



(RESEARCH ARTICLE)



ENHANCING SOIL PROPERTIES AND CAPSICUM (*CAPSICUM ANNUUM* VAR. *GROSSUM* L.) PRODUCTIVITY THROUGH THE APPLICATION OF RICE STRAW-DERIVED BIOCHAR

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ABSTRACT

Capsicum, often known as sweet pepper (*Capsicum annuum* var. *grossum* L.), is becoming more and more popular in Bangladesh as a vegetable. However, a number of obstacles must be overcome for its production to occur, such as limited cation exchange capacity, poor soil fertility, fast mineralization of soil organic matter, and acidity of the soil. These problems are addressed by applying biochar, a carbon-rich biomass made by pyrolysis under low or no oxygen conditions, as a soil amendment. The purpose of this research was to evaluate how applying biochar affected the qualities of the soil and the production of capsicum in the experimental fields of the Soil Science Department at Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Salna, Gazipur 1706. The treatments included T0 (control, no biochar), T1 (2.5 t/ha biochar), T2 (5.0 t/ha biochar), T3 (7.5 t/ha biochar), and T4 (10.0 t/ha biochar). The experiment followed a Randomized Complete Block Design (RCBD) with three replications. Two capsicum genotypes, BU capsicum 1 (G-1) and a capsicum line (G-2), were used as test crops. Biochar application improved soil properties, such as increasing pH, organic carbon (OC), cation exchange capacity (CEC), and the content of nitrogen, phosphorus, and sulfur. Soils amended with rice straw biochar showed significantly higher plant height, fruit number, fruit length, fruit weight, and capsicum yield compared to untreated soils. The most notable improvement in plant growth due to biochar was reflected in the biomass yield. Fruit yield varied significantly, ranging from 54.17 t/ha (T0) to 88.36 t/ha (T2) for G-1 and 92.44 t/ha (T2) for G-2. These findings suggest that converting rice residues into biochar and applying it to soil has significant potential to enhance capsicum production and improve soil health. Farmers are

encouraged to apply 5.0 t/ha of rice residue-derived biochar to sustainably increase capsicum yields and improve soil quality.

Keywords: Soil quality; Fruit yield; Biomass; Rice residue

1 INTRODUCTION

Sweet pepper, or capsicum (*Capsicum annuum* var. *grossum* L.), is a member of the *Capsicum* genus and family of Solanaceae. Despite being a commercially important crop that was initially indigenous to temperate regions [1], attempts are currently being made to grow capsicum in tropical and subtropical nations like Bangladesh and India. Soil acidity, low cation exchange capacity, low fertility, rapid mineralization of soil organic matter, and soil erosion are some of the many issues that affect capsicum production in Bangladesh. Strategies include recycling crop residues, providing organic amendments, fertilizing, liming, and putting in place soil erosion control measures are necessary to address these issues.

Crop wastes are frequently disposed of as waste and left on agricultural fields, either burned or left untended. However, research has demonstrated that by increasing soil microbial diversity and organic carbon levels, organic remediation materials might lessen obstacles to continuous cropping [2-4]. In example, burning rice wastes leads to air pollution and causes the loss of vital nutrients like sulfur and nitrogen [5-7]. Recycling organic wastes is a viable strategy for resolving soil fertility issues in Bangladesh's uplands [8]. For example, rice wastes can be recycled by direct soil incorporation or composting. Through quick decomposition, these techniques can produce nutrients, but they may also result in the release of greenhouse gases like carbon dioxide.

The use of biochar in agricultural systems has gained considerable attention due to its dual benefits for crop production and environmental health [9,10]. Water-holding capacity, structure, porosity, bulk density, and general fertility are among the physical characteristics of soil that are improved by biochar [11,12]. It is well known for enhancing crop yields under difficult circumstances and promoting soil health. Applying biochar improves soil structure and aggregate stability, boosts soil organic matter, improves nutrient and water retention, and encourages the growth of helpful fungi and microorganisms. These advantages help people become more resilient to biotic and abiotic stressors [13].

A more sustainable approach to managing crop residues involves converting them into biochar and applying it to the soil. An efficient soil amendment is biochar, a carbon-rich substance made by pyrolyzing biomass in the absence of oxygen [14,15]. Biochar is thought to have a half-life of hundreds to thousands of years, depending on its kind and production conditions [16]. Its stable carbon content, which mostly consists of aromatic compounds that are resistant to breakdown, accounts for its longevity [17-19]. Therefore, as compared to uncharred organic products such as compost, manure, or crop leftovers, biochar offers soil advantages that endure longer. Its application changes the chemical and physical characteristics of soil, as several studies have shown [20-25].

Biochar can be integrated into agricultural practices for agronomic or environmental management purposes [26, 27]. Its agronomic advantages include enhancing soil quality and promoting plant growth [28, 20]. Furthermore, biochar has been found to improve plant growth, physiological performance, and water use efficiency under water stress when combined with reduced irrigation schedules [13]. This demonstrates its potential as an innovative technology in agriculture, capable of improving nutrient availability across diverse soil types. However, the effects of biochar vary depending on soil type and plant species, with research often focusing on its impacts under agronomic conditions [29,30]. Biochar is particularly beneficial for acidic soils with low water-holding capacity or low organic matter, where it enhances soil quality and crop productivity [28,31,32,33]. Its alkaline pH helps neutralize acidic soils but can be detrimental in soils with naturally high pH, as evidenced by reduced plant productivity when alkaline biochars are applied to Calcarosols [34].

In Bangladesh, the demand for capsicum is rising due to its growing popularity in salads, spices, and pickles within the retail and food service industries. Although significant research has focused on the effects of biochar on soil quality and crop performance, limited studies have explored its impact on vegetable species. It is hypothesized that biochar application could enhance soil fertility and vegetable crop productivity. As such, biochar has garnered global attention from researchers, policymakers, and farmers for its potential to improve soil health and crop yields, making it a subject of active investigation. However, this area of research remains underexplored in Bangladesh. To address this gap, the present study aimed to examine the effects of rice straw-derived biochar with two specific objectives: (i) to evaluate its impact on soil properties and (ii) to assess its influence on capsicum production.

2 MATERIAL AND METHODS

2.1 Experimental site and planting materials

The experiment was conducted at the research field of the Department of Soil Science at Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), located in Salna, Gazipur-1706. The site is situated at a latitude of 24°09' N and longitude of 90°26' E, with an elevation of 8.4 meters above sea level, approximately 40 kilometers north of Dhaka. Capsicum genotypes BU Capsicum I (G-1) and one Capsicum line (G-2) were used as the test crops. Seeds were obtained from the Genetics and Plant Breeding Department of BSMRAU.

2.2 Characteristics of Initial Soil

The soil of the experimental field belongs to the Salna series and is classified as Shallow Red Brown Terrace Soil in Bangladesh [35,36]. Soils from the Madhupur Tract (AEZ - 28) are characterized by heavy clay layers within 50 cm from the surface and have poor chemical properties. Soil samples were collected prior to the project for analysis to assess the initial soil properties. The results of the chemical analysis of pre-project soil are presented in Table 1.

Table 1: Pre-project soil properties status of the experimental soil

Parameters	Value
pH	5.99
OC (%)	0.75
CEC (Cmol kg ⁻¹ Soil)	2.95
Total N (%)	0.056
P (mg kg ⁻¹)	9.80
S (mg kg ⁻¹)	10.80

2.3 Design of experiment and Treatments

A Randomized Complete Block Design (RCBD) with three replications was used to carry out the experiment. Two types of capsicum were grown in each of the thirty plots that were used. Each plot was 1 m by 1.2 m, with a 40 cm line-to-line and a 25 cm plant-to-plant spacing. Each plot has ridges built (20 cm high) to stop irrigation water from running off laterally. Biochar was used in five different treatments: T0 (control without biochar), T1 (2.5 t/ha), T2 (5.0 t/ha), T3 (7.5 t/ha), and T4 (10.0 t/ha). The soil was mixed with biochar before to the last stage of land preparation. Final land preparation involved broadcasting and thoroughly mixing phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and one-third of the nitrogen (N) into the soil. After transplanting, the remaining two-thirds of the nitrogen were top-dressed in two equal applications at 15 and 35 days.

2.4 Initial status and making of biochar

The modified stove at BSMRAU produced around 5 kg of biochar in about three hours. Rice straw was gathered from a rice field outside the university campus in Gazipur and allowed to dry completely in the sun. A modified pyrolysis stove created by the BSMRAU Department of Soil Science was used to create the biochar from the dried rice straw. Under conditions of limited oxygen, the pyrolysis process was conducted at temperatures ranging from 400°C to 550°C. Following pyrolysis, distilled water was used to cool the hot biochar, which was then gathered, allowed to dry in the sun, milled into a powder, weighed, and kept for use in the experimental field. Table 2 lists all of the characteristics of the rice straw biochar.

Table 2: Analytical parameters of rice straw biochar used in the experiment

Parameter	Value
pH	7.63
OC (%)	44.50
CEC (cmol+/kg Biochar)	32.12
Total N (%)	0.80
P (%)	0.07

S (%)	0.005
Ca (Cmol kg ⁻¹)	16.80
Mg (Cmol kg ⁻¹)	4.86
K (Cmol kg ⁻¹)	8.36
Na (Cmol kg ⁻¹)	2.10

2.5 Management practices and harvesting

Seeds were sown in pots filled with a mixture of sand and cow dung at a 1:1 ratio. Before sowing, the seeds were soaked in water for 12 hours. Ten-day-old seedlings with 3-4 leaves were then transferred into separate poly bags containing a potting mixture of soil, compost, and sand in a 3:1:1 ratio. Healthy and uniform 30-day-old seedlings were transplanted into the experimental plots. The plots were prepared using a spade, breaking clods, and removing weeds to achieve a good tilth. Each plot contained four rows of three plants each. Before transplanting, the polybags were carefully removed to allow the roots to grow into the soil, ensuring smooth establishment. During this process, the earth ball and surrounding soil were protected. Immediate irrigation was provided after transplanting to ensure seedling establishment with adequate soil moisture. After the seedlings were established, the soil around the base was pulverized, and any damaged seedlings were replaced with healthy ones from the same stock as needed. Irrigation was applied as necessary immediately after transplanting, with further inspections daily to assess the need for watering. When signs of water stress appeared, plots were uniformly irrigated the next day using a hose pipe until thoroughly wetted. Irrigation was scheduled at 6-7day intervals. Additionally, after each top-dressing of urea, irrigation was provided to ensure proper nutrient absorption. Bavistin (5g/l), an insecticide, was applied just after seedling establishment to control mite infestations, and there were no incidences of disease. Other cultural practices such as gap filling and weeding were carried out as required. Six randomly selected plants from each plot were harvested at the mature stage, visually determined by the size and color of the fruits. Harvesting took place at one-week intervals, concluding with the final harvest.

2.6 Data collection

2.6.1 Yield contributing characters

The data pertaining to the following characters were recorded from six randomly selected capsicum plants and average was calculated.

- Plant height (cm): It was measured by using meter scale in cm (centimeter) from the base of plant to the tip of the biggest leaf at the time of harvesting.
- Number of fruits per plant: Number of fruits per plant of six randomly selected plants was counted individually.
- Fruit length (cm): Fruit length was measured by a scale and expressed in centimeter.
- Fruit weight (g/plant): The weight of individual fruit was taken by electrical balance.
- Total yield of capsicum (ton/ha): The individual fruit was taken from each plot and then calculated the total yield of capsicum in ton/ha.

2.6.2 Chemical analysis of soil

The soil chemical properties assessed included pH, organic carbon, nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B). The following standard methods were used for soil analysis:

Cation exchange capacity (CEC) (Cmol+/kg): The CEC was determined by the ammonium acetate (pH 7.0) leaching method [37].

Nitrogen (N) estimation (%): Air-dried soil samples were digested using the Kjeldahl flask method, which involved sulfuric acid digestion and distillation with 40% NaOH. The ammonia released during distillation was collected in boric acid and titrated against 0.02 N H₂SO₄ [38].

Phosphorus (P) estimation (ppm): Air-dried soil samples were placed in a plastic container, followed by the addition of NH₄F and shaking for 5 minutes. Ammonium molybdate solution was then added, and absorbance readings were taken using a double beam spectrophotometer at a wavelength of 890 nm [39].

Sulfur (S) estimation (ppm): Soil samples were mixed with CaH₂PO₄, shaken for 30 minutes, filtered, and 0.5 ml aliquots were taken. To the solution, 1 ml of gum acacia and 1 ml of 6 N HCl were added. After mixing, 0.5 g of BaCl₂ was added before measuring absorbance at 420 nm using a spectrophotometer [40].

Organic carbon analysis (%): One gram of soil was placed in a plastic container, followed by the addition of 10 ml of 1 N $K_2Cr_2O_7$ and 10 ml of concentrated H_2SO_4 . The mixture was then stirred for 10-20 minutes with a glass rod. After adding 2-3 drops of PAA, the sample was titrated against 0.2 N AFS until the color changed to deep light green [41].

Soil pH analysis: Ten grams of air-dried soil were added to a plastic container, followed by 25 ml of distilled water. The mixture was shaken for 30 minutes, and the pH was measured using a glass electrode pH meter adjusted with a standard buffer solution at pH 7.0. The electrode was rinsed with distilled water between readings [42].

2.7 Statistical analysis

The computer program R was used to statistically analyze the data, and Microsoft Excel was used to create the graphs. To interpret the data, the least significant difference (LSD) test was used to determine the mean differences between treatments at a 5% level of probability.

3 RESULTS

3.1 Impact of rice straw derived biochar (RSB) on soil properties

As the amount of biochar added to the soil, both the pH and organic carbon (OC) levels progressively rose, demonstrating statistically significant differences from the untreated soil (Table 3). Comparing treated plots to the control, biochar also significantly increased the soil's cation exchange capacity (CEC). Consequently, in comparison to the control, the soil's pH, OC, and CEC rose by 17.72%, 30.67%, and 107.8%, respectively. There was no discernible genotypic influence on soil pH, OC, or CEC despite the use of two capsicum genotypes (G-1 and G-2) in different tests.

Table 3: Effect of rice straw biochar on soil properties in the experimental plot of cultivars of capsicum

Treatment	pH		OC %		CEC (Cmol+/kg)	
	G-1	G-2	G-1	G-2	G-1	G-2
T ₀	5.99±0.05e	5.99±0.05d	0.75±0.05e	0.75±0.05e	2.95±0.13e	2.95±0.13d
T ₁	6.12±0.15d	6.11±0.11c	0.82±0.16d	0.80±0.05d	4.59±0.07d	4.43±0.36c
T ₂	6.15±0.03c	6.16±0.07b	0.85±0.2c	0.86±0.18c	4.98±0.09c	4.95±0.08b
T ₃	6.26±0.17b	6.20±0.16ab	0.93±0.15b	0.92±0.16b	5.57±0.21b	5.66±0.32a
T ₄	6.34±0.11a	6.36±0.15a	0.97±0.09a	0.98±0.15a	6.13±0.20a	6.13±0.20a
CV (%)	1.85	1.82	2.18	2.15	2.36	3.15
Significance level	*	*	**	**	**	**

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. * estimates of error, * significant at $p<0.05$, ** significant at $p<0.01$, ^{CV} Co-efficient of variation, ^{OC} Organic Carbon, ^{CEC} Cation Exchange Capacity, T₀ Control (without biochar), T₁ 2.5 t/ha biochar, T₂ 5.0 t/ha biochar, T₃ 7.5 t/ha biochar and T₄ 10.0 t/ha biochar, G⁻¹ BU Capsicum I and G⁻² one capsicum line.

Table 4: Effect of rice straw biochar on N, P and S in the experimental plot of capsicum genotypes

Treatments	Total N (%)		P (ppm)		S (ppm)	
	G-1	G-2	G-1	G-2	G-1	G-2
T ₀	0.056±0.001c	0.056±0.001d	8.39±0.24e	8.37±0.27e	10.11±0.30c	10.11±0.30d
T ₁	0.090±0.005b	0.088±0.003c	8.89±0.005d	8.91±0.03d	10.58±0.25b	10.61±0.29c
T ₂	0.114±0.002a	0.107±0.006b	9.27±0.028c	9.24±0.05c	12.40±0.35a	12.23±0.36b
sT ₃	0.118±0.002a	0.117±0.006a	9.83±0.06b	9.83±0.06b	12.54±0.52a	12.53±0.52ab
T ₄	0.123±0.005a	0.123±0.005a	10.15±0.15a	10.14±0.15a	12.76±0.10a	12.73±0.14a
CV (%)	6.41	4.43	1.54	1.70	2.11	1.95
Significance level	*	*	*	*	**	**

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. * estimates of error, * significant at $p<0.05$, ** significant at $p<0.01$, ^{CV} Co-efficient of variation, ^N Nitrogen, ^P Phosphorus, ^S Sulphur, T₀ Control (without biochar), T₁ 2.5 t/ha biochar, T₂ 5.0 t/ha biochar, T₃ 7.5 t/ha biochar and T₄ 10.0 t/ha biochar, G⁻¹ BU Capsicum I and G⁻² one capsicum line.

Nitrogen (N), phosphorus (P), and sulfur (S) availability were gradually and considerably increased by adding rice straw biochar (RSB) to the soil, as shown in Table 4. However, this growing tendency was only noticeable for nitrogen up to a 2.5 t/ha biochar application rate; even at the highest dose of 10 t/ha, no additional significant increase was seen. In contrast, when the rates of biochar application increased, the availability of sulfur and phosphorus continued to improve. Both G-1 and G-2 soils showed a similar response to biochar in terms of N, P, and S, suggesting that variations in soil genotype had no effect on these nutrients' availability in comparison to the effect of biochar.

3.2 Impact of RSB on the crop growth

The use of rice straw biochar (RSB) resulted in a considerable improvement in soil conditions, as seen by the increased production and growth of capsicum cultivars. In comparison to plants produced in untreated control soils, capsicum plants cultivated in RSB-amended soils showed improved yield, longer fruit length, heavier fruit weight, and more fruits per plant.

In terms of height, capsicum plants in plots treated with RSB were noticeably ($p < 0.05$) taller than those in soils that were not treated (Figure 2). For both genotypes of capsicum, T2 (5.0 t/ha) showed the greatest significant impact on plant height among the biochar treatments. The plants in the biochar-treated soils grew to a height of 50.22 cm for BU Capsicum 1, which was much higher than the control (43.72 cm). Plants of the Capsicum line also grew to a height of 61.0 cm in soils treated with biochar, as opposed to 54.02 cm in control soils. These results demonstrate that RSB has a beneficial effect on plant height in both capsicum cultivars. Furthermore, a substantial ($p < 0.05$) variation in plant height was noted between the G-1 and G-2 genotypes with and without the application of biochar.

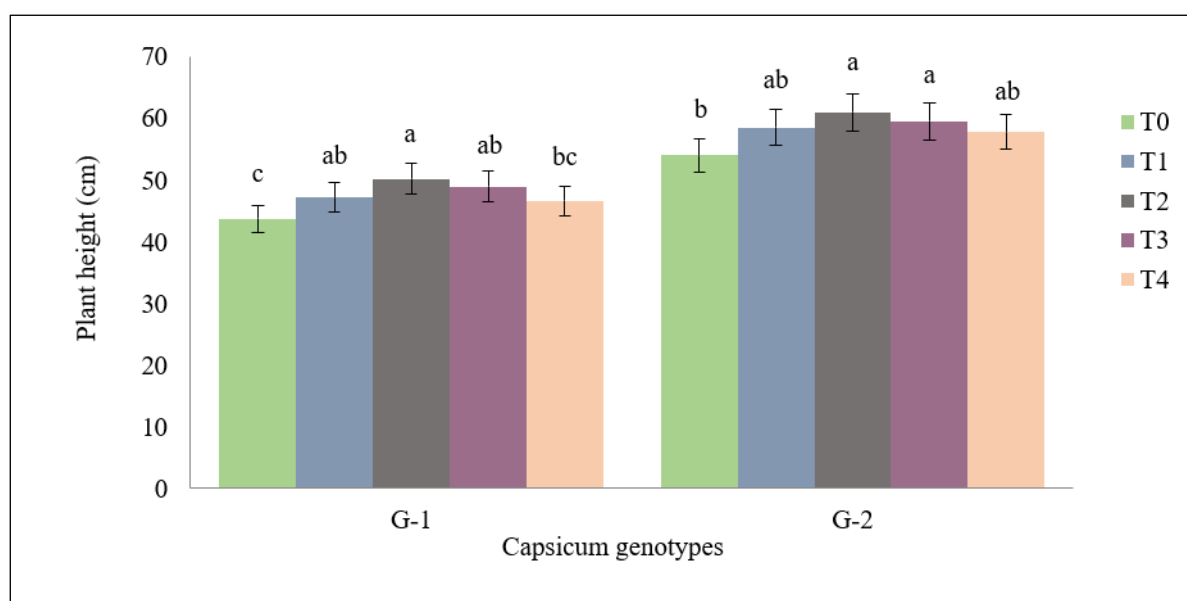


Figure 1: Effect of rice straw derived biochar on capsicum plant height.

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. T_0 Control (without biochar), T_1 2.5 t/ha biochar, T_2 5.0 t/ha biochar, T_3 7.5 t/ha biochar and T_4 10.0 t/ha biochar, G^{-1} BU Capsicum I and G^{-2} one capsicum line.

The application of different doses of rice straw biochar (RSB) significantly affected the number of fruits per plant. Both capsicum genotypes produced significantly more fruit ($p < 0.05$) in soil supplemented with charcoal than in the control (Figure 3). Both types produced the most fruit when treated with T2 (5.0 t/ha). Fruit production was higher in BU Capsicum 1 plants cultivated on soil treated with charcoal (39) than in the control (30). Capsicum line plants in soil modified with biochar also produced a much higher number of fruits (36) than those in soil that was not treated (25). These results support RSB's beneficial impact on fruit output across both genotypes of capsicum. Furthermore, a substantial ($p < 0.05$) variation in fruit quantity was noted between the G-1 and G-2 genotypes with and without the use of biochar.

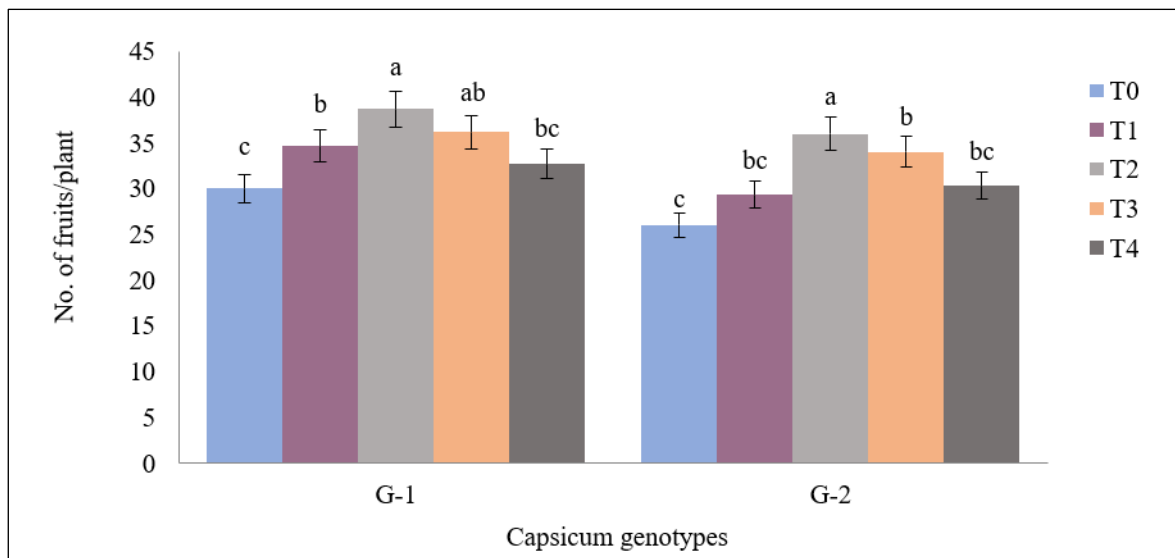


Figure 2: Impact on rice straw derived biochar on the quantity of fruits per capsicum plant.

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. T_0 Control (without biochar), T_1 2.5 t/ha biochar, T_2 5.0 t/ha biochar, T_3 7.5 t/ha biochar and T_4 10.0 t/ha biochar, G^{-1} BU Capsicum I and G^{-2} one capsicum line.

The experimental results showed that different biochar treatments had a substantial impact on capsicum fruit length (Figure 4). In comparison to those planted in untreated soils, capsicum plants that were cultivated in soils altered with rice straw biochar produced noticeably ($p < 0.05$) longer fruits. Among the treatments, T_3 (7.5 t/ha) produced the longest fruits in both capsicum genotypes. In BU Capsicum 1, biochar application resulted in a fruit length of 15.77 cm, significantly exceeding the control (12.91 cm). Similarly, Capsicum line plants in biochar-treated soils achieved a fruit length of 16.76 cm, compared to 13.54 cm in control soils. These results highlight the beneficial impact of rice straw biochar on fruit length in both capsicum varieties. Additionally, a significant ($p < 0.05$) difference in fruit length was observed between the two genotypes (G-1 and G-2) with and without biochar application.

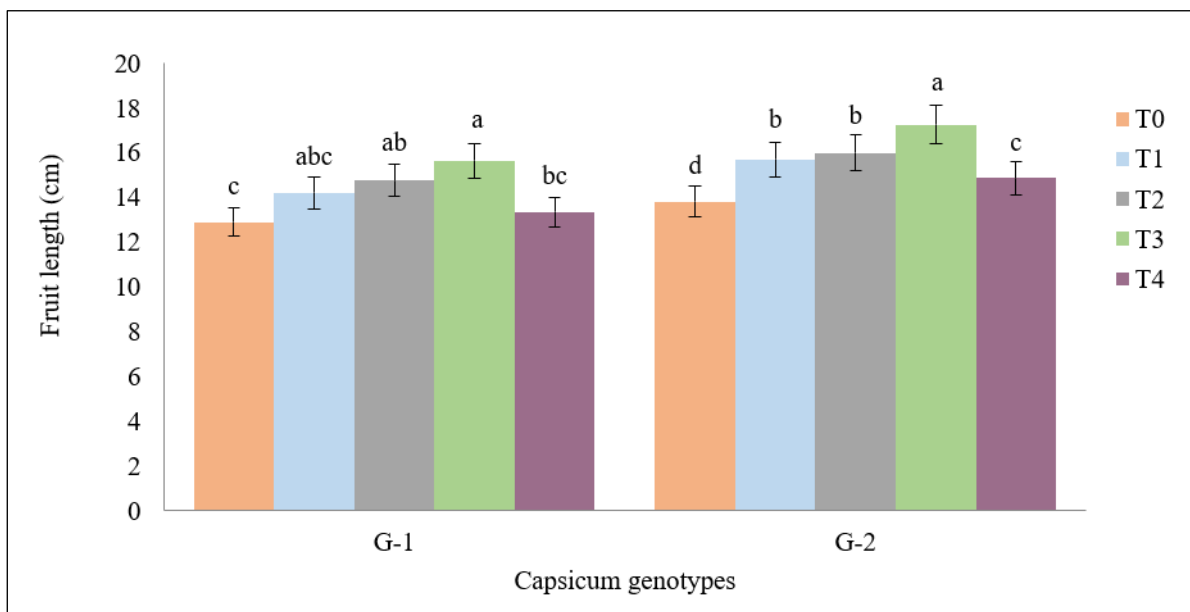


Figure 3: Effect of rice straw derived biochar on fruit length of capsicum genotypes.

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. T_0 Control (without biochar), T_1 2.5 t/ha biochar, T_2 5.0 t/ha biochar, T_3 7.5 t/ha biochar and T_4 10.0 t/ha biochar, G^{-1} BU Capsicum I and G^{-2} one capsicum line.

The fruit weight of capsicum plants was significantly ($p < 0.05$) higher in soils treated with rice straw biochar compared to untreated soils (Figure 5). Among the treatments, T2 (5.0 t/ha) resulted in the highest fruit weight for both capsicum genotypes. In BU Capsicum 1, biochar application increased fruit weight to 23.35 g, compared to 18.04 g in the control. Similarly, the Capsicum line produced significantly heavier fruits (30.45 g) in biochar-treated soils than in control soils (23.90 g). These results show that rice straw biochar increases fruit weight in both genotypes of capsicum. Although there was a notable ($p < 0.05$) variation in fruit weight between the G-1 and G-2 genotypes, the impact of biochar was the same for both. This suggests that genotype has no bearing on the effect of rice straw biochar on fruit weight.

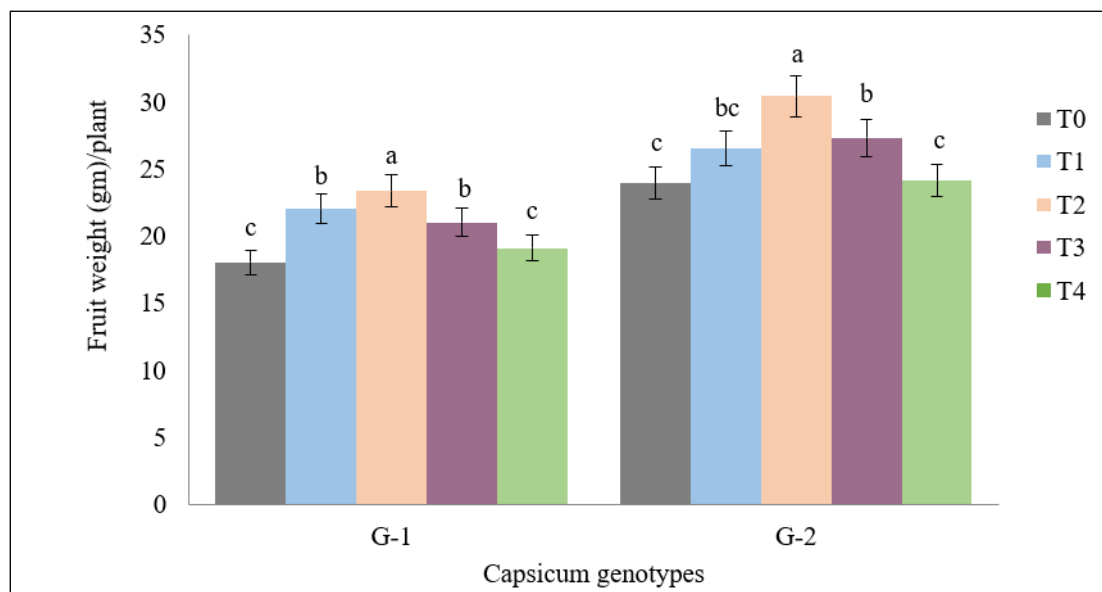


Figure 4: Effect of rice straw derived biochar on individual fruit weight per plant of capsicum genