17 to 299.5 nm, while CNBs-DW exhibited a size range of 1.63 to 216.1 nm. In the CNBs-TW, the pH and EC both underwent a notable decline, transitioning from initial values of 7.68 to 3.78 and 112.1 to 99.6, respectively. Conversely, in the CNBs-DW, the pH decreased from its original level of 7.41 to a significantly lower reading of 2.13, while the EC exhibited a substantial increase, rising from 4.15 to 32.1 within the span of 0 to 40 minutes (Fig. 1b-c). In both CNBs-TW and DW, the concentration of dissolved CO_2 exhibited a notable increase, ranging from 2 to 24 ppm within a 40-min timeframe (Fig. 1d).

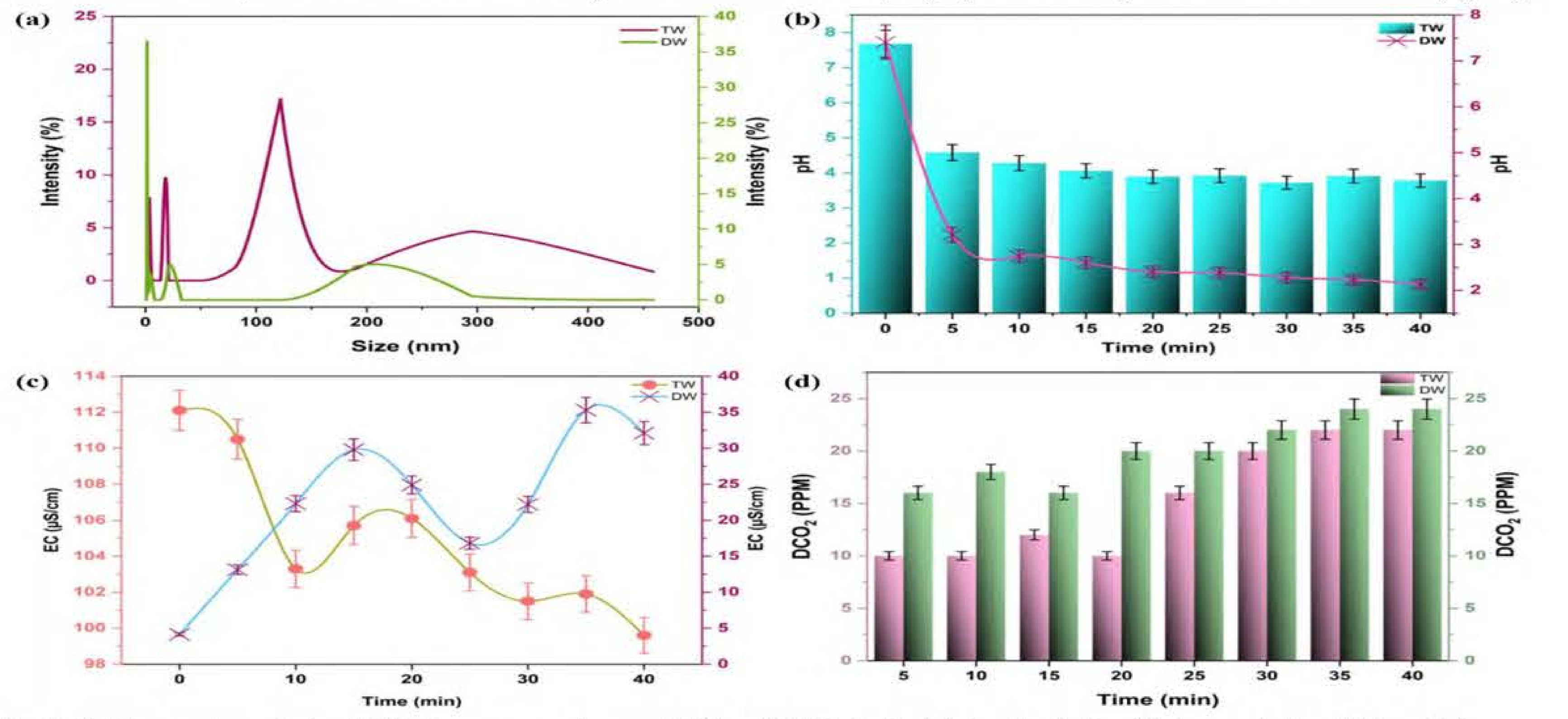

Fig. 1: Multi-parameter analysis of CNBs in aqueous environment (TW and DW) including (a) size distribution, (b) change of pH and EC, and (c) dissolved CO_2 concentration with time.

