Journal of Climate and Community Development

A Double-Blind, Peer-Reviewed, HEC recognized Y-category Research Journal

E-ISSN: 3006-7855 P-ISSN: 3006-7847

Effect of Biochar on Plant Growth and Soil Properties in Arid Conditions through Greenhouse Evaluation

Sania Kanwal [1] Satesh Kumar Devrajani [2] Zeeshan Memon [3] Saif Ali Khan Hashmani [4]

[1] Department of Sciences of Civil, Environmental, and Architectural Engineering, University of Padova, Via 8 Febbraio, 2, 35122, Padova, Italy.

[2] Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Via Branze 43, 25123, Brescia, Italy.

[3] Department of Agricultural Engineering, College of Engineering, China Agricultural University, Beijing, China.

[4] Department of Energy and Environment, Faculty of Agricultural Engineering, Sindh Agriculture University, TandoJam, Pakistan.

Corresponding Author: saniakanwal086@gmail.com

ARTICLE INFO

Vol. 3, Issue 2, 2024

Pages: 252-263

Received:

2024-11-17

Revised:

2024-12-07

Accepted:

2024-12-31

Keywords:

Biochar,
Pyrolysis,
Soil fertility,
Plant Growth,
Greenhouse.

ABSTRACT

The purpose of this study is to determine whether adding biochar—which is made from the leftovers of cabbage—to soil can enhance its quality and promote plant development in these kinds of environments. Various quantities of biochar (0 to 5.0% wt/wt) were added to alkaline sandy loam soil in controlled greenhouse trials to assess the impact on soil characteristics and tomato plant performance. The application of biochar was found to have a complex relationship with plant development; higher concentrations of biochar (2.5% wt/wt) had a negative effect on tomato growth, but there was no discernible difference in biomass between the 1.0% biochar treatment and the control. Interestingly, the application of biochar changed the nutrient dynamics in tomato leaves, with higher levels of biochar being associated with higher concentrations of proline; additionally, biochar significantly changed the properties of the soil, with pH and electrical conductivity (EC) rising by 1.6% to 5.5% and 35.8% to 192.4% and 1.6% to 5.5%, respectively, in comparison to the control. According to this study, biochar can be a beneficial soil supplement for improving soil quality and agricultural sustainability, according to this study.

Introduction

Soil degradation is a major global issue that eventually affects people's quality of life everywhere by reducing land productivity and endangering food security (Mohawesh and Durner 2019). As the world's population grows, the need for sustainable soil management practices grows, particularly in areas with delicate soil ecosystems and scarce water supplies. One of the more recent options that is gaining a lot of attention is the use of natural soil additives, such as biochar, which has been extensively studied and recommended for its ability to improve soil quality, increase carbon sequestration, and maximize the chemical and physical properties of soil (Lemus und Lal 2005; Radin u. a. 2018). By heating biomass with little to no oxygen, organic waste materials are pyrolyzed to create biochar, a substance rich in carbon (Mohawesh et al., 2021; Novak et al., 2014). With this method, a variety of materials with customizable properties are produced, depending on the feedstock and pyrolysis temperature used. According to (Dynarski et al., 2020), biochar exhibits long-lasting stability after being put to soil, inhibiting microbial degradation and effectively storing carbon for extended periods of time. Biochar is a promising soil addition that has the potential to significantly boost agricultural output due to these unique characteristics (Ginebra et al., 2022).

Because of the severe consequences of soil degradation, biochar has been authorized by the UN Convention to Combat Desertification as a sustainable land management technique. Biochar can significantly boost land productivity, according to study (Biederman & Harpole, 2013). These benefits are ascribed to the way biochar modifies soil properties. Biochar can also lessen the loss of essential soil elements like potassium (K), nitrogen (N), and phosphorus (P), according to research by (Yilangai et al., 2014).

Poor water retention, low soil fertility, and low organic matter content are common problems for vegetable farmers. (Al-Karaki & Al-Omoush, 2002) state that in order to overcome these limitations and maintain agricultural productivity, farmers typically apply excessive amounts of inorganic fertilizers. According to (Cely et al., 2015), this gives biochar the opportunity to serve as an essential soil additive for improving the quality of agricultural soil. For example, the selection of feedstock and production conditions may affect the efficiency of biochar with varying soil types, crop varieties, and temperatures (Novak et al., 2014).

These variables may also affect how effective biochar is. Although much research has been conducted in tropical and temperate nations, little is known about how biochar affects crop development and production in arid and semi-arid regions with alkaline soils. This research gap highlights the importance of the study that aims to evaluate the effects of biochar as a soil amendment on plant development and soil parameters, with an emphasis on the possible advantages of biochar for agricultural systems in alkaline soils in arid and semi-arid settings.

Material and Methods

Biochar Preparation

The biochar was prepared using the cabbage crop residues in a kiln at slow pyrolysis of 350°C for three hours. Before the pyrolysis, the raw material was air-dried in a greenhouse with natural light after being cleaned of contaminants using distilled water. The biochar was then grounded, crushed and sieved using a 2 mm mesh screen and then mixed with the soil.

Biochar Characterization

This method was previously employed to demonstrate the physicochemical properties of biochar. To conduct this, triplicate testing was done using a biochar to purify water ratio of 1:1, and the mixture was automatically shaken for an hour at 200 RPMs. The biochar cation exchange capacity

(CEC) was determined using 1 M ammonium acetic acid derivation method at neutral pH 7. The biochar's morphology and its qualitative elements were studied using energy-dispersive X-ray spectroscope (EDS) and scanning electron microscopy (SEM) in the JEOL system (Tokyo, Japan). Also, the specific surface area of biochar was determined using Brunauer-Emmett-Teller (BET) surface area analysis by a rapid surface area porosimeter (ASAP2010 Micrometrics, Norcross, GA, USA). The procedure explained by (Zahid et al., 2018) was slightly modified to determine the water-holding capacity (WHC) of the biochar using gravimetric analysis.

Collection of Soil Samples

The soil samples were collected from Tharparkar region of Pakistan (25.1747^{o}N, 69.9859^{o}E). The soil samples were taken from the field at depths of 0 to 0.1 m, 0.1 to 0.2 m, and 0.2 to 0.3 cm. The samples were packed in airtight plastic bags and brought to the laboratory of Sindh Agriculture University, TandoJam, Paksitan, for further experiments and analysis. Prior to soil analysis and pot tests, the samples of the soil were combined, dried, and sieved through a 2 mm stainless steel mesh sieve. The texture of soil was assessed by hydrometer method (Klute, 2018). After the determination of the percentages of clay, silt and sand in the soil, using the USDA textural triangle, the textural class was assigned. The texture of the soil, collected from Tharparkar, is classified as sandy loam soil (containing 56% sand, 41% silt and 3% clay) according to USDA textural classification triangle.

Pot experiment

The experiments were carried out in a greenhouse at Sindh Agriculture University, TandoJam. Tomato seedlings were transplanted into ceramic pots, each with a diameter of 20 cm, containing 600 g of sandy loam soil with organic matter content of 1.10%, pH 7.4, EC 0.28 dS/m, N_{tot} 0.32 mg/L, available phosphorus 3.70 mg/L, accessible potassium 106 mg/L, and 48% calcium carbonate (CaCO3). Four biochar treatments (0%, 0.5%, 1%, 2.5%, and 5% wt/wt) were applied based on the dry weight of the soil, and the study was conducted in triplicate, including control samples, using a total of 15 pots. Each pot was filled with tomato seeds once the soil and biochar had been well combined. NPK fertilizer, containing 7.46% nitrogen, 5.13% phosphorus, and 2.92% potassium, was applied to each pot before planting. Irrigation began once 50% of the available water had been consumed. To assess EC and pH of the soil, samples were collected from each pot at the beginning and end of the experiment. The soil samples were combined with distilled water in a 1:1 ratio, then dried, crushed, sieved through a 2 mm mesh, and put through EC and pH tests. Additionally, the texture of the soil was determined employing a hydrometer (Klute, 2018).

Plant measurements and analysis

After the experiment, leaf samples were taken from each pot with the intention of checking proline, potassium, phosphorus, nitrogen, and chloroplast pigments concentrations. The leaves were maintained inside plastic boxes at four degrees celcius under moist tissue paper blankets. The collected leaves were analyzed for chlorophyll content one to two hours after collection. The proline content was determined by using Bate's method for the leaves (Liu et al., 2022). Following drying at 75°C, the leaves were ground into a powder to facilitate the analysis of nitrogen, phosphorus, and potassium. The phosphorus concentration was determined using the vanadate-molybdate method in conjunction with UV spectrophotometry, while the potassium content was evaluated through atomic absorption spectrometry (Murtaza et al., 2024). The assessment of soil cation exchange capacity (CEC) was conducted utilizing the ammonium acetate method, while the total nitrogen content was determined through the Kjeldahl method.

Upon the conclusion of the trials, the plants were extracted from their pots following a thorough cleaning process to eliminate any soil remnants from the roots. The weights of both fresh and dried roots and shoots (SFW, SDW, RFW, and RDW) were documented. Before proceeding with further analysis, the roots and shoots were subjected to a drying period of four days at a temperature of 75°C.

Result and Discussion

Biochar characterization

The physicochemical properties of the biochar utilized in the experiments are presented in Table 1. The biochar exhibited notable concentrations of phosphate (P), potassium (K), nitrogen (N), and electrical conductivity (EC). With a pH value of 9.4, it was classified as alkaline. The cation exchange capacity (CEC) of the biochar was measured at 30.8 cmol/kg, in contrast to the 250–350 cmol/kg range typically observed for humified organic waste. Research conducted by (Radin et al., 2018) indicates that the mineral composition, which influences CEC, varies based on the type of feedstock employed, including elements such as calcium and potassium. Consequently, CEC can differ significantly depending on both the feedstock and the production conditions of the biochar.

Figure 1 illustrates the scanning electron microscopy (SEM) image of the biochar derived from cabbage. Previous research has shown that the ability of biochar to modify soil characteristics is closely linked to its microstructural properties (Murtaza et al., 2024). During the pyrolysis process, the surface area of the charcoal feedstock can increase dramatically—potentially by several hundred times. This enhanced surface area enables the biochar to effectively retain and store water, thereby serving as a valuable resource for water management and soil enhancement.

The physical characteristics of biochar, such as its pore size, distribution and volume, are typically correlated to its capability to hold nutrients and water. Soil characteristics, minerals and microbial activity can be affected by these factors (Liu et al., 2022). According to (Mohawesh et al., 2021), the type of feedstock utilized has a significant influence on biochar properties. The cabbage residue derived biochar had properties similar to those made from maize, including being fine, friable, and easily decomposing (Dunham-Cheatham et al., 2020).

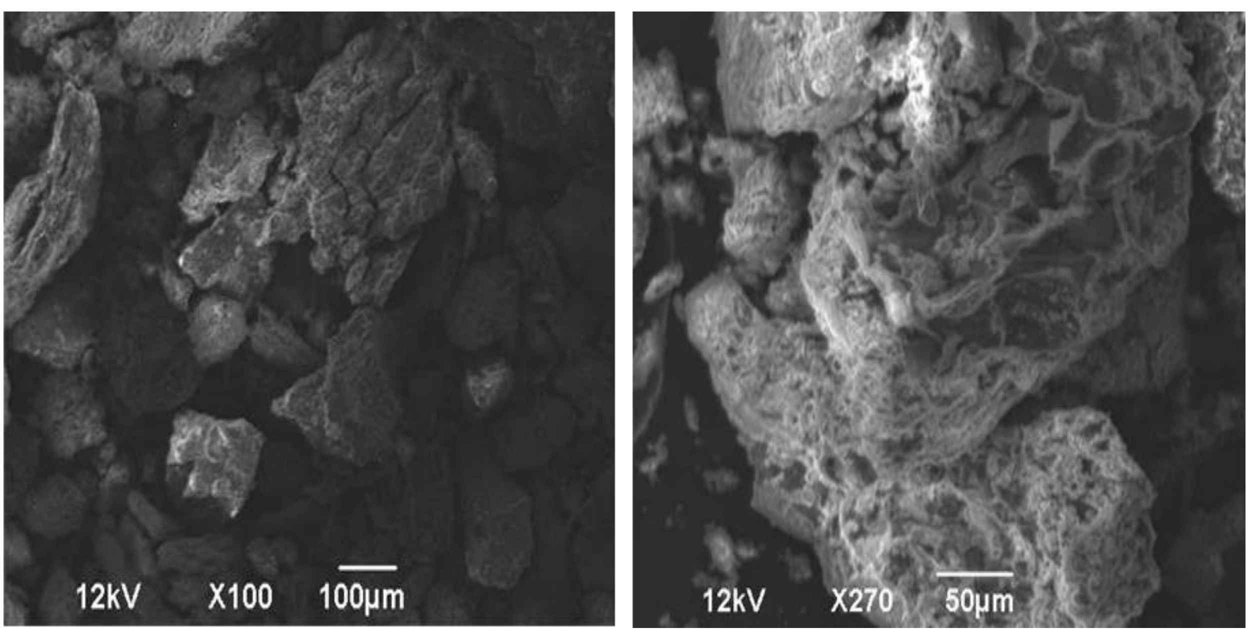

Figure 1: *SEM analysis of biochar derived from cabbage crop leftovers*

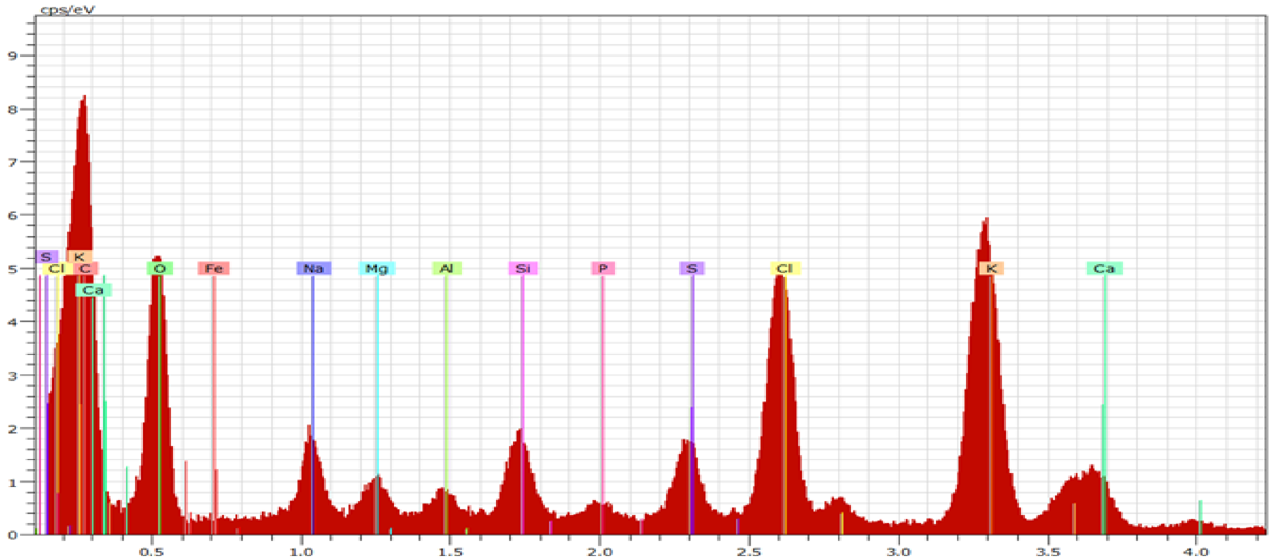

Figure 2: *EDS analysis of biochar generated from cabbage residues*

Table 1: *Characterization of cabbage residue and biochar generated from cabbage residues*

Parameters	Unit	Cabbage residues	Biochar
pH	-	-	8.50
EC (1:10)	dS/m	-	6.8
Yield	%	-	54.60
Surface area	m^2/g	-	12.9
Pore volume	m^3/g	-	0.037
CEC	cmol/kg	-	28.59
MC	%	5.4	2.6
Ash	%	12.95	29.33
Volatile matter	%	24.07	9.77
C	%	28.23	61.56
N	%	1.60	4.7
K	%	-	16.15
P	%	-	2.84
O	%	-	12.76
Ca	%	-	8.03
C/N ratio	%	230.50	25.89
WHC	g/g	-	9.57

Plant and soil measurements and analysis

Tomato plant development was negatively impacted by the application of biochar, especially at higher doses of 2.5% and 5%, as illustrated in Figures 3 (a) and (b). Although some pots exhibited slower growth rates, there were no signs of salt damage or nutrient deficiencies. The initial development of plants in pots with 2.5% and 5% biochar treatments was weaker contrasted to those in the control group. However, about a month after transplanting, these plants began to recover and thrive.

In contrast, tomato plants treated with 0.5% and 1% concentrations of biochar grew more quickly and produced a greater amount of biomass than plants treated with 2.5% and 5% concentrations of biochar, as exhibited in Figures 3 (a) and (b). The reduced biomass production at elevated biochar levels is likely linked to increases in soil EC and pH. Specifically, biochar application resulted in a 36.9% to 189.8% increase in soil EC and a pH increase of 1.7 to 5.6 associated to the control group. The inherent high pH of the biochar itself contributed to this rise in soil pH. Previous research by (Garcia-Barreda et al., 2017) has indicated that elevated soil pH and EC can lead to nutrient deficiencies, resulting in an overall decline in plant growth at higher biochar application levels.

While our study did not conduct detailed research on potential mitigating factors, it is important to recognize that pH of soil can be momentarily raised by applying biochar. However, the soil's natural buffering capacity plays a crucial role in stabilizing pH levels. The alkaline components of biochar combine with ambient carbon dioxide (CO_2) and microbial activity to form bicarbonate, which helps control and maintain soil pH, as noted by (Zhang, Liu, et al., 2012).

In terms of tomato plant growth, no significant improvement was observed with the lower biochar concentrations of 0.5% and 1%, as depicted in Figures 3 (a) and (b). While our findings indicate that low levels of biochar did not enhance plant growth, previous studies by (Naeem et al., 2016; Videgain-Marco et al., 2020) reported that biochar application could improve plant performance. Similarly, (Simiele et al., 2022; Yilangai et al., 2014) found that biochar treatment enhanced tomato plant growth. Additionally, research on radish dry matter production using green waste indicated a significant yield increase, particularly by applying biochar rates exceeding 50 tonnes per hectare.

These discrepancies imply that a number of variables, such as the type of plant, biochar, and the rate of application, may affect how biochar affects plant growth. According to (Mohawesh u. a. 2021), the positive impacts of biochar on the growth of plant can be credited to several components, such as improved soil water retention, enhanced nutrient retention (as established by (Simiele u. a. 2022), and better soil structure. Furthermore, studies indicate that biochar modifications can enhance nutrient availability in the soil. Together, these effects underscore the prospective benefits of biochar for promoting plant growth and enhancing overall soil health.

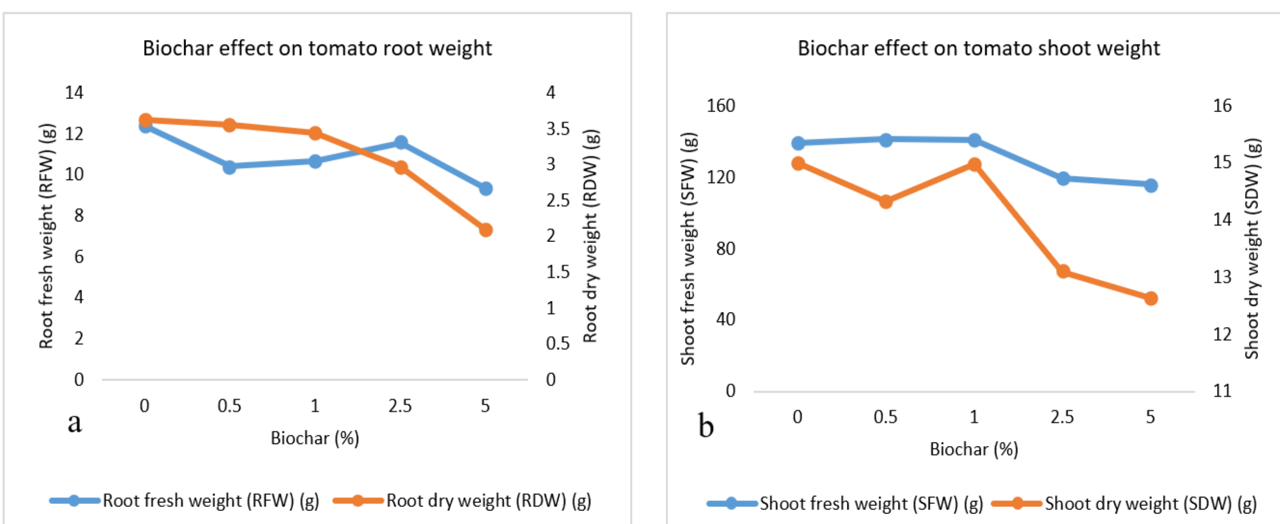

Figure 3: *Effect of biochar on (a) root weight and (b) shoot weight of tomato crop*

The Impact of Biochar on Calcium, Potassium, Sodium, Nitrogen, and Phosphorus Levels in Tomato Plant Shoots

Tomato plant leaf nutrient contents were affected by the application of biochar. The nitrogen (N) levels in the leaf tissue did not vary significantly across the different soil-biochar mixtures (Figure 4). Similarly, (Herath et al., 2013) reported that leaf nitrogen content remained unaffected by varying soil-biochar combinations. It is likely that inadequate nitrogen uptake was not the cause of the study's reported lower growth because the leaf nitrogen levels were within ranges that tomato plants could tolerate.

In contrast, phosphorus (P) concentration increased at a biochar concentration of 0.5%. This increase can be credited to the biochar's high levels of available and exchangeable phosphorus. (Salim, 2016; Simiele et al., 2022) also noted that biochar enhanced the concentrations of N, P, and K in leaf tissue. The highest levels of phosphorus and potassium in tomato plants were observed at the 0.5% biochar concentration, while calcium (Ca) and sodium (Na) reached their peak at 1% biochar, with only slight differences compared to the control treatment. The control group exhibited the lowest foliar potassium concentrations.

Research by (Herath et al., 2013) acquired that when biochar was added to the soil, the amounts of potassium (K) increased in the comparison of control group. Furthermore, studies indicated that biochar enhanced phosphorus and potassium concentrations in plants, as seen in radish dry matter production using green waste (Biederman & Harpole, 2013; Videgain-Marco et al., 2020). However, at higher levels of biochar application, the availability of certain essential nutrients for optimal plant growth and development appeared to decrease, likely due to the elevated pH levels associated with the biochar treatments.

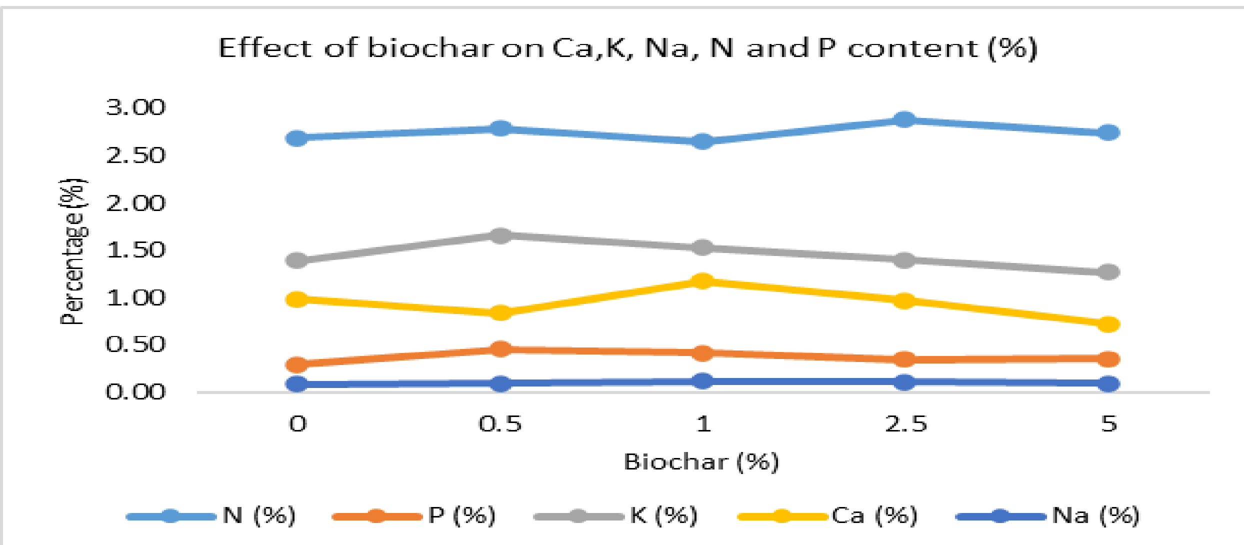

Figure 4: *Impact of biochar on tomato plant shoot Ca, K, Na, N, and P concentrations*

Biochar effect on total chlorophyll and proline of tomato

As biochar levels increased, the leaf proline content in tomato plants rose significantly, as illustrated in Figure 5. The control group exhibited the lowest levels of leaf proline. The application of biochar may induce stress in plants, particularly immediately after application, as indicated by the elevated proline levels and the reduced availability of certain minerals, such as calcium (Ca). At the highest biochar concentration of 5.0%, the total chlorophyll levels in tomato leaves decreased markedly. (Zhang, Bian, et al., 2012) also reported a decline in leaf chlorophyll content associated with biochar amendments, noting that the lowest chlorophyll levels were found with the highest biochar applications.

The increase in the carbon-to-nitrogen (C/N) ratio due to biochar application can lead to nitrogen immobilization, which is believed to contribute to the reduced chlorophyll levels observed. However, in our study, nitrogen uptake did not seem to be impacted by the application of biochar. The diminished chlorophyll content at elevated biochar concentrations may be linked to the excessive electrical conductivity of the soil-biochar mixtures, potentially leading to salinity stress in the plants. Higher chlorophyll content typically indicates enhanced photosynthesis, which can promote improved plant growth (Alburquerque et al., 2013; Liu et al., 2022).

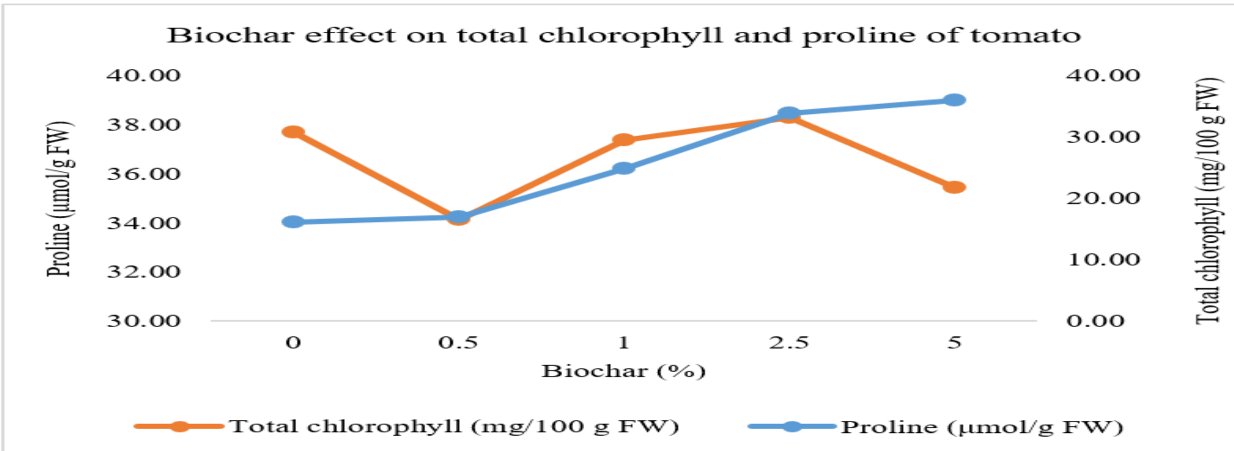

Figure 5: *Biochar effect on total chlorophyll and proline of tomato crop*

Biochar effect on EC and pH of at the intermediate and the end of the experiment

The pH levels significantly increased when the biochar was added, rising from 1.9 to 5.5% at the midpoint of the trials and from 1.6 to 5.4% by the end of the experiments. Figure 6 illustrates a notable increase at the 5% biochar concentration associated with the control group. This rise can be attributed to the alkaline nature of biochar, which contains inorganic carbonates and organic ions that can elevate soil pH. Supporting this observation, (Novak et al., 2014) found that adding 2% biochar raised soil pH from 4.8 to 6.3.

In addition to the changes in pH, EC of the soil also boosted with higher biochar amounts. The EC was significantly higher at 2.5% and 5% biochar treatments contrasted to the control. Specifically, at the 5% biochar concentration, the EC quantities rose by 193.5% at the midpoint and 146.7% by the end of the trial. Furthermore, research indicated that applying more than 50 tonnes of green waste biochar per hectare resulted in noticeably higher EC levels in the soil. Similar increases in EC were observed with poultry litter biochar, as noted by (Cely et al., 2015).

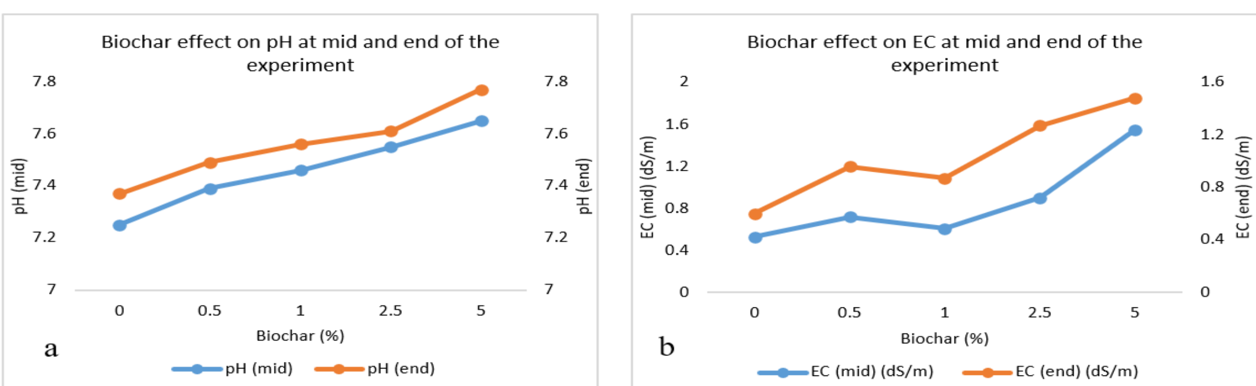

Figure 6: *The impact of biochar on pH and EC during the mid- and final stages of the experiment*

Conclusion

The study indicated that while low concentrations of biochar did not exhibit any substantial benefits for plant growth, larger concentrations had adverse effects on development. It's interesting to note that applying biochar did raise the concentrations of several nutrients in tomato plant leaves. But it also caused the pH and electrical conductivity (EC) of the soil to rise noticeably. An increase in proline levels, a sign of abiotic stress, suggested that the plants would be stressed by increased biochar treatments, which could impede their development and growth.

All the results indicate the potential benefits of applying biochar to soil at concentrations lower than 2.5% (weight to weight). To further understand how biochar affects dry and semi-arid soils, more research is needed to look at how different biochar sources and pyrolysis methods affect different soil types, plant species, and climatic conditions over time.

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