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作品名稱 Exploiting the beneficial role of Biochar and Titanium (Ti) as a Sustainable and Green Strategy for Improving Agricultural Output in Saudi Arabia: Wheat as an Using Wheat as a Model

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關鍵詞 Titanium, Biochar, Wheat, Growth, chlorophyll, antioxidants

نموذج تفاصيل المشروع

Project Detail Form

عنوان المشروع بالعربي

استخدام الدور المفيد للبيوشار و التيتانيوم كاستراتيجية خضراء و مستدامة لتحسين الإنتاج الزراعي في المملكة العربية السعودية : القمح كمثال للدراسة

Project Title in English

Exploiting the beneficial role of Biochar and Titanium (Ti) as a Sustainable and Green Strategy for Improving Agricultural Output in Saudi Arabia: Wheat as an Using Wheat as a Model

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القسم 1: مقدمة

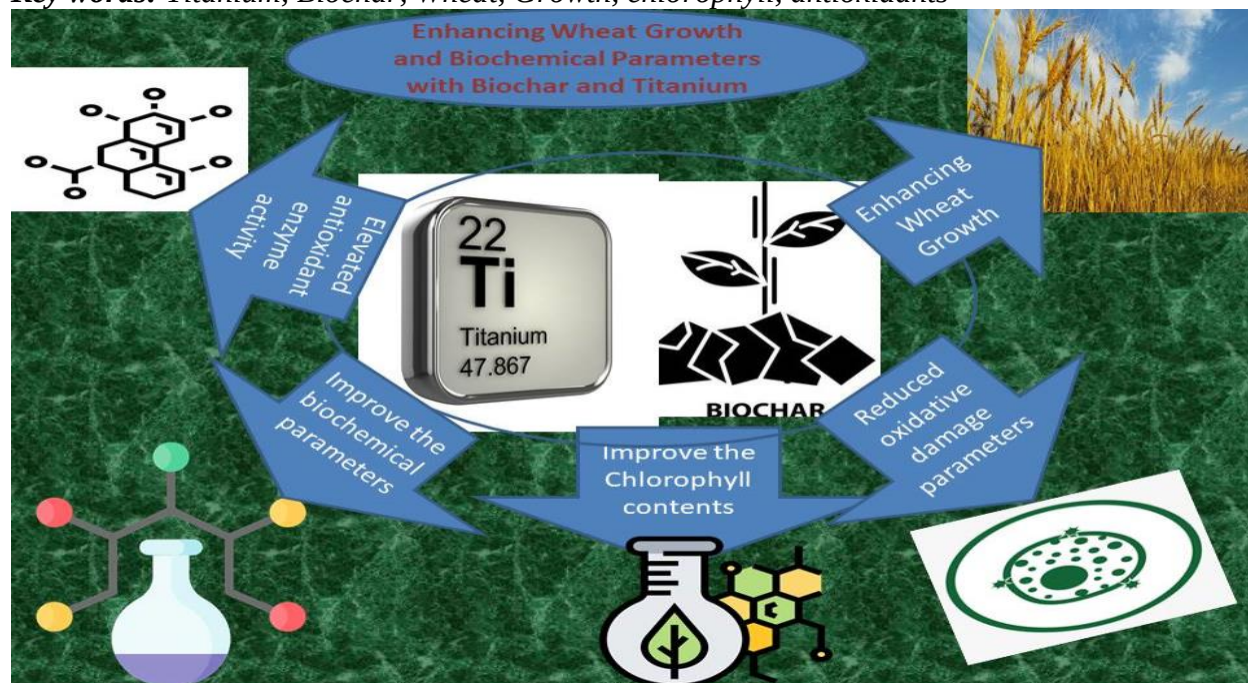
SECTION 1: INTRODUCTION

(على سبيل المثال، المشكلة ومدى تأثيرها على المجتمع)
(e.g., The problem and the impact of the problem)

Abstract

The present research work aimed to assess the impact of biochar (BC) amendment (5%) and foliar supplementation of titanium (Ti) at a concentration of 50 mg L⁻¹ TiO₂ on the growth, chlorophyll content, and biochemical parameters of wheat (*Triticum aestivum* L). The results demonstrated significant improvements in several aspects of wheat physiology due to these treatments, both individually and in combination. Plant height, as well as fresh and dry weight of wheat, exhibited substantial increases when subjected to Ti and BC treatments, with the highest enhancements observed in plants treated with both Ti and BC. Furthermore, chlorophyll content, including chlorophyll a, chlorophyll b, total chlorophylls, and carotenoids, showed marked increases in response to individual Ti and BC treatments, with even greater improvements when both treatments were combined. In terms of biochemical parameters, the content of proline, sugars, and free amino acids significantly increased in plants grown in soils amended with BC. Additionally, foliar Ti treatment led to elevated levels of these biochemical constituents. The combined treatment of Ti and BC resulted in the most pronounced effects. Moreover, oxidative damage parameters, such as hydrogen peroxide, lipid peroxide, and electrolyte leakage, were notably reduced in plants subjected to Ti and BC treatments, either individually or together. The activity of antioxidant enzymes, including superoxide dismutase, catalase, and ascorbate peroxidase, exhibited significant increases in response to Ti and BC treatments, further emphasizing their beneficial effects on wheat plants. Overall, this investigation shows that biochar amendment and titanium foliar supplementation both have beneficial effects on wheat development and biochemical parameters; these findings may be relevant to efforts to increase crop productivity and stress tolerance.

Key words: Titanium, Biochar, Wheat, Growth, chlorophyll, antioxidants



Graphical Abstract

Introduction

Global climate change, characterized by irregular rainfall patterns, excessive use of fertilizers, metal pollution, and temperature extremes, has led to a significant decline in agricultural productivity, severely affecting the growth and development of plants (Eckardt *et al.*, 2023). These environmental changes reduce photosynthesis, chlorophyll production, enzyme activity, nutrient uptake, and ultimately impact crop yields (Bibi and Rahman, 2023). The global population is expected to reach 9.8 billion by 2050, posing a significant threat to the world's agricultural system (Ayaz *et al.*, 2021). To meet the growing demand for grains and organic food sustainably, agriculture increasingly relies on technological advancements and chemical inputs (Hemathilake and Gunathilake, 2022). Improved farming systems, including agroforestry, agroecology, sustainable agriculture, and organic agriculture, have been developed worldwide to address these challenges (Nair *et al.*, 2017; Gamage *et al.*, 2023). The primary goal of these improvements is to reduce hunger, boost crop yields, and promote sustainable agriculture and environmental stewardship (Giller *et al.*, 2021). This shift in focus has led both the scientific community and farmers to explore natural residues and organic materials over commercially prepared products (Durán-Lara *et al.*, 2020). Biochar is a notable result of scientific experimentation and plays a crucial role in achieving agricultural sustainability and addressing environmental concerns (Oni *et al.*, 2019; Lu *et al.*, 2020).

