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Synthesis of Boron Composite Biochar and Its Evaluation for Growth Effectiveness in Rice

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ABSTRACT

The availability of boron (B), an important micronutrient, in soil is restricted, despite the fact that it is vital for optimal plant growth. Conventional chemical fertilizers increase agricultural output, but they also have major negative effects on the environment and the economy. As a soil supplement, biochar is becoming more and more popular. Biochar-boron composites have shown promise as a soil additive for improving crop health and nutrient availability. In order to obtain the final volume of the product with 7% boron using the hot technique, boric acid and sodium borate were used to make the biochar composite doped with boron. An application of thus manufactured B composite biochar was made. To determine the optimal level of B for improved crop development and rice yield, six treatments of B enriched biochar were used at the levels of T1 = control, T2 = 0.5 mg/kg, T3 = 1.0 mg/kg, T4 = 1.5 mg/kg, T5 = 2.0 mg/kg soil and T6 = Foliar application of B enriched biochar @ 0.1%. It was observed that maximum plant height, root length, panicle length, grain weight/panicle, 1000 grains weight, grain yield and boron content of rice straw was obtained with foliar application of B enriched biochar @ 0.1% (T6). On the other hand, maximum leaf area index, evapotranspiration (ET) and straw yield was noted from T4 (B enriched biochar = 1.5 mg/kg soil). However, highest SPAD values, boron and protein content of rice grains, organic carbon and boron content of soil was observed from T5 (B enriched biochar = 2.0 mg/kg soil).

Keywords: Boron, composite, biochar, rice

Introduction

Plant growth and nutrient uptake are greatly influenced by boron's interactions with other nutrients such as nitrogen, phosphorus, and potassium. For example, nitrogen and boron work in concert to control nitrogen metabolism and plant protein synthesis. Reduced plant growth and yields might result from poor nitrogen uptake and utilization caused by a boron deficiency. In a similar mood,

phosphorus and boron work together to improve phosphorus uptake and use, supporting the growth and development of healthy roots. Additionally, boron and potassium work together to maintain membrane function and cell wall structure, which affects the general health of plants. The necessity of applying boron and other nutrients in a balanced manner for the best possible plant growth is highlighted by the fact that an imbalance in any of these nutrients can impair plant growth and productivity. Under intensive agricultural methods or in soils with intrinsic nutrient deficits, this equilibrium is especially important (Long & Peng, 2023).

A potential soil additive for boosting crop yield and soil health is biochar, a carbon-rich substance made by pyrolyzing organic biomass in low-oxygen settings (Lehmann & Joseph, 2024). The type of feedstock utilized and the pyrolysis conditions, such as temperature and time, greatly influence the properties of biochar, such as high surface area, porosity, and cation exchange (Shehzad et al., 2025). Biochar is helpful for improving soil because of its vast surface area and porous structure, which provide plenty of places for water retention and nutrient absorption. Biochar is an adaptable amendment for a variety of soil types due to its alkaline composition, which can help alleviate soil acidity (Khan et al., 2024). Pyrolysis, the heat decomposition of organic compounds in low-oxygen settings, is the method used to produce biochar. Urban green trash, wood chips, manure, and agricultural wastes can all be used as feedstock. Chemical and physical properties of final biochar are significantly influenced by pyrolysis temperature, which normally falls between 300°C and 700°C. Higher temperatures usually improve stability and adsorption capacity of biochar while increasing the carbon content and decreasing yield (Wei et al., 2024).

Combining the advantages of biochar with the vital micronutrient qualities of boron, boron composite biochar is a promising soil supplement. While boron promotes plant development, cell wall stability, and nutrient uptake, biochar increases soil structure, water retention, and nutrient cycling (Siddiqui, 2025; Kabir et al., 2023). According to studies, biochar enhanced with boron can boost crop yields, enhance soil fertility, and lessen nutritional deficits. For instance, a study discovered that while boron supplementation improved plant growth and development, biochar application boosted phosphorus availability by a ratio of 4.6 (Yadav & Ramakrishna, 2023).

As a staple food, a major cash crop, and a substantial source of foreign exchange profits, rice is vital to Pakistan's economy. For millions of Pakistanis living in rural areas, rice is the second most important food crop after wheat and the second-largest exportable commodity after cotton. It also makes a significant contribution to the agricultural GDP of the nation. Its influence goes beyond

financial gains, promoting rural development and food security, making it an essential part of Pakistan's economy and agricultural sector. A staple crop with a modest tolerance to salt is rice (Kalita & Tanti, 2020). In salty soils, boron has been demonstrated to assist a variety of crops withstand salt stress (Zhao et al., 2019). However, because of increased B uptake made possible by high salt (Na^+) levels, high B concentrations in saline soils might impede plant growth and lower yields (Martinez-Ballesta et al., 2008). Rice farmers should use the right amounts of B fertilizer to lessen the negative effects of salt on water and nutrient uptake (Moraes et al., 2015). Although earlier research has emphasized B's significance in controlling biological systems (Mosa et al., 2016; Uluisik et al., 2018), more investigation is required to comprehend B's function in reducing salt stress and improving rice yield components.

The use of boron composite biochar has improved rice crop growth and yield with encouraging results. Rice root development, nutrient uptake, and grain yield are all enhanced by the combined advantages of biochar's soil conditioning qualities and boron's crucial micronutrient role (Gao et al., 2022; Li et al., 2020). Research has shown that by enhancing soil fertility, water retention, and nutrient availability, boron-enriched biochar can boost rice yields. For example, compared to control treatments, boron-modified biochar considerably increased rice plant height, tiller number, and grain output (Luo et al., 2021). Boron composite biochar provides a sustainable way to increase rice productivity by improving soil conditions and nutrient delivery. Hence, current research has been conducted to assess the impact on rice crop growth and yield of various biochar-boron composite application rates (0.5, 1.0, 1.5, and 2.0 mg. kg^{-1} soil), to ascertain the ideal biochar-boron composite application rate for enhancing crop development, yield, and soil health in rice farming and to evaluate how the biochar-boron composite affects organic carbon and boron content of the soil.

Materials and Methods

This research was designed to explore the possible advantages of utilizing biochar-boron composites as a soil amendment for sustainable rice cultivation with objectives; to develop biochar-boron composites with 7% boron content using boric acid and sodium borate, to evaluate effectiveness of different application rates of biochar-boron composite on rice growth and yield, to determine optimal application rate of biochar-boron composite for crop growth, yield and soil health and to appraise outcome of biochar-boron composite on soil characteristics.

Preparation of Biochar

The biochar was prepared from agricultural waste such as rice husk and wheat straw. This material was collected from a nearby farm and transferred to the lab for cleaning, drying, and pyrolysis. Rice and wheat straw biochar was produced by pyrolysis the relevant feedstock at a temperature of 300°C with a residence time of one hour. The end outcome of pyrolysis was analyzed using various methods. After the characterization of biochar, this biochar was modified using Boric Acid and Sodium Borate. In this section, biochar composite doped with B was prepared by using boric acid and sodium borate to get final volume of the product with 7% boron by using hot method. Biochar modified with boric acid and sodium borate was dried in open air for final use.

Plant Material

The rice cultivar used in this study was *Oryza sativa*L. cv. **Super Basmati**, obtained from the Punjab Seed Corporation, Pakistan. Seed lot details: category – rice crop seed; pack size – 20 kg; year of release – 1996; recommended area – Punjab, Pakistan; sowing window – 1–28 June; maturity – 115 days; average plant height – 110 cm; grain length – 7.45 mm (long grain); grain type – aromatic, good cooking quality. Seeds were procured through an institutional collaboration between the University of Sargodha and the Punjab Seed Corporation for research purposes and sown in the nursery as described below.

Transplanting of Rice Crop

Rice nursery at the age of 40 days was transplanted to get it matured and above mentioned and prepared B composite biochar was applied to rice plants @ 0.5, 1.0, 1.5, and 2.0 mg. kg^{-1} soil to assess best level of B for better crop growing and produce of rice.

Treatments:

T1 = Control/CK- (B0)

T2 = B enriched biochar = 0.5 mg/kg soil

T3 = B enriched biochar = 1.0 mg/kg soil

T4 = B enriched biochar = 1.5 mg/kg soil

T5 = B enriched biochar = 2.0 mg/kg soil

T6 = Foliar application of B enriched biochar @ 0.1%

All these treatments were replicated four times and layout was made according to completely randomized design (CRD) of statistics.

Collection of Rice Plant's Samples

Rice was cultivated to maturity, and yield-related factors like plant height, root length, shoot length, leaf area, total chlorophyll content, shoot dry weight, root dry weight, yield, and B content in rice plant components (root, shoot, and grain) were measured at maturity.

Collection of Soil Samples

All soil samples were analyzed for EC, pH, nitrogen, phosphorus, potassium, organic matter, and boron levels.

Laboratory Examination Samples

Laboratory investigates of samples (soil and plant) were performed using methods described in Handbook 60 by the USDA Laboratory Staff (1969), unless noted otherwise.

Texture of Soil

A complete process was followed to classify the soil texture. Textural class of soil was assessed based on ratios of soil separates (sand, silt, and clay) using International Textural Triangle outlined by Moreno et al. (2022).

Soil Organic Matter

Total soil organic carbon was measured with method of Walkley & Black (1934). Organic matter was assessed through quick dichromate oxidation of soil samples.

Available/Olsen Phosphorus

Amount of available/Olsen phosphorus was determined using $NaHCO_3$ and ammonium molybdate and ascorbic acid reagents as described in standard methods (Olsen et al., 1954).

Soil Boron:

It was performed to determine boron levels in soil samples using the techniques outlined by Sah and Brown (1997). In this procedure, 10 g soil was taken. Mixture of all required materials was boiled under reflux for approximately 5–7 minutes to extract available boron. After cooling, the suspension is filtered through a filter paper (e.g., Whatman No. 42) into plastic containers. If the extract is colored, it may require purification.

Plant Boron:

It was done to determine boron content in plant samples using methods of Sah and Brown (1997). After drying, these samples were grinded to pass through 0.5-1.0 mm sieve and were stored in plastic containers to avoid contamination from glass materials as every glass item contains boron. A quantity of 1.0 g ground plant sample was taken in porcelain crucible that was placed in muffle furnace to get dry ashing at about 550 ºC for 4-6 hours. After it, crucibles were taken out of furnace

and allowed to cool down. Later on 10 ml solution of 1M HCl was added in the ash to dissolve it and subsequent filter in plastic flask. All crucibles and filter papers were washed 3-4 times with deionized water and volume was made up. Sample of 1 ml was taken into plastic tube and 2 ml buffer masking reagent composed of ammonium acetate, EDTA and acetic acid was added along with 2 ml Azomethine H reagent. All contents were mixed and allowed for an hour to develop yellow colour. An absorbance reading at 412nm was measured using UV-Vis Spectrophotometer.

Total Chlorophyll/SPAD Values

The spectrophotometric technique is frequently used to assess chlorophyll levels in plants. The procedure begins by gathering fresh plant leaves, which are subsequently washed to eliminate any dirt and dried using a paper towel. Leaves are ground and crushed to extract chlorophyll. Little quantity of this extract is placed in a test tube or cuvette, and its absorbance is recorded with a spectrophotometer. The absorbance values are utilized to calculate contents of chlorophyll through using formula of Lichtenthaler (1987).

Statistical Analysis of Data

Application "Statistics 8.1" was utilized to perform statistical analysis on data gathered from soil and crop characteristics. Fisher's ANOVA was utilized for the statistical examinations. Microsoft Excel was employed for the computations and visual displays. Least Significant Difference (LSD) test was utilized at a 1% probability threshold to identify significant discrepancies among treatment sound effects, using letters (a, b, c, etc.) indicating variations (Steel et al., 1997).

Results and Discussion

Effect of Biochar-Boron Composites on Plant Height of Rice

Biochar-Boron composites can significantly impact the plant height of rice. Studies show that biochar application can lead to significant increases in shoot length/plant height of rice. Data indicated that plant height of rice increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 1). Minimum plant height of 82 cm was noted in control treatment (T1) whereas treatment T6 (foliar application of B enriched biochar @ 0.1%) indicated maximum height of 91 cm. Treatment T4 (B enriched biochar = 1.5 mg/kg soil) indicated plant height of 90 cm and remained non-significant with T6 (foliar application of B enriched biochar @ 0.1%) when compared statistically. However, differences of both these treatments T4 (B enriched biochar = 1.5 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) were noted as significant for all remaining treatments.

Plant height increased in all the treatments in a systematic way except T5 (B enriched biochar = 2.0 mg/kg soil) where it remained 87 cm after deviating the linear pattern. Similarly, plant heights of 85 and 86 cm were noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively.

Research suggests that biochar application can increase plant height, with varying effects liable on nature and amount of biochar used. For example, fertilized water hyacinth biochar treatment resulted in a plant height of 54 inches, outperforming other treatments (Hossain et al., 2019). Rice husk and cocoa shell biochar at 5% application rate achieved the maximum produces (Cedeño et al., 2024). Consequence of biochar on plant height can also be influenced by factors like soil type, crop variety, and fertilizer application. For example, biochar application improved plant growth in acid soils with pH levels between 5.5 and 6.5 (Hossain et al., 2019). Regarding Boron, a study on Boro rice found that applying 2kg B/ha (B2) resulted in the highest plant height (96.378 cm), while another treatment combination (S20B3) achieved a plant height of 100.30 cm. So, S20B3 represents a treatment where Sulfur was applied at 20 kg/ha and Boron was applied at 3 kg/ha. This combination resulted in a plant height of 100.30 cm in the study (Promi et al., 2022). A study found that biochar application increased shoot length by 15-25% compared to the control (Glaser et al., 2002). Another research found that rice husk biochar at 5% application rate achieved the highest shoot length, contributing to improved plant growth (Lehmann et al., 2003).

Effect of Biochar-Boron Composites on Leaf Area Index of Rice Plants

Biochar-Boron composites can increase leaf area of rice. Studies show that biochar application can lead to significant increases in leaf area index. Data indicated that leaf area index of rice plants increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 2). Minimum leaf area index of 28 was noted in control treatment (T1) whereas treatment T4 (B enriched biochar = 1.5 mg/kg soil) indicated maximum leaf area index of 35. Treatment T5 (B enriched biochar = 2.0 mg/kg soil) indicated leaf area index of 31 and remained significant with T6 (foliar application of B enriched biochar @ 0.1%) when compared statistically. Leaf area index increased in all the treatments in a systematic way except T5 (B enriched biochar = 2.0 mg/kg soil) where it remained 31 after deviating the linear pattern. Similarly, leaf area index of 30 and 33 were noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively.

Numerical value of 29 was noted for leaf area index of treatment T6 (foliar application of B enriched biochar @ 0.1%).

A study by Liu et al. (2019) stated that usage of biochar increased leaf area index by 15-25% compared to the control. Another research by Huang et al. (2018) said that rice straw biochar @ 5% achieved the highest leaf area, contributing to improved plant growth. Boron application also plays a role in leaf development. A study by Kaur & Dhaliwal (2020) found that applying 2kg B/ha (B2) resulted in increased leaf area index.

Effect of Biochar-Boron Composites on SPAD Values of Rice

Biochar-Boron composites can increase total chlorophyll content of rice. Studies show that biochar application can lead to significant increases in chlorophyll content. SPAD values of any crop are measurements of chlorophyll and nitrogen contents at particular time. Data indicated that SPAD values of rice plants increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 3). Minimum SPAD values of 37 was noted in control treatment (T1) whereas treatment T5 (B enriched biochar = 2.0 mg/kg soil) indicated maximum SPAD values of 49. SPAD values increased in all the treatments in a systematic way following linear pattern from treatments T1 (control) to T5 (B enriched biochar = 2.0 mg/kg soil). Similarly, SPAD values of 39, 43 and 45 were noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil), T3 (B enriched biochar = 1.0 mg/kg soil) and T4 (B enriched biochar = 1.5 mg/kg soil) respectively. However, numerical value of 42 was noted for SPAD values of treatment T6 (foliar application of B enriched biochar @ 0.1%). In this case treatments T3 (B enriched biochar = 1.0 mg/kg soil) and T4 (B enriched biochar = 1.5 mg/kg soil) were noted as non-significant for each other and similarly, treatments T3 (B enriched biochar = 1.0 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) were also noted as non-significant for each other when examined through statistics.

A study by Ali et al. (2020) found that biochar application increased total chlorophyll content by 10-20% compared to the control. Another research by Hussain et al. (2019) found that rice husk biochar at 5% application rate achieved the highest total chlorophyll content, contributing to improved plant growth. Boron application plays a role in chlorophyll synthesis. A study by Shah et al. (2022) found that applying 2kg B/ha (B2) resulted in increased total chlorophyll content.

Effect of Biochar-Boron Composites on Straw Yield of Rice

Studies show that biochar application can lead to significant increases in straw yield. Data indicated that straw yield of rice increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 4). Minimum straw yield of 8.30 t. ha^{-1} was noted in control treatment (T1) whereas treatment T4 (B enriched biochar = 1.5 mg/kg soil) indicated straw yield of 10.96 t. ha^{-1}. Similarly, straw yield of 10.15 and 10.23 t. ha^{-1} was noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively. Treatments T1 (control) to T4 (B enriched biochar = 1.5 mg/kg soil) followed a linear pattern of increase in straw yield of rice. Straw yield of 10.14 and 10.26 t. ha^{-1} were recorded for treatments T5 (B enriched biochar = 2.0 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) respectively. In this case, however, treatments T2 (B enriched biochar = 0.5 mg/kg soil), T3 (B enriched biochar = 1.0 mg/kg soil), T5 (B enriched biochar = 2.0 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) remained non-significant when compared with each other in terms of statistics.

A study by Liu et al. (2019) concluded biochar application increased shoot dry weight/straw yield by 22-35% compared to the control. Another research by Huang et al. (2018) claimed rice straw biochar @ 5% application rate achieved the highest shoot waterless weight, contributing to improved plant growth. Boron application also plays a role in shoot development. A study by Kaur & Dhaliwal (2020) found that applying 2kg B/ha (B2) resulted in increased shoot dry weight.

Effect of Biochar-Boron Composites on Grain Yield of Rice

Studies show that biochar application can lead to significant increases in rice yield. Data indicated that grain yield of rice increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 5). Minimum grain yield of 3.75 t. ha^{-1} was noted in control treatment (T1) whereas treatment T6 (foliar application of B enriched biochar @ 0.1%) indicated grain yield of 4.97 t. ha^{-1}. Grain yield increased in all the treatments in a systematic way except T5 (B enriched biochar = 2.0 mg/kg soil) where it remained 4.54 t. ha^{-1} after deviating the linear pattern. Similarly, grain yield of 4.16 and 4.45 t. ha^{-1} was noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively. Likewise, grain yield of 4.72 t. ha^{-1} was recorded for treatments T4 (B enriched biochar = 1.5 mg/kg soil). In this case, all treatments proved significant when compared with each other in terms of statistics.

A study by Zhang & Wang (2020) found that biochar increased rice yield by 10-15% compared to control. Similarly, Ali et al. (2019) found that rice husk biochar at 5% application achieved the highest yield, paying to improved growth. Boron use also plays a role in yield enhancement. A study by Rehman et al. (2021) found that applying 2kg B/ha (B2) resulted in increased rice yield.

Effect of Biochar-Boron Composites on Boron Content of Rice Straw

Biochar-Boron composites can increase boron content in rice straw. Biochar application can increase boron content in rice straw by improving soil boron availability and retention. Data indicated that boron content of rice straw increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 6). Minimum boron content of rice straw of 13.30 mg. kg^{-1} was noted in control treatment (T1) whereas treatment T6 (foliar application of B enriched biochar @ 0.1%) indicated maximum boron content of rice straw of 32.41 mg. kg^{-1}. Boron content of rice straw increased in all the treatments in a systematic way following the linear pattern. Similarly, boron content of rice straw of 22.14 and 24.65 mg. kg^{-1} was noted for T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively. Likewise, boron content of rice straw of 27.62 and 30.72 mg. kg^{-1} was recorded for T4 (B enriched biochar = 1.5 mg/kg soil) and T5 (B enriched biochar = 2.0 mg/kg soil) respectively. In this case, all treatments proved significant statistically.

Studies show that applying 2% rice husk biochar increases boron content in straw/shoots by 28-35% compared to the control. Additionally, foliar application of nanocomposite (Ca + Mg) nanoparticles increases boron content in shoots by 16-32% (Ali et al., 2024; Riaz et al., 2025). Boron shows a critical character in plant growth, besides its deficiency can lead to reduced yields. Applying boron fertilizers, either through soil or foliar application, can increase boron uptake and improve rice productivity (Songsriin et al., 2023). Some studies have also explored the potential of biochar-based composites for boron removal from aqueous solutions, highlighting their effectiveness and sustainability (Amirshekari et al., 2025).

Effect of Biochar-Boron Composites on Boron Content of Rice Grains

Studies show that applying boron fertilizers, either through soil or foliar application, can significantly improve boron uptake and grain yield (Lordkaew et al., 2013; Songsriin et al., 2023). Data indicated that boron content of rice grains increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 7). Minimum boron content of rice grains of 5.32 mg. kg^{-1} was noted in control treatment

(T1) whereas treatment T5 (B enriched biochar = 2.0 mg/kg soil) indicated maximum boron content of rice grains of 8.96 mg. kg^{-1}. Boron content of rice grains increased in all the treatments having soil application in a systematic way following the linear pattern. Similarly, boron content of rice grains of 7.11 and 7.26 mg. kg^{-1} was noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively. Likewise, boron content of rice grains of 7.54 and 7.85 mg. kg^{-1} was recorded for treatments T4 (B enriched biochar = 1.5 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) respectively. In this case, all treatments proved significant when compared with each other in terms of statistics.

In a study, residual boron application at 2-3 kg B/ha resulted in higher grain boron concentration, with borax and phosphate boron (PC) being equally effective. Another study found that soil boron usage created grain produce of 4.7 t/ha, when compared with control, however foliar boron use reduced grain produce by 10.9%. Over-all B absorption was highest when boron was added to soil, being greater than foliar boron use and control plots. Boron application also improved grain yield attributes, such as panicle number, grain weight, and filled grain percentage (Songsriin et al., 2023; Saleem et al., 2011).

Effect of Biochar-Boron Composites on Soil Organic Carbon after Rice Crop

Biochar-Boron composites can increase soil organic carbon (SOC) after rice crop. Studies show that biochar application can lead to significant increases in SOC. Data indicated that organic carbon content of soil increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 8). Minimum organic carbon content of soil of 5.78 g. kg^{-1} was noted in control treatment (T1) whereas treatment T5 (B enriched biochar = 2.0 mg/kg soil) indicated maximum organic carbon content of soil of 9.15 g. kg^{-1}. Organic carbon content of soil increased in all the treatments having soil application in a systematic way following the linear pattern. Similarly, organic carbon content of soil of 8.16 and 8.32 g. kg^{-1} was noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively. Likewise, organic carbon content of soil of 8.95 and 8.74 g. kg^{-1} was recorded for treatments T4 (B enriched biochar = 1.5 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) respectively. In this case, all treatments proved significant when compared with each other in terms of statistics.

A study by Khan et al. (2024) found that biochar use increased SOM by 10-20% compared to the control. Biochar's high carbon content and stability help improve SOM, enhancing soil fertility

and structure. Another research by Yadav et al. (2018) found that rice husk biochar at 5% application rate increased SOM, contributing to improved soil health. Boron application also plays a role in improving soil health, but its impact on SOC is relatively minor compared to biochar.

Effect of Biochar-Boron Composites on Soil Boron Content after Rice Crop

Biochar-Boron composites can increase soil boron content after rice crop. Biochar's porous structure helps retain boron, reducing leaching and increasing availability for plants. The composite can provide a sustained release of boron, benefiting crops. Data indicated that boron content of soil increased in all the treatments when compared with control (T1). Differences among various treatments were noted as significant in terms of statistics (Figure 9). Minimum boron content of soil of 0.34 mg. kg^{-1} was noted in control treatment (T1) whereas treatment T5 (B enriched biochar = 2.0 mg/kg soil) indicated maximum boron content of soil of 0.78 mg. kg^{-1}. Boron content of soil increased in all the treatments having soil application in a systematic way following the linear pattern. Similarly, boron content of soil of 0.44 and 0.53 mg. kg^{-1} was noted for treatment T2 (B enriched biochar = 0.5 mg/kg soil) and T3 (B enriched biochar = 1.0 mg/kg soil) respectively. Likewise, B content of soil of 0.67 and 0.46 mg. kg^{-1} was recorded for treatments T4 (B enriched biochar = 1.5 mg/kg soil) and T6 (foliar application of B enriched biochar @ 0.1%) respectively. In this case, all treatments proved significant when compared with each other in terms of statistics except treatments T2 and T6 which remained non-significant for each other.

Biochar-Boron composites can enhance soil boron availability by slowly releasing boron. A study by Rehman et al. (2021) found that applying Biochar-Boron composites increased soil boron content and improved rice growth. Research showed that soil boron application increased absorption of boron and yield of rice (Songsriin et al., 2023). Biochar-Boron composites can increase soil boron after rice crop. Studies show that applying Biochar-Boron composites can enhance soil B availability by slowly releasing boron, benefiting crops (Hoque et al., 2025).

Conclusions

Foliar application of B-enriched biochar @ 0.1% maximized rice growth and grain yield parameters, while soil application @ 1.5 mg/kg optimized vegetative growth and straw yield, and @ 2.0 mg/kg improved grain quality, SPAD values, and soil boron/organic carbon. Thus, application method and rate of B-enriched biochar should be targeted based on desired outcome: yield vs. quality vs. soil health.

Declarations

Ethics Approval

This study did not involve human participants or animals. The experiment was conducted on rice plants (*Oryza sativa* L. cv. Super Basmati) under greenhouse and field conditions on government-owned land. The collection and use of the plant material complied with local and national guidelines for agricultural research. The seeds were a commercially released variety obtained from the Punjab Seed Corporation through institutional collaboration. No endangered or protected plant species were involved. Therefore, ethics approval for plant research guidelines was duly followed and considered not applicable for this type of study.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Clinical Trial Registration

Not applicable. This study is not a clinical trial.

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Conflict of Interest

The authors declare that they have no competing interests.

Authors Contribution

Ghulam Fatima: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. Mukkram Ali Tahir: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration. Noor-Us-Sabah: Methodology, Investigation, Data curation, Formal analysis. Hassnain Haider: Conceptualization, Methodology, Resources, Writing – review & editing, Supervision. Kadambot H.M. Siddique: Writing – review & editing, Supervision, Resources. Warda Masoma: Investigation, Formal analysis, Writing – review & editing.

Data Availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Permissions to Collect Plant Material

The rice seeds (Super Basmati) were obtained from the Punjab Seed Corporation under an existing institutional collaboration for research material exchange. The field experiment was conducted on government-owned land. No additional permits were required for the use of this commercially available certified seed variety. The authors confirm that all necessary permissions for the use of the research material and the experimental site were in place.

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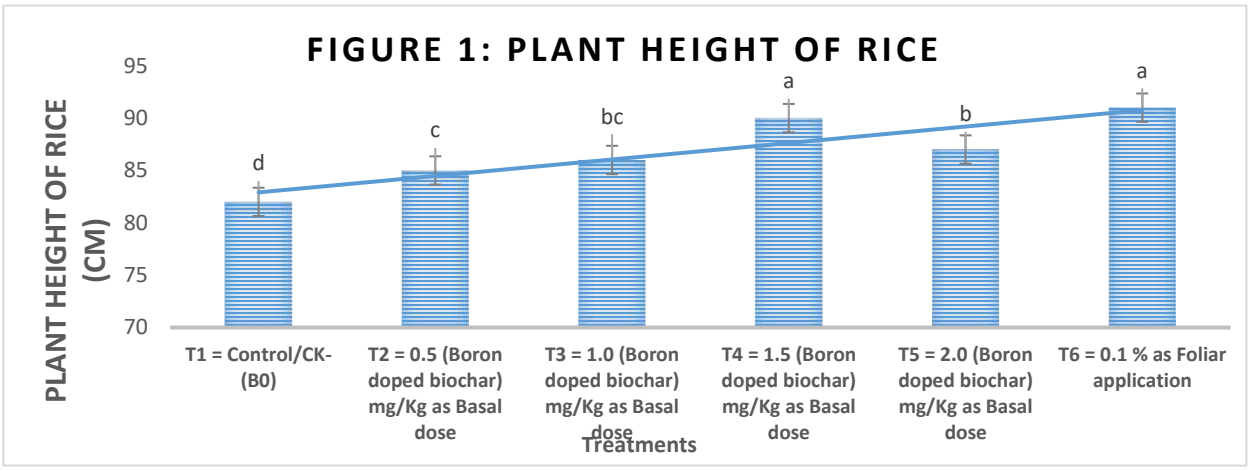
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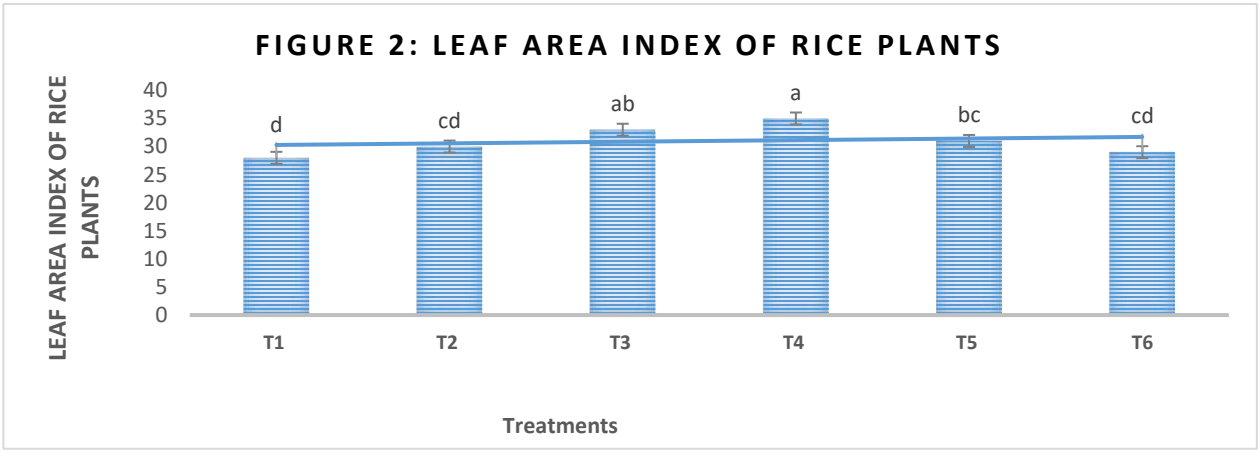
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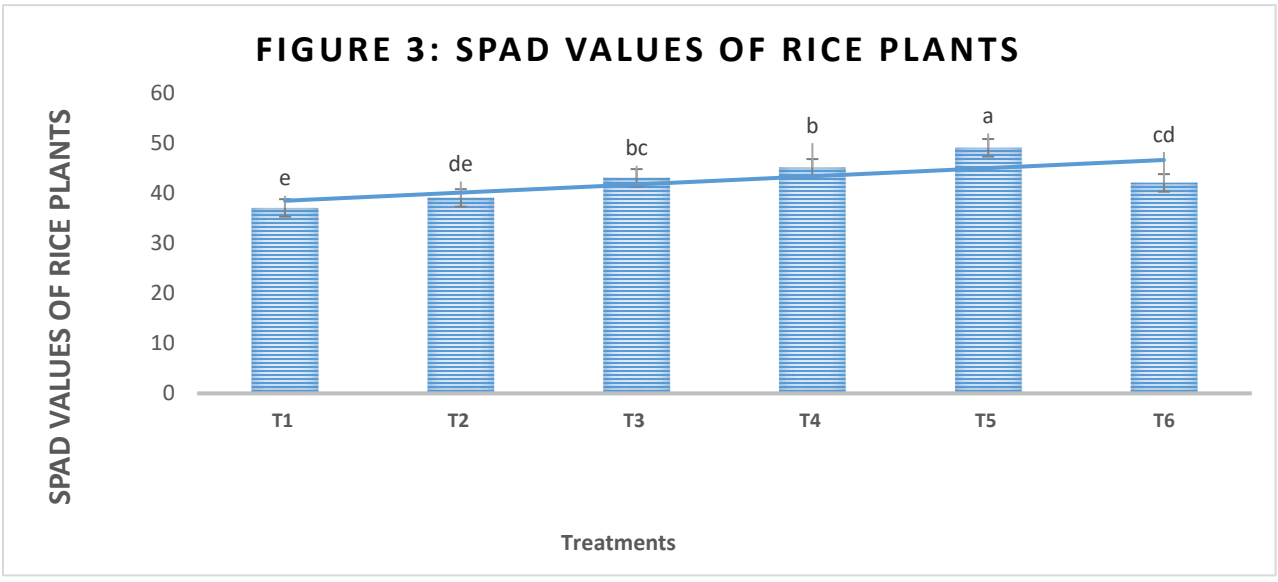
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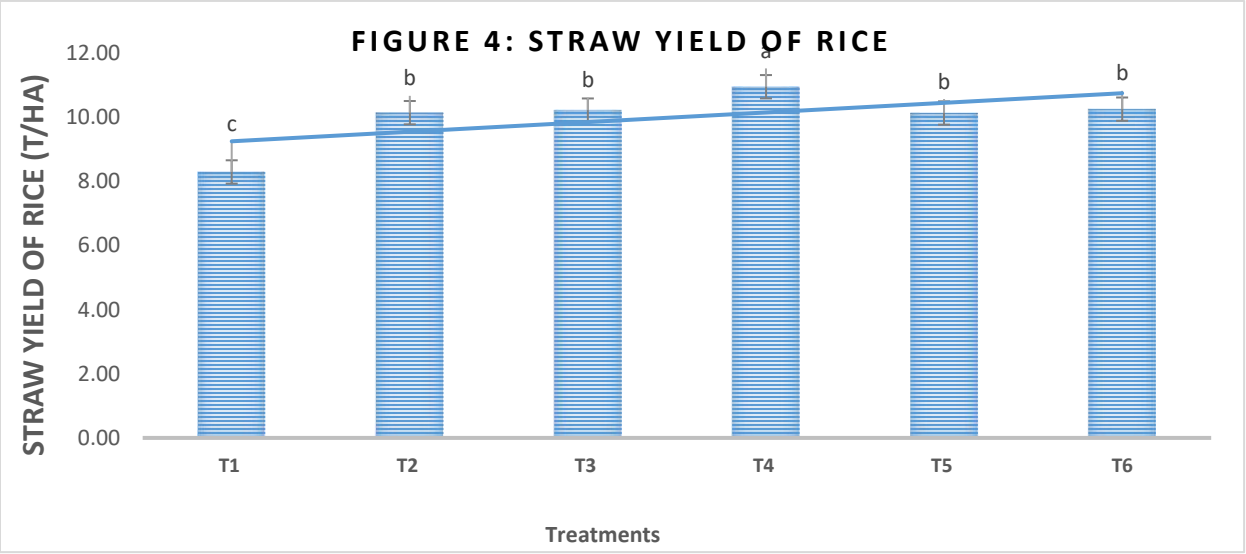
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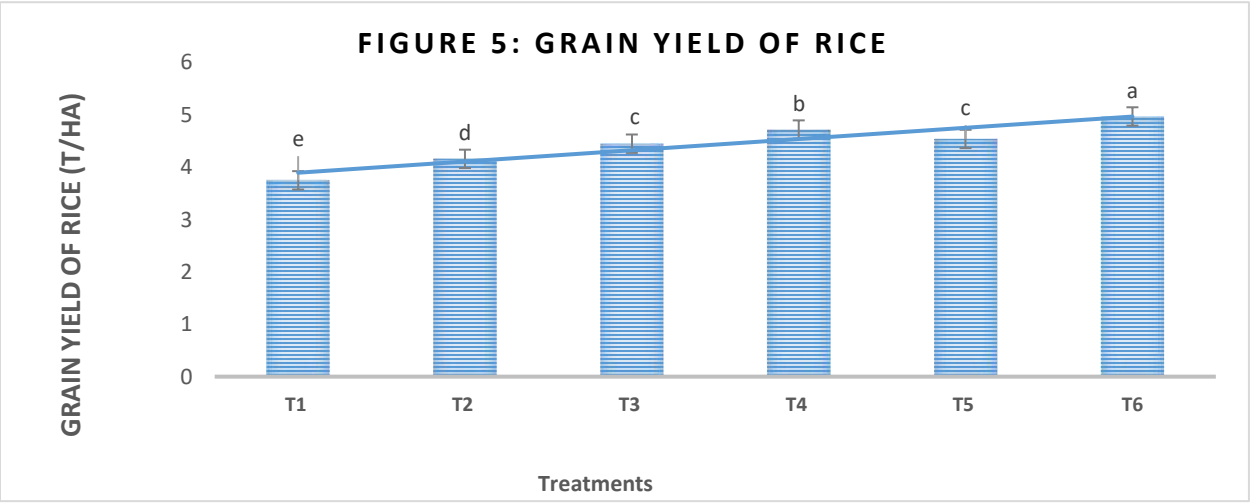
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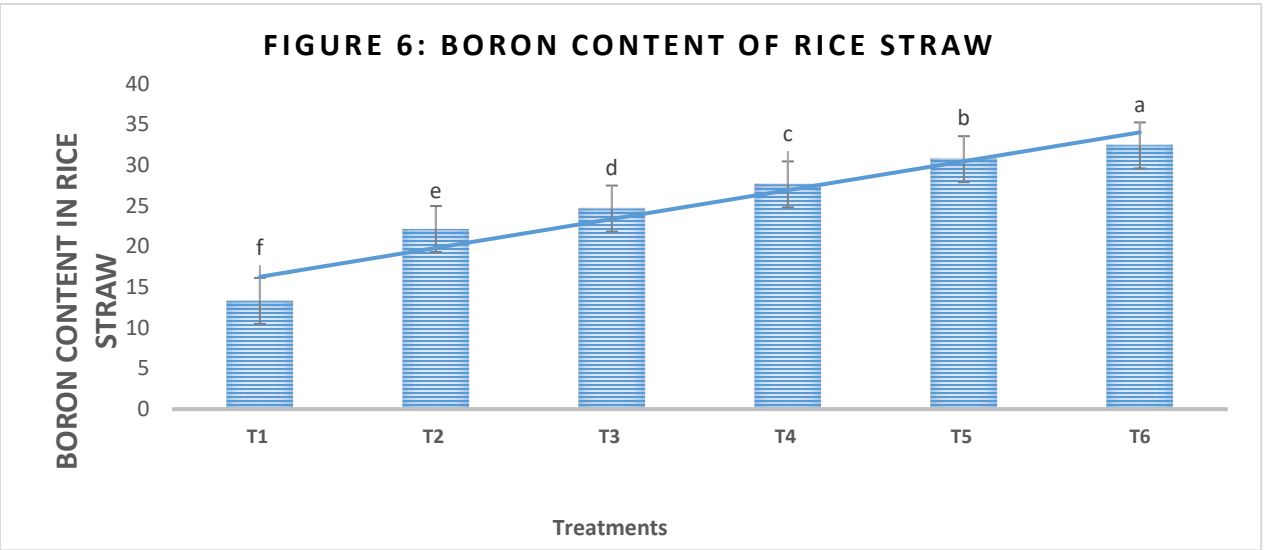

FIGURE 1: PLANT HEIGHT OF RICE
PLANT HEIGHT OF RICE (CM)
95
90
85
80
75
70
d
c
bc
a
b
a
T1 = Control/CK-(B0)
T2 = 0.5 (Boron doped biochar) mg/Kg as Basal dose
T3 = 1.0 (Boron doped biochar) mg/Kg as Basal dose
T4 = 1.5 (Boron doped biochar) mg/Kg as Basal dose
T5 = 2.0 (Boron doped biochar) mg/Kg as Basal dose
T6 = 0.1 % as Foliar application
Treatments

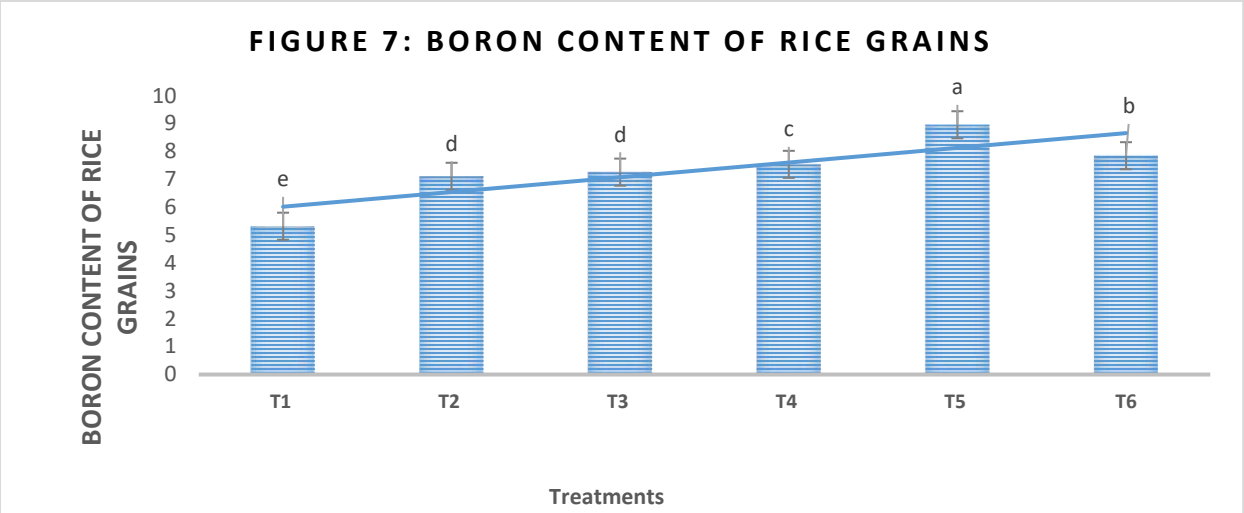

FIGURE 2: LEAF AREA INDEX OF RICE PLANTS
LEAF AREA INDEX OF RICE PLANTS
40
35
30
25
20
15
10
5
0
d
cd
ab
a
bc
cd
T1
T2
T3
T4
T5
T6
Treatments

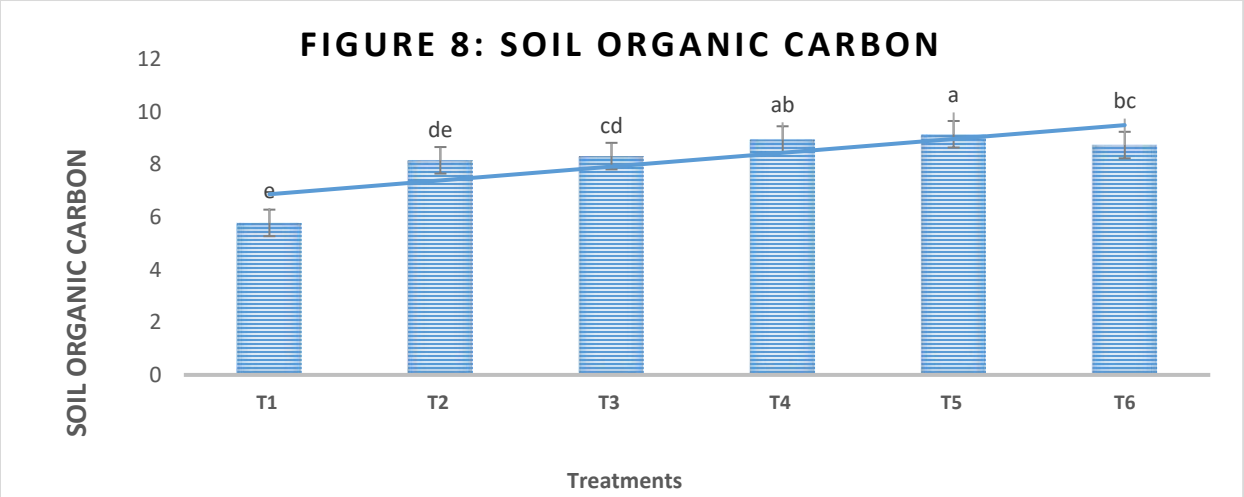

FIGURE 3: SPAD VALUES OF RICE PLANTS
SPAD VALUES OF RICE PLANTS
60
50
40
30
20
10
0
e
de
bc
b
a
cd
T1
T2
T3
T4
T5
T6
Treatments

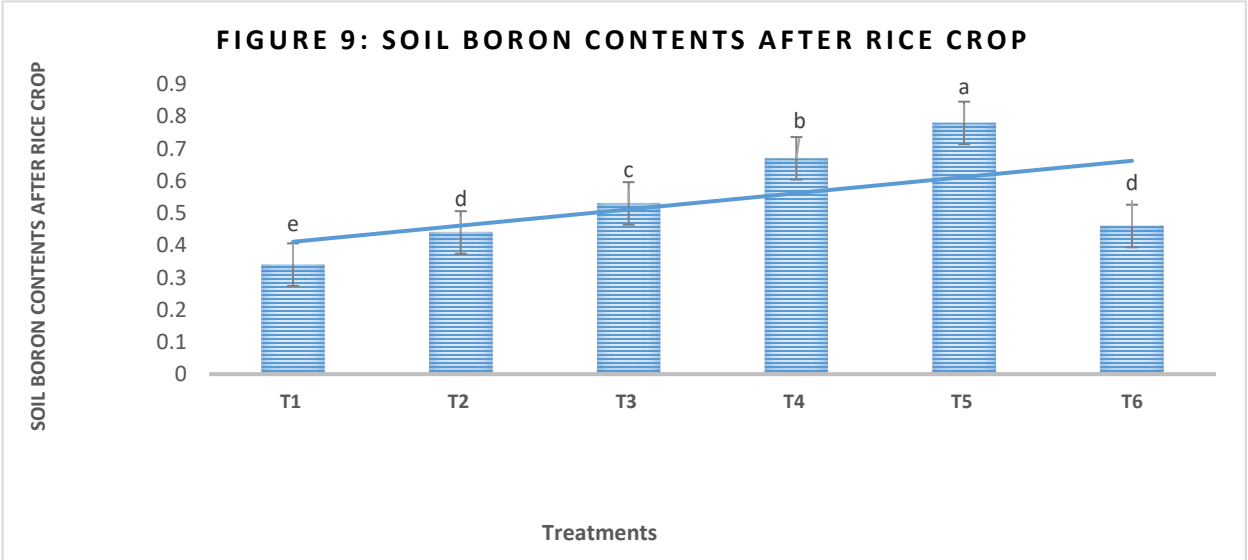

FIGURE 4: STRAW YIELD OF RICE
STRAW YIELD OF RICE (T/HA)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
c
b
b
a
b
b
T1
T2
T3
T4
T5
T6
Treatments


FIGURE 5: GRAIN YIELD OF RICE
GRAIN YIELD OF RICE (T/HA)
6
5
4
3
2
1
0
e
d
c
b
c
a
T1
T2
T3
T4
T5
T6
Treatments


FIGURE 6: BORON CONTENT OF RICE STRAW
BORON CONTENT IN RICE STRAW
40
35
30
25
20
15
10
5
0
f
e
d
c
b
a
T1
T2
T3
T4
T5
T6
Treatments


FIGURE 7: BORON CONTENT OF RICE GRAINS
BORON CONTENT OF RICE GRAINS
10
9
8
7
6
5
4
3
2
1
0
e
d
d
c
a
b
T1
T2
T3
T4
T5
T6
Treatments


FIGURE 8: SOIL ORGANIC CARBON
SOIL ORGANIC CARBON
12
10
8
6
4
2
0
e
de
cd
ab
a
bc
T1
T2
T3
T4
T5
T6
Treatments


FIGURE 9: SOIL BORON CONTENTS AFTER RICE CROP
SOIL BORON CONTENTS AFTER RICE CROP
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
e
d
c
b
a
d
T1
T2
T3
T4
T5
T6
Treatments