Plant growth responses

Fig. 2a-b provide a comprehensive view of the effects of various treatments on both leaf count and plant height in beans and tomato plants. A notable observation was made in the case of tomato plants grown in BC-treated soil and irrigated with CNBs-TW, resulting in a remarkable increase in plant height, reaching 25.4 cm. Conversely, for bean plants, irrigation with CNBs-DW led to enhanced height growth, with plants reaching an impressive height of 89.6 cm. Furthermore, the influence of the interaction between CNBs and BC on chlorophyll content in beans and tomato leaves was also examined (Fig. 2c-d).

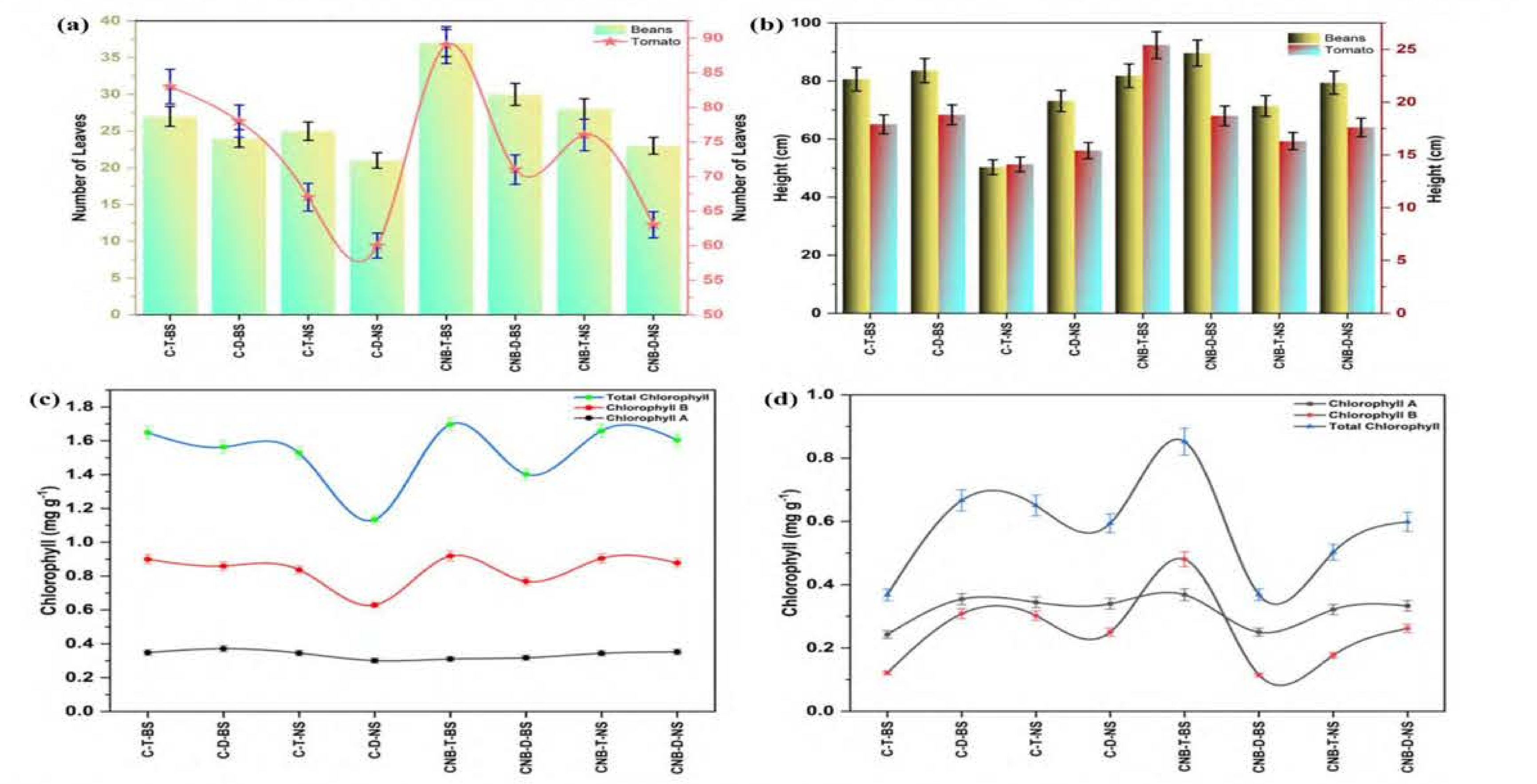

Fig. 2: Influence of CNBs and BC on number of leaves (a) plant height (b) and chlorophyll content in beans (c) and tomato (d) plants

Characterization of BC

The BC produced from farm waste biomass exhibited alkaline properties, as evidenced by the pH measurement of 8.95. The biochar's spectrum exhibited prominent peaks at 2914 cm^{-1} and 2848 cm^{-1}, indicating aliphatic C-H stretching vibrations. These peaks suggest the presence of aliphatic hydrocarbons within the biochar. Additionally, a distinct band at 1712 cm^{-1} was observed, corresponding to carbonyl C=O stretching vibrations, suggesting the presence of carbonyl compounds like aldehydes, ketones, and carboxylic acids. Peaks observed at 1464 cm^{-1} and 724 cm^{-1} are indicative of aromatic C-H bending vibrations. While, peaks observed at 924 cm^{-1} are characteristic of ether C-O stretching vibrations, hinting at partial oxygenation of the BC. BC had a high C content, which indicates that the amount of char formed will be less, but the quality will be better (Table 1).

Table 1: Proximate and ultimate analysis of BC

Sample	Proximate Analysis (wt.%)				Ultimate Analysis (wt.%)			
	MC	VC	FC	AC	C	H	N	O
BC	3.50	7.41	43.13	45.96	58.07	2.62	1.06	12.04

Soil characterization

Fig. 3a illustrates the soil organic carbon (SOC) content, which exhibited a range of 19.20 to 24.96 ppm in beans and 18.33 to 22.35 ppm in tomato plants. Soil AP content was observed to range from 4.03 to 8.06 kg ha-1 in beans and 3.58 to 7.16 kg ha^{-1} in tomato plants (Fig. 3b). The range of soil AK content was found to be 5.67 to 55.74 kg ha^{-1} in beans and 17.57 to 43.79 kg ha^{-1} in tomato plants (Fig. 3c). The NH_4^+ concentration in the soil was higher in tomato plants grown in BC-treated soil and irrigated with CNBs-TW than in tomato plants grown in BC-treated soil and irrigated with CNBs-DW or without CNBs as can be seen in Fig. 3d.

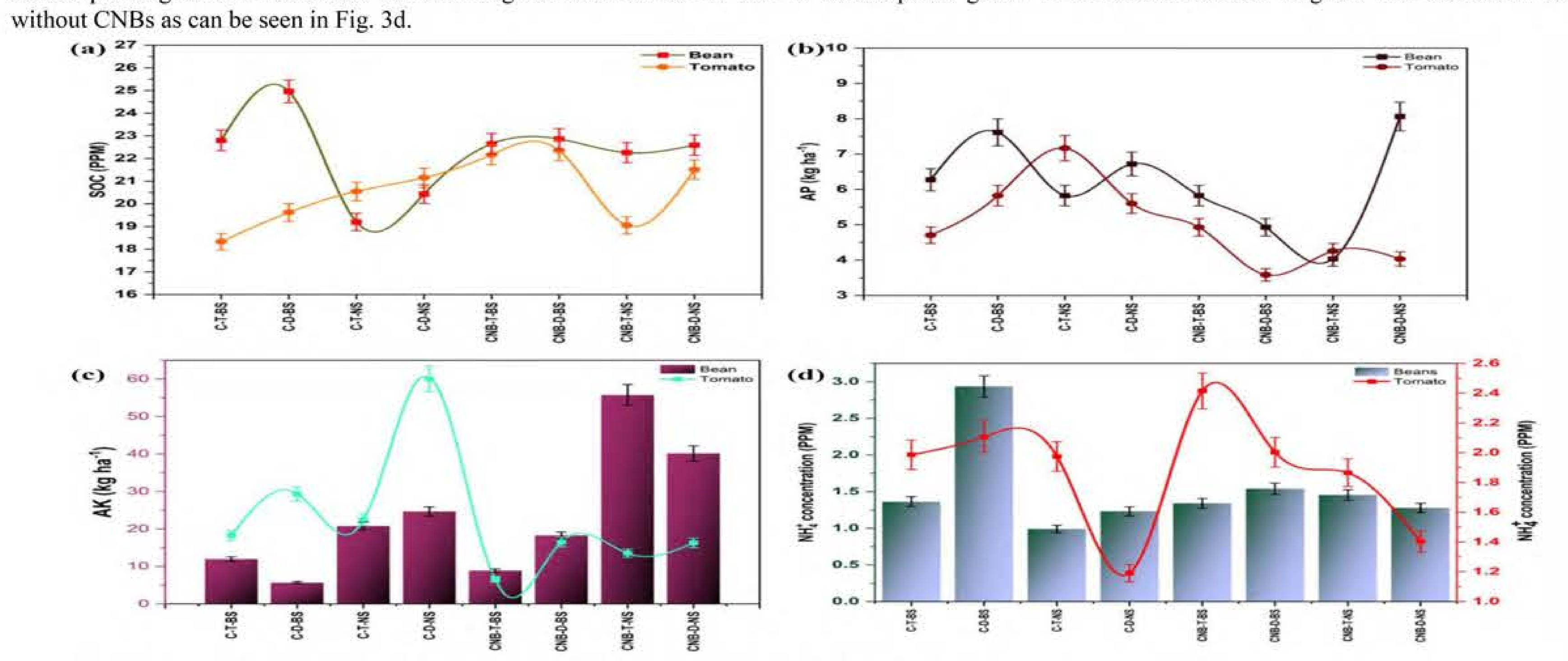

Fig. 3: Impact of the application of CNBs and BC on (a) SOC, (b) AP, (C) AK and (d) NH4+ concentration in soil

Comparative analysis of factors influencing plant growth and soil quality

In this study, ten PC were derived from experimental data. The first two PCs, PC1 and PC2, capture 44.04% and 15.39% of the variance, totaling 59.43% of the overall variance. Fig. 4 illustrates the PCA plot, encompassing both loadings (arrows) and scores (dots) derived from the obtained data.

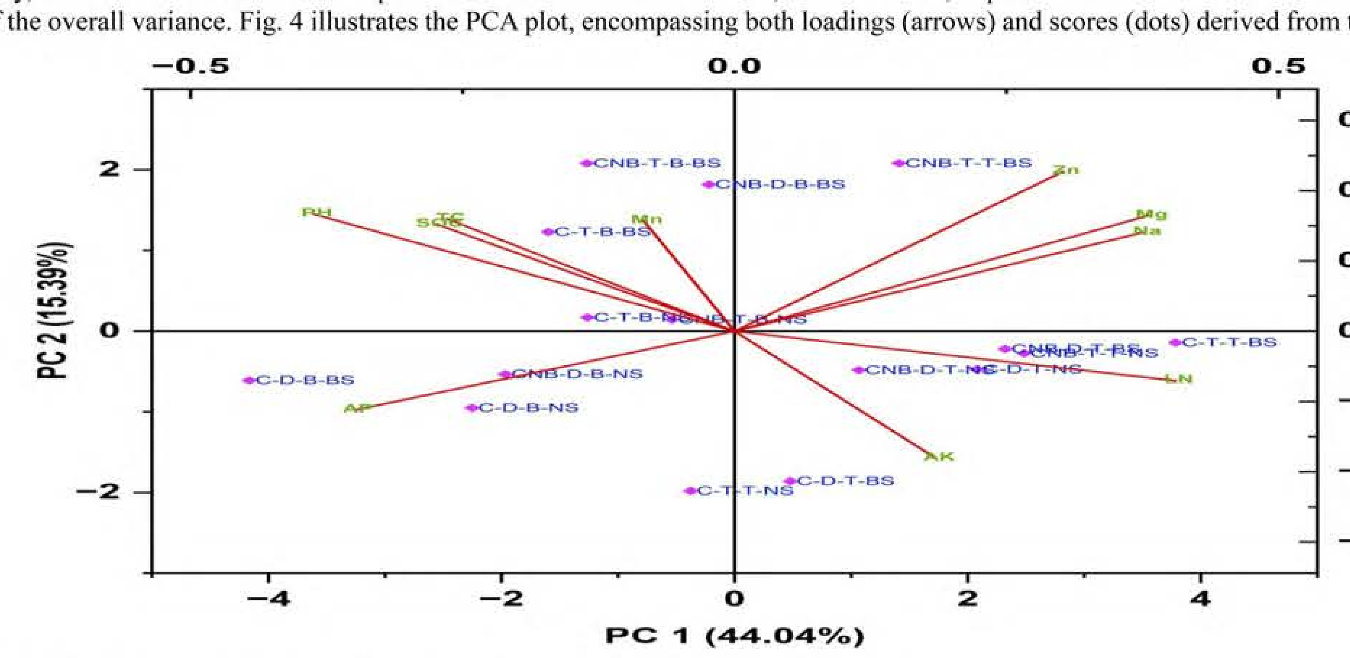

Fig. 4: PCA of treatment performance patterns observed by CNBs in DI and TW water

Conclusion

This study found that CNBs and biochar can improve plant growth and soil quality while also mitigating climate change. CNBs-TW were larger than CNBs-DW, which suggests that dissolved ions in TW stabilize CNBs. The biochar had an alkaline pH and was thermally stable. Plant growth experiments showed that CNB and biochar treatments increased leaf count and plant height. Soil analysis showed that CNB and biochar treatments increased the availability of phosphorus and potassium. Advanced statistical techniques uncovered relationships between plant growth factors and soil quality indicators. This study makes a significant contribution to climate change mitigation efforts by recirculating waste CO_2 back into the agricultural system.