Biochar is solid carbonaceous material produced through pyrolysis of biomass from agricultural and forest waste. This process excludes black carbon obtained from fossil fuels or non-biomass sources and typically occurs at temperatures ranging from 300°C to 700°C in oxygen-depleted conditions (Wang and Wang, 2019; Rombel *et al.*, 2022; Soliman *et al.*, 2023). Gasification and hydrothermal carbonization are alternative processes for obtaining biochar as a byproduct, releasing volatile gases and leaving behind carbon-rich biochar (Amalina *et al.*, 2022). Compared to the original biomass feedstock, which primarily contains polysaccharides, hemicellulose, and lignin, biochar falls under the category of materials known as "charcoal" or "black carbon" (Wang and Wang, 2019). Biochar demonstrates remarkable durability when applied to soil, remaining in the ground for hundreds to thousands of years (Tsolis and Barouchas, 2023). On average, biochar retains approximately 50% of the carbon initially present in the biomass, with the remaining elements being hydrogen, oxygen, and nitrogen (Bashir *et al.*, 2020; Soliman *et al.*, 2023).

The practice of supplementing soils with organic carbon-rich by-products, such as biochar, has a long history dating back millennia (Tsolis and Barouchas, 2023). Biochar production processes and their interaction with different soils are essential considerations in enhancing soil fertility and combating global warming (Murtaza *et al.*, 2023). Biochar has the capacity to retain carbon in the soil for hundreds to thousands of years, making it a valuable tool for sustainable agriculture (Yuan *et al.*, 2023). It can also help small-scale farmers by retaining nutrients and water, reducing the need for synthetic fertilizers (Allohverdi *et al.*, 2021; Joseph *et al.*, 2021; Soliman *et al.*, 2023). Sustainable agriculture seeks to minimize environmental damage while ensuring profitability. Biochar can positively influence plant growth and development and has the potential to enhance sustainable food production systems and protect the environment (Luigi *et al.*, 2022; Murtaza *et al.*, 2023). Farmers and ranchers can benefit from using biochar as a soil amendment that increases fertility and reduces the need for other fertilizers.

Plants obtain the necessary minerals and nutrients for their growth and development through a process known as mineral nutrition. While there are 112 components present in soil, plants selectively uptake only about 60 of them. Among these, 16-20 mineral elements are considered essential for plant growth (Jacoby *et al.*, 2017). To address this issue and maximize crop yields, fertilizers and soil amendments are commonly used (Ahanger *et al.*, 2017; AbdelRahman, 2023; Soliman *et al.*, 2023). However, the efficiency of nutrient uptake by plants varies, with estimated values of 50-90% for nitrogen, 10% or less for phosphorus, and 30-40% for potassium.

Titanium (Ti) is recognized as a beneficial element for plant growth, and its application through roots or leaves at low concentrations has been shown to improve crop performance (He *et al.*, 2022). This improvement is attributed to Ti's ability to stimulate enzyme activity, enhance chlorophyll content and photosynthesis, promote nutrient uptake, strengthen stress tolerance, and improve crop yield and quality (Lyu *et al.*, 2017). Commercial fertilizers containing Ti, such as Tytanit and Mg-Titanit, have been used as biostimulants for crop production, though the exact mechanisms behind their beneficial effects remain unclear (Lyu *et al.*, 2017). The absorption of Ti by plants is influenced by various factors, including plant species, soil Ti concentration, and pH levels.

Different plants absorb titanium (Ti) to varying degrees, influenced by factors such as soil pH and Ti concentration in the soil (Dumon and Ernst, 1988; Hussain *et al.*, 2021). For instance, *Brassica oleracea* contains about 20 mg kg⁻¹ of Ti, while *Quercus robur* L. wood can contain up to 1,900 mg kg⁻¹ (Dumon and Ernst, 1988). In some cases, plants like horsetail can accumulate Ti concentrations ranging from 42 to 14,000 mg kg⁻¹ when grown in lead and zinc-enriched soils (Cannon *et al.*, 1968). Ti application in the soil affects Ti uptake by plants (He *et al.*, 2022). Increased Ti application can result in higher Ti concentrations in crops like *Brassica oleracea* (Hara *et al.*, 1976), *Phaseolus vulgaris* L. (Pais, 1983), *Zea mays* L. (Pais, 1983), and *Capsicum annum* L. (Giménez *et al.*, 1990). Typically, plant roots accumulate Ti, with minimal transport to the shoots (Lyu *et al.*, 2017).

Soil pH also plays a crucial role in Ti absorption by plants. Acidic sandy soil with a pH of 3.1 increases Ti solubility, leading to higher leaf Ti concentrations in certain plants (Ernst, 1985; Lyu *et al.*, 2017). Conversely, in soil with a nearly identical total Ti concentration but a pH of 4.9, leaf Ti concentrations are significantly lower. In instant, Ti uptake by various plant species depends on soil conditions, plant traits, and Ti application, emphasizing the significance of these factors in understanding Ti absorption by plants (Lyu *et al.*, 2017; He *et al.*, 2022).

Wheat (*Triticum aestivum* L) is a crucial cereal crop globally, widely consumed by the majority of the world's population (Mitura *et al.*, 2023). In Saudi Arabia, it serves as a primary food source and is valued for its rich content of proteins, carbohydrates, and vitamins, making it a fundamental component of daily diets (Al-Turki *et al.*, 2020). As the world's population continues to grow, there is an increasing need to enhance wheat productivity to meet the rising demand for food (Hemathilake and Gunathilake, 2022). Various strategies have been developed to improve the growth and yield of wheat. Efficient and economically viable management approaches are essential to achieve this goal. In this context, the utilization of biochar and the foliar application of titanium (Ti) have been studied to assess their impact on regulating wheat growth, enzyme functions, and oxidative damage. These strategies aim to enhance wheat yields sustainably and meet the challenges of feeding a growing population.

القسم 2: مراجعة الأدبيات

SECTION 2: Literature Review

(على سبيل المثال، مراجعة الأدبيات والخلفية العلمية)
(e.g., Literature Review and Scientific Background)

Review of Literature

Agriculture plays a pivotal role in the economic, commercial, and social development of many countries, particularly in the developing world (Raihan, 2023). Agricultural growth faces multiple challenges that necessitate innovative approaches to enhance crop productivity (Hassan *et al.*, 2019). These challenges include shrinking arable land, climate change, water scarcity, temperature fluctuations, altered rainfall patterns, rising input costs, and substantial rural-to-urban migration (Malhi *et al.*, 2021). To meet the growing global population's food demands, doubling food production by 2050 is imperative (Fróna *et al.*, 2019). (Araus *et al.*, 2008) advocate prioritizing optimizing yield through alternative methods over expanding production areas to increase wheat output. One promising solution gaining global attention is biochar (BC) as a soil amendment (Zulfiqar *et al.*, 2022). Biochar is produced through the pyrolysis of organic matter in a low-oxygen environment and offers several potential benefits, such as binding heavy metals, acting as a carbon sink, and mitigating greenhouse gas emissions to combat climate change (Rizwan *et al.*, 2016; Abbas *et al.*, 2018). The literature contains numerous examples illustrating the positive effects of BC when applied in the presence of trace elements (Rehman *et al.*, 2016; Zhang *et al.*, 2016; Lyu *et al.*, 2017; Hussain *et al.*, 2021; He *et al.*, 2022).

Recently, titanium (Ti) has garnered attention as a beneficial element when used in low concentrations through fertilizer application. This approach has been shown to enhance various aspects of plant growth, stress tolerance, and nutrient uptake, particularly in crops such as corn, sugar beets, and peas. Notable studies by (Pais, 1983; Dumon and Ernst, 1988; Lyu *et al.*, 2017; Hussain *et al.*, 2021; He *et al.*, 2022) have reported growth improvements of up to 20% in these crops. The precise mechanisms responsible for these positive effects are not yet fully understood, but they are believed to involve the activation of specific enzymes and the enhancement of processes like chlorophyll biosynthesis and photosynthesis, as suggested by (Pais, 1983) and (Lyu *et al.*, 2017). Wheat (*Triticum aestivum* L) is of particular significance, accounting for roughly 30% of global cereal production and occupying approximately 218 million hectares of land (Giraldo *et al.*, 2019). With an average yield of 771 million tons, wheat plays a critical role in meeting the dietary needs of 21% of the world's population (Mustafa *et al.*, 2021). To address the escalating demands of a growing population, it is estimated that wheat yield must increase by up to 60% by 2050. Wheat ranks as the third most important crop globally, following rice and corn, and serves as a vital source of carbohydrates and proteins, nourishing millions of people (Daryanto *et al.*, 2016; Ahmadian *et al.*, 2021). The current research aims to evaluate the impact of two treatments on wheat: biochar (BC) amendment at a rate of 5% and foliar supplementation of titanium (Ti) at a concentration of 50 mg L⁻¹ TiO₂. The study intends to investigate how these treatments influence wheat growth, chlorophyll content, and various biochemical parameters.

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القسم 3: الأهداف

SECTION 3: Objectives

(على سبيل المثال، أسئلة البحث، والغرض من البحث والأصالة و/أو الفرضية)
(e.g., Research Questions ,Purpose ,Novelty, and/or Hypothesis)

Objectives of the Study

- To investigate the effects of biochar (BC) and titanium (Ti) foliar application on wheat growth.
- To assess the impact of BC and Ti on chlorophyll content and biochemical parameters in wheat.
- To examine how BC and Ti treatments influence oxidative damage parameters in wheat plants.
- To explore the potential of BC and Ti to enhance wheat yield sustainably and contribute to food security in the face of a growing global population.

القسم 4: المنهجية

SECTION 4: METHODOLOGY

(على سبيل المثال، المتغيرات والضوابط والمواد والإجراءات وطريقة التقييم/النموذج الأولي)
(e.g., Variables, Controls, Materials, Procedures, and evaluation method\prototype)

Material and methods

Plant materials, Soil and Biochar amendment Sources

Healthy seeds of wheat (*Triticum aestivum* L); was obtained from Ministry of Agriculture and water resources, Saudi Arabia; were disinfected with 5% sodium hypochlorite for 5 minutes. After disinfecting the seeds, ten seeds were sown per pot. Plastic pots (40 × 40 cm) were filled with 2 kg sterilized sandy, loamy soil. For biochar amendment (SB), half of these pots contained 5% (W/V) Eucalyptus wood-derived biochar (E.W. biochar). For attaining the accurate BC concentrations 5 gm of BC and 95 gm of soil was thoroughly mixed and filled in pots. Eucalyptus wood-derived biochar (E.W. biochar) was obtained from Ministry of Agriculture and water resources, Saudi Arabia, which was prepared by pyrolysis of Eucalyptus wood materials at a temperature of 400 °C according to the recommendation of Lehmann and Joseph (Lehmann and Joseph, 2015) using an oven for 2 hours. Pots were irrigated with full strength Hoagland solution and arranged in complete randomized block design.

Titanium treatemnts

After germination at 21 days after sowing (DAS), BC amended and BC-unamended pots were foliar supplied with titanium obtained from TiO₂ as (50 mg L⁻¹ TiO₂), and for each pot 15 mL was applied using manual sprayer. Plants were allowed to grow for fifty days and were maintained in botanical garden under natural conditions. Overall we have final four treatments: Control, 5% biochar (BC), titanium (Ti) and BC + Ti. At the end of the experimental growth period of fifty days, all samples were carefully uprooted and examined for various criteria.

Measurement of growth parameters

Growth parameters including plant height, fresh weight and dry weight of plants was measured. Plant height was measured by using a manual tape. Fresh weight was measured by weighing the entire

shoot (stem and leaf) immediately after uprooting the plants. Dry weight of same tissue was recorded after drying the tissue at 70 °C for 48 hours.

Photosynthetic pigments

Fresh leaf tissue was taken and homogenated in acetone using pestle and mortar. Thereafter the homogenate was centrifuged at 2000 rpm for 20 minutes and supernatant was collected and made to 5 mL using acetone. The absorbance of the solution was estimated at 480, 645 and 663 nm on spectrophotometer (Arnon, 1949).

Determination of Relative water content (RWC)

The relative water content (RWC) of leaves was determined by punching equal number of leaf discs from each treatment with a sharp cork borer and their fresh weight (FW) was taken. Thereafter, the same leaf discs were floated in petri dishes containing distilled water for 1 hr for measuring the turgid weight (TW). The same discs were oven dried at 80 °C for 24 hrs for the dry weight (DW) measurement (Smart and Bingham, 1974). RWC was calculated by the following formula:

$$RWC = [(FW - DW) / (TW - DW)] \times 100$$

Estimation of stress-induced biomarkers

Malondialdehyde (MDA) Content

MDA content in leaves was measured according to the method described by (Heath and Packer, 1968). Briefly, 0.5 leaf sample was homogenized with 10 mL ethanol followed by centrifugation (10,000g) for 10 min. The extract (1 mL) was mixed with 2 mL mixture of thiobarbituric acid (TBA, 0.65%) in trichloroacetic acid (TCA, 20%). The mixture was boiled for 30 min and then cooled rapidly. After centrifugation (10,000g) again for 5 min, the MDA contents were determined from the difference in non-specific absorption at 600 and 532 nm.

Hydrogen peroxide (H₂O₂)

Hydrogen peroxide (H₂O₂) content was determined by the following methods (Velikova *et al.*, 2000). Fresh 0.3 g leaf was homogenized in 0.1% trichloroacetic acid (3 mL) and the mixture was centrifuged at 12000×g for 15 min at 4 °C. To 0.5ml supernatant was added 0.1 M potassium phosphate

buffer (pH 7.8, 0.5ml) and 1ml potassium iodide (1M). The mixture was kept in the dark for 1 hour and the absorbance was taken at 390nm.

Electrolyte leakage (EL)

The method described by (Dionisio-Sese and Tobita, 1998) was employed for measurement of electrolyte leakage. Pieces of leaves were kept into a test tube containing deionized water and heated at 40 °C. Therefore, test tubes were cooled at room temperature and primary electrical conductivity (EC_1) was collected using CON 700 EC meter. Again, the test tubes were heated using an autoclave and cooled at room temperature and, thus, final electrical conductivity (EC_2) was observed. To calculate EL, the following formula was used: $EL (\%) = EC_1 / EC_2$

Estimation of osmolytes

Total soluble sugar was estimated according to the modified method of (Irigoyen *et al.*, 1992) using an anthrone reagent and the absorbance was recorded at 625 nm using glucose as a standard. Method of (Bates *et al.*, 1973) was used to estimate proline. Briefly, 0.5 g of dried leaves were extracted in 3% sulphosalicylic acid. After centrifugation at $10,000 \times g$ for 10 min, the supernatant was mixed with ninhydrin reagent and absorbance was taken at 520 nm. The Method of (Moore and Stein, 1948) was used for estimation of free amino acids.

Antioxidant enzymes

For extraction of antioxidant enzymes, fresh 500 mg leaf tissue was homogenized in chilled phosphate buffer (pH 7.0) supplemented with 1% PVP, PMSF and EDTA using pestle and mortar. The homogenate was centrifuged at $15,000g$ for 15 minutes at 4 °C and supernatant was used as enzyme source for assaying the activity of enzymes. Activity of superoxide dismutase (SOD, EC 1.15.1.1) was measured using (Beyer and Fridovich, 1987) method. Photoinhibition of nitroblue tetrazolium chloride (NBT) by enzyme was measured in assay mixture that contained phosphate buffer, riboflavin, EDTA, methionine, enzyme and NBT. Samples were incubated under fluorescent lights for 15 minutes and absorbance was taken at 560 nm. The activity of catalase (CAT, EC 1.11.1.6) activity was measured according to the method of (Aebi, 1984). Change in the optical density was taken at 240 nm for 2 min in an assay mixture containing phosphate buffer, enzyme and H_2O_2 . The activity of ascorbate peroxidase (APX, EC 1.11.1.11) was measured according to (Nakano and Asada, 1981) and change in absorbance was recorded for 3 minutes at 290 nm.

Statistical Data Analysis.

Data is mean of four replicates and standard error ($\pm$ SE) was calculated. Different letters on the bars show significant difference at $P < 0.05$ calculated after performing ANOVA.

القسم 5: النتائج

SECTION 5: RESULTS

(على سبيل المثال ، الجداول والرسوم البيانية وتحليل البيانات و / أو الإحصائيات)
(e.g., Tables, Graphs, Data Analysis, and/or Statistics)

Results

Effect of Ti and BC supplementation on growth parameters

Results showing the effects of BC and Ti treatments on plant height, fresh weight and dry weight of shoot are shown in figure 1. Relative to control height, fresh weight and dry weight of shoot increased by 7.01%, 11.01% and 21.00% due to Ti spray, by 33.00%, 24.01% and 30.0% due to BC and by 42.84%, 31.44% and 40.51% due to combined application of Ti + BC (Figure 1).

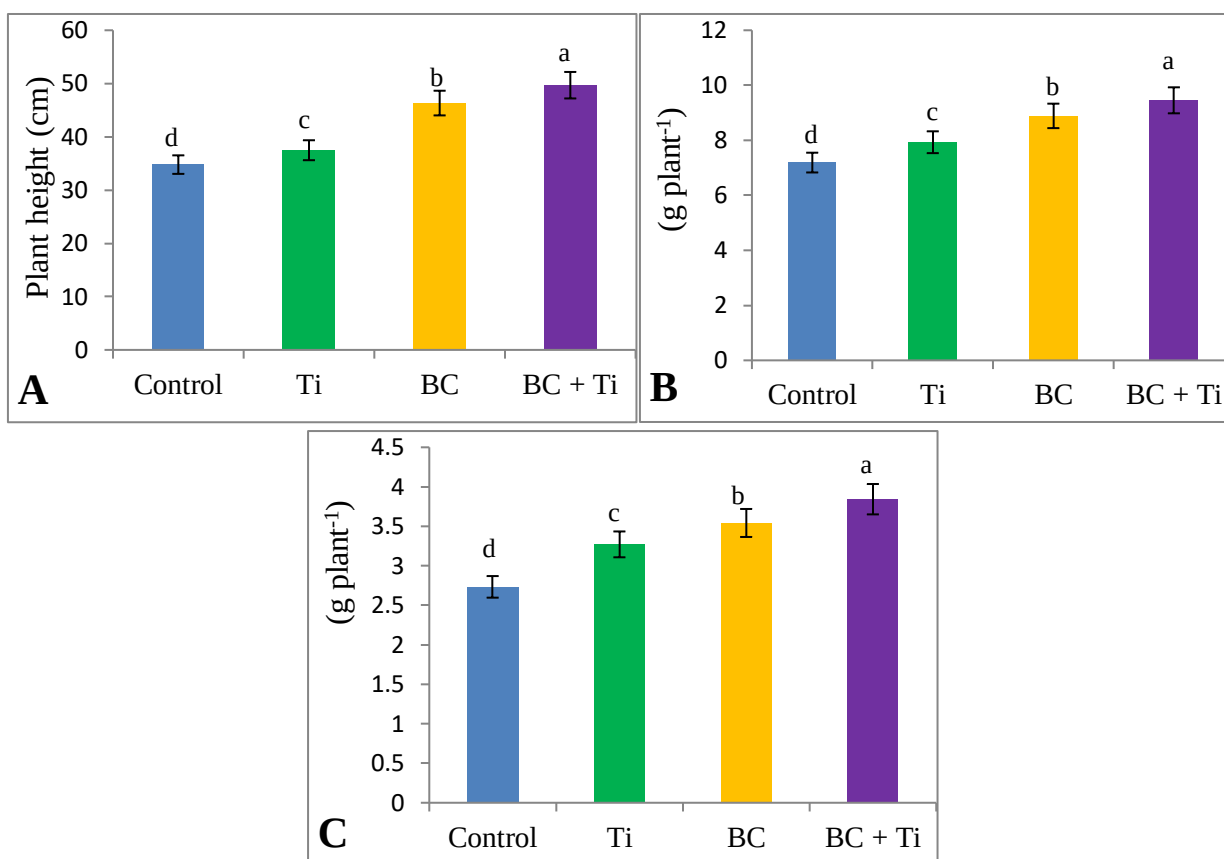


Figure 1: Effect of biochar (5% BC) amendment and the foliar application of titanium (50 mg L⁻¹ TiO₂) on (A) plant height (B) shoot fresh weight and (C) shoot dry weight of wheat (*Triticum aestivum* L). Data is mean of four replicates and different letters denote significant difference at P<0.05.

Effect of Ti and BC supplementation on chlorophyll pigments

Treatment of BC and Ti increased content of chlorophyll pigments with maximum increase in plants treated with both Ti and BC. Percent increase of 48.46% for chlorophyll a, 28.05% for chlorophyll b, 37.70% for total chlorophyll and for 42.01% carotenoids was (Figure 2).

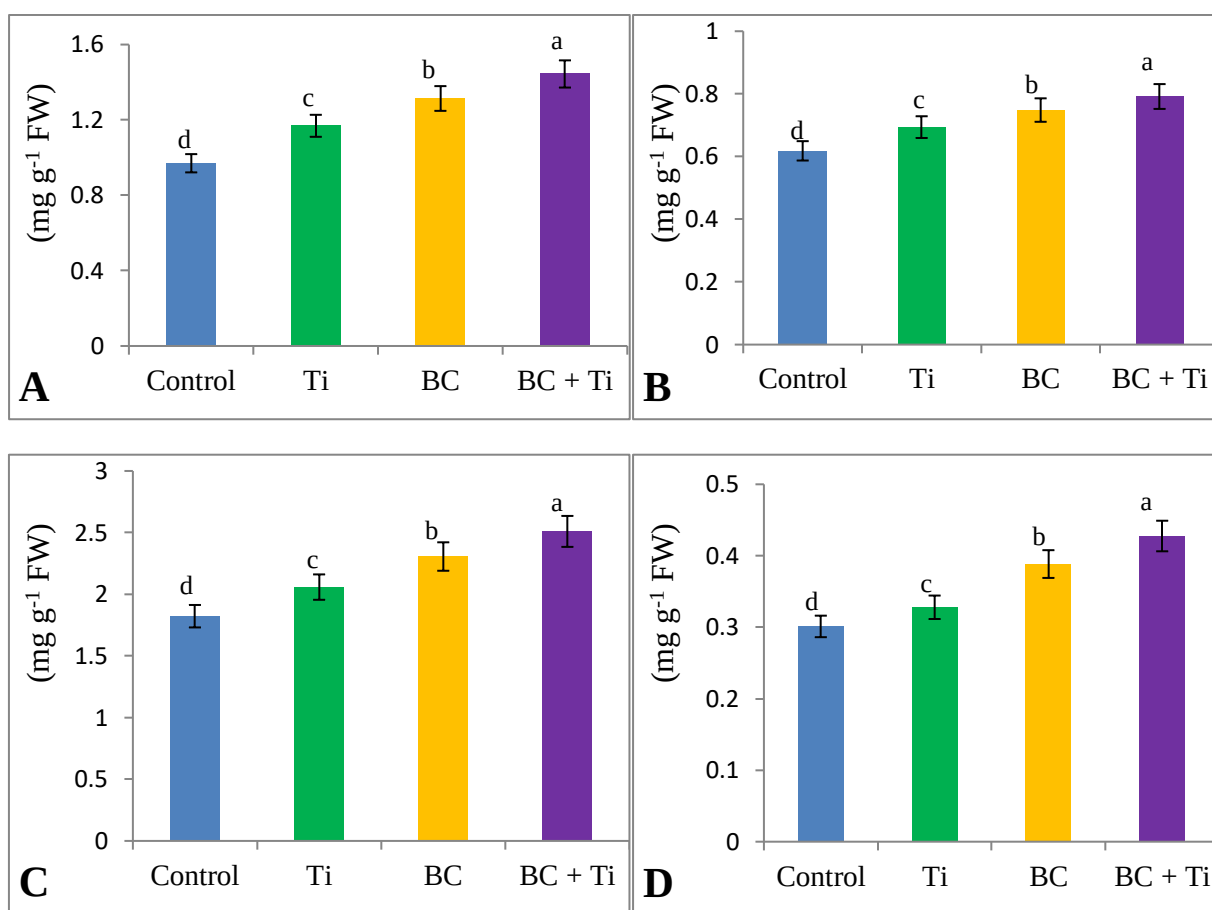


Figure 2: Effect of biochar (5% BC) amendment and the foliar application of titanium (50 mg L⁻¹ TiO₂) on (A) chlorophyll a, (B) chlorophyll b, (C) total chlorophylls and (D) carotenoids in wheat (*Triticum aestivum* L). Data is mean of four replicates and different letters denote significant difference at P<0.05.

Effect of Ti and BC supplementation on proline, sugars and amino acids

Application of Ti and BC amendment increased the content of proline, sugars and free amino acids over the control. Relative to control, Ti treated plants showed an increase of 25.45% for proline, 16.67% for sugars and 15.35% for free amino acids respectively. However, plants grown on BC amended soils exhibited an increase of 56.02%, 37.64% and 25.34% in proline, sugars and free amino acids respectively. Maximum increase of 80.71%, 62.91% and 32.88% in content of proline, sugars and free amino acids was shown by seedlings treated with both Ti and BC (Figure 3).

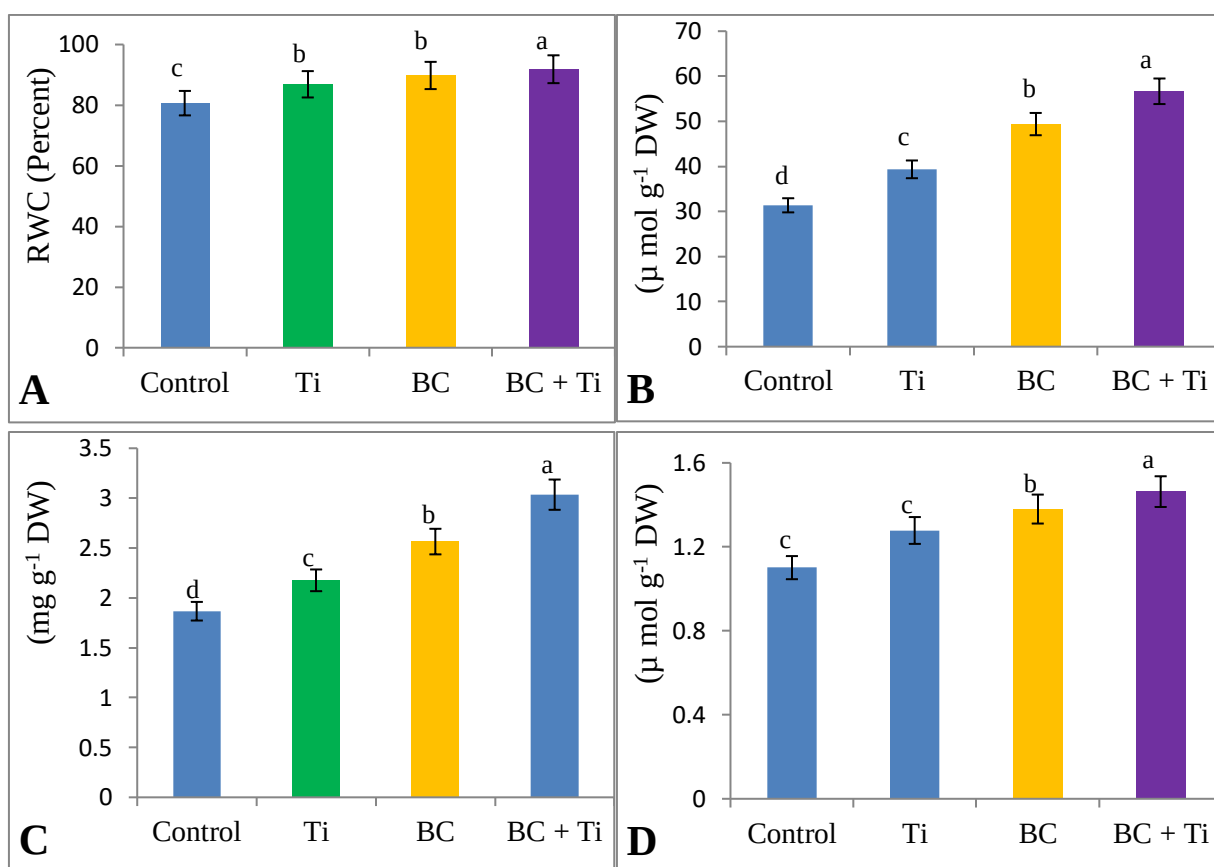


Figure 3: Effect of biochar (5% BC) amendment and the foliar application of titanium (50 mg L⁻¹ TiO₂) on (A) relative water content, (B) proline, (C) soluble sugars and (D) free amino acids in wheat (*Triticum aestivum* L). Data is mean of four replicates and different letters denote **significant** difference at P<0.05.

Effect of Ti and BC supplementation on oxidative stress parameters

Plants grown on BC amended soil and foliarly treated with Ti exhibited decline in hydrogen peroxide, lipid peroxidation and electrolyte leakage over the control. Percent decline in hydrogen peroxide, lipid peroxidation and electrolyte leakage was 30.16%, 31.39% and 27.29% in Ti treated plants, 43.32%, 40.58% and 38.71% in BC treated plants. However hydrogen peroxide, lipid peroxidation and electrolyte leakage declined maximally by 56.24%, 59.28% and 54.82% respectively due to combined treatment of Ti and BC over control (Figure 4).

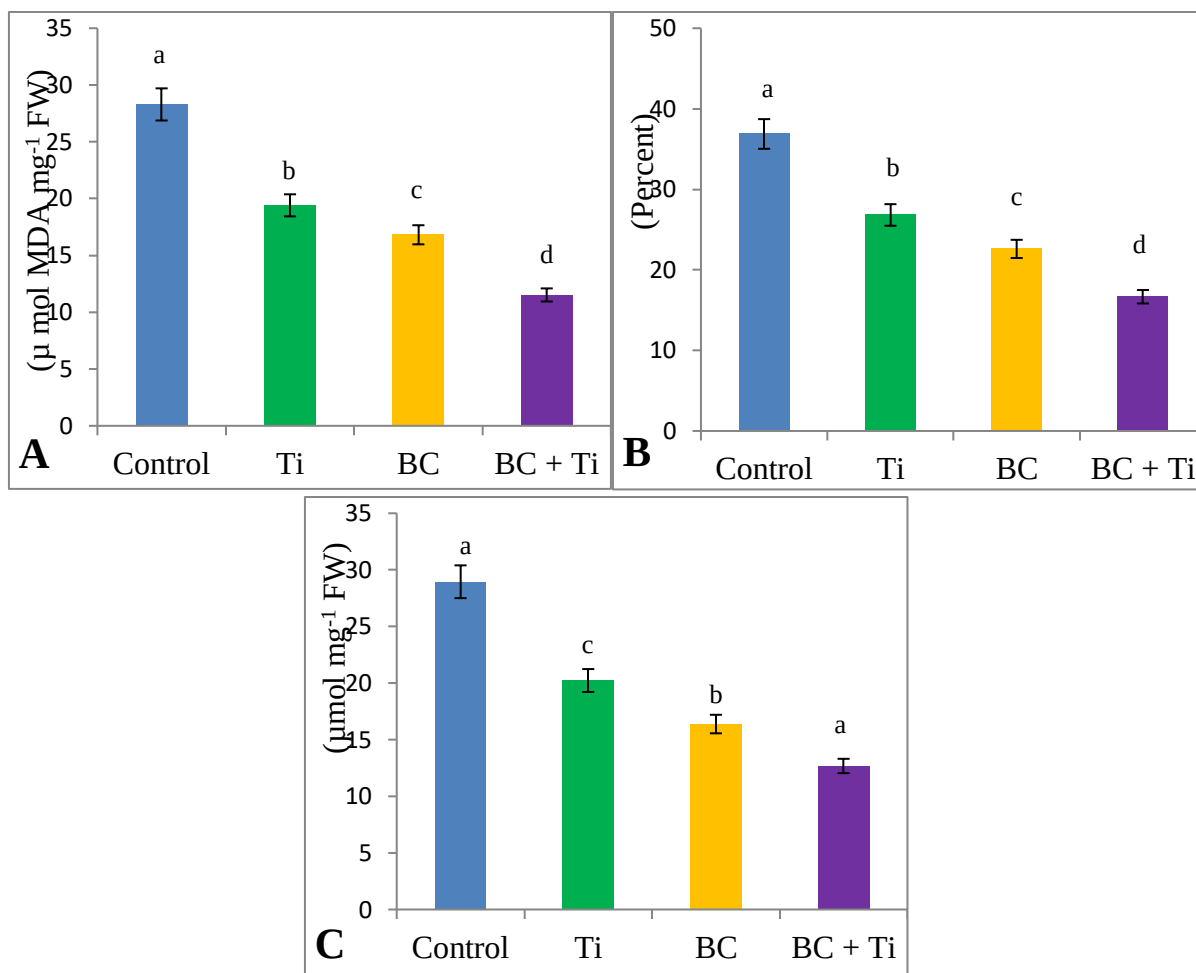


Figure 4: Effect of biochar (5% BC) amendment and the foliar application of titanium ($50\text{ mg L}^{-1}\text{ TiO}_2$) on (A) membrane lipid peroxidation (MDA), (B) electrolyte leakage, and (C) hydrogen peroxide in wheat (*Triticum aestivum* L). Data is mean of four replicates and different letters denote **significant** difference at $P < 0.05$.

Effect of Ti and BC supplementation on antioxidant enzyme activities

Application of Ti and amendment of BC to soil resulted in increased activities of antioxidant enzymes including superoxide dismutase, catalase and ascorbate peroxidase. Relative to control, the activities of superoxide dismutase, catalase and ascorbate peroxidase increased by 18.75%, 14.64% and 34.29% due to Ti application while as showed an increase of 25.31%, 38.37% and 56.43% due to BC treatment. Combined treatment of Ti and BC imparted an increase of 46.30%, 66.97% and 75.72% in superoxide dismutase, catalase and ascorbate peroxidase respectively over the control (Figure 5).

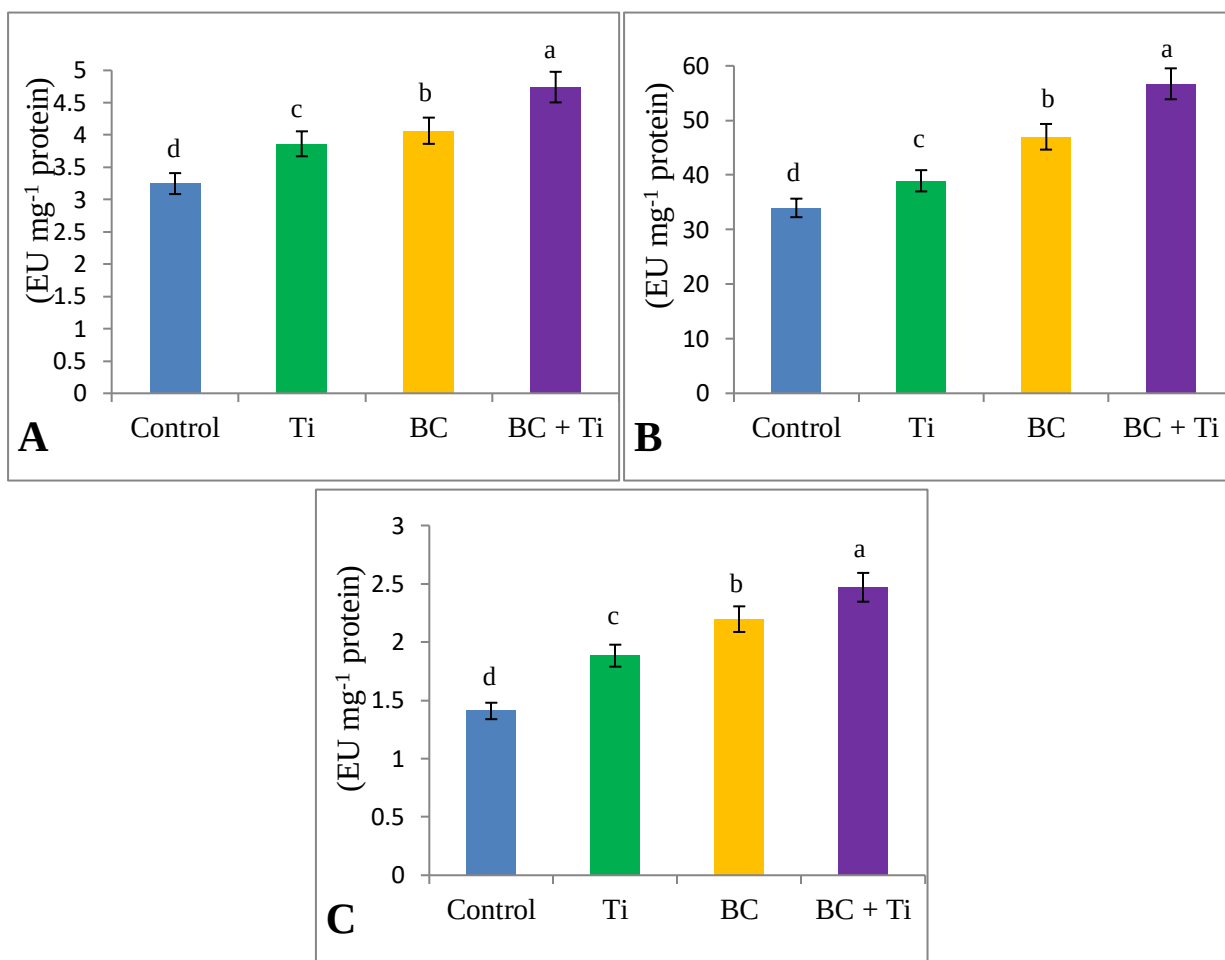


Figure 5: Effect of biochar (5% BC) amendment and the foliar application of titanium ($50 \text{ mg L}^{-1} \text{ TiO}_2$) on the activity of (A) superoxide dismutase, (B) catalase, and (C) ascorbate peroxidase in wheat (*Triticum aestivum* L). Data is mean of four replicates and different letters denote significant difference at $P < 0.05$.

القسم 6: التفسير والاستنتاجات

SECTION 6: INTERPRETATION & CONCLUSIONS

(على سبيل المثال ، المساهمات والقيمة المضافة والتأثير و/أو التطبيقات)
(e.g., Contributions, Value Add, Impact, and/or Applications)

Discussion

Several environmental conditions pose serious threats to agriculture, and many different management systems for maximizing plant growth and harvest have been developed and evaluated (Shah and Wu, 2019; Kumar *et al.*, 2022). Feeding a growing population that is also adjusting to new weather patterns is a major issue for farmers everywhere (Fróna *et al.*, 2019). The major agricultural production productivity is expected to go up by 119% by 2050, according to experts (Berners-Lee *et al.*, 2018; Malhi *et al.*, 2021). One such environment-friendly approach for improving crop performance under stressed environments is addition of biochar to the affected soils (Malik *et al.*, 2022; Soliman *et al.*, 2023). The employment of BC has been used from last few years as an important beneficial management strategies for increasing the growth and productivity of plants (Hemathilake and Gunathilake, 2022). A analogous impact on plant growth and development and an increase in crop yields has been shown to occur with the foliar supplementation of mineral nutrients (Kumar *et al.*, 2022; Kumari *et al.*, 2022). The efficient management strategies have been found to contribute significantly to sustainable food productivity (Joseph *et al.*, 2021). Biochar is rich in essential nutrients and has the potential to maintain the soil moisture content optimal for supporting the growth (Sg *et al.*, 2021). Similar to the results of this study earlier increased growth in terms of increased plant height, fresh and dry weight has been reported in tomato (Rasool *et al.*, 2020). In another study, scientists demonstrated significant increase in the growth and biomass producton of rice (Shetty *et al.*, 2021). By promoting root growth and increasing availability to vital nutrients, biochar has the potential to mitigate the negative consequences of adverse environmental conditions (Duan *et al.*, 2023). Plants need mineral nutrients to regulate their growth and development. A minor change in their concentrations, however, can have a profound effect on normal growth patterns (Alharbi and Alaklabi, 2022). Supplementation of one mineral nutrient affects the uptake and assimilation of other nutrients thereby imparting beneficial effects on overall plant performance (Sofy *et al.*, 2022; Tripathi *et al.*, 2022). Titanium application increased growth of *Dracocephalum moldavica* significantly (Gohari *et al.*, 2020). It seems that Ti and BC improved growth of wheat by increasing water content, enzyme functioning and chlorophyll synthesis therefore

contributing significantly to the growth and development of wheat (Algethami *et al.*, 2023). It has been reported that BC amendment maintain high relative water content by increasing the moisture retention potential in the soil (Tanure *et al.*, 2019). In the present study, soil amendment through BC application resulted in increased growth and the water content wheat plant. Results from the present study reveal that positive response of the growth parameters to BC application and increase was much evident due to combined Ti and BC application. Improved growth due to Ti and BC results from the significant increase in mineral uptake and assimilation thereby contributing significantly to overall plant performance (Buates and Imai, 2021). Further studies are required to know the actual mechanisms. The amendment of soil with BC improves the soil quality by increasing pH, water holding capacity, cation-exchange and microbial flora which ultimately leads to growth improvement in plants (Mensah and Frimpong, 2018). Increased chlorophyll in Ti and BC treated plans can be due to the significant increase in the mineral ions like nitrogen which forms and important part of chlorophyll molecule. Increased synthesis of chlorophylls due to the BC (Cong *et al.*, 2023) and Ti (Hussain *et al.*, 2019; Vatankhah *et al.*, 2023) affects the photosynthetic regulation.

According to our findings, the concentration of osmolytes including proline, sugars, and free amino acids all rose after BC and Ti therapy. Important metabolites that do not harm plants at increasing quantities are the compatible osmolytes. To optimize their metabolism and development, plants store up sufficient amounts of these metabolites (Farouk *et al.*, 2023). Compatible osmolytes including proline, sugars, free amino acids etc are involved in regulating the key functions like germination, enzyme functioning, redox homeostasis signaling, stress tolerance, antioxidant functioning, protein synthesis, photosynthesis etc (Elkelish *et al.*, 2019; Sharma *et al.*, 2019). It has been reported that treatment of BC (Soliman *et al.*, 2023) and Ti (Gohari *et al.*, 2020) increased the content of osmolytes including proline, sugars and free amino acids significantly in different plants. Plants accumulating increased content of compatible osmolytes show better growth performance and can also with stand the adverse environmental conditions better (Sharma *et al.*, 2019; Soliman *et al.*, 2023). The increased content of the osmolytes is direct influence of BC and Ti on the biosynthesis pathway of these metabolites and further studies in this direction can be worthwhile. It has been reported that plants accumulating increased concentration of osmolytes show increased growth by exhibiting significant increase in the photosynthesis and the associated metabolic pathways (Ahanger and Ahmad, 2019; Soliman *et al.*, 2020).

It was interesting to note that BC amendment and Ti treatment increased the activity of antioxidant enzymes including superoxide dismutase, catalase and ascorbate peroxidase. This increased functioning of these protective enzymes was evident as decreased oxidative damage measured in terms of hydrogen peroxide, lipid peroxidation and electrolyte leakage. Similar to our results, earlier increased functioning of antioxidant enzymes due to the supplementation of Ti (Gohari *et al.*, 2020) and BC (Soliman *et al.*, 2023) has been reported in other crop plants. However the combined effect of Ti and BC has not been reported. Superoxide dismutase is unique for the neutralization of superoxide thereby preventing the damage to sensitive photosynthetic machinery (Fujii *et al.*, 2022). However, catalase and ascorbate peroxidase scavenge the excess hydrogen peroxide thereby protecting the cellular structures and their functioning (Elkelish *et al.*, 2019). It has been reported that increased functioning of the antioxidant enzymes contributes to quick removal of toxic excess free radicals thereby preventing damage to metabolism (Ahanger and Ahmad, 2019; Soliman *et al.*, 2020). Excess free radical accumulation in plant cells impairs the structural integrity of key macromolecules, including proteins and lipids, thereby influencing their normal functioning (Mansoor *et al.*, 2022; Soliman *et al.*, 2023).

Conclusion and Future Prospective

From the present study it can be concluded that BC and Ti treatments increased growth of wheat significantly with obvious increase in BC individual treatments, however enhancement in growth was more evident due to combined treatment of BC and Ti. Increase in growth due to BC and Ti treatment was due to the significant enhancement in the chlorophyll pigments, osmolytes synthesis and antioxidant functioning. In addition, increased the synthesis of osmolytes and the activities of antioxidant enzymes were correlated with reduction in oxidative stress parameters. Future studies to know the impact of combined BC and Ti application on the physiology and biochemistry under stressed conditions can be worthwhile. In addition, further studies should be undertaken to look into biochar-rhizosphere microorganism interaction with genotypes, and to explore the potential to engineer plant rhizosphere for better production with biochar soil amendment in various crop species agriculture.

القسم 7: المراجع

SECTION 7: REFERENCES

ضع قائمة بأهم المراجع (كتب ، مقالات علمية، ...)

List the most important references (books, journal\conference articles, ...)

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【評語】 060017

1. This study demonstrates the potential of biochar and titanium in improving crop growth performance and stress tolerance, and has practical value in improving agricultural yields and sustainability.
2. The study design covers a variety of physiological and biochemical parameters and emphasizes the synergistic effects of biochar and titanium. However, the current results are based on short-term experiments, and its long-term effects and economic feasibility need to be further verified under field conditions.
3. The long-term soil improvement effect of biochar and the possible impact of titanium on the environment require in-depth investigation to ensure the sustainability of this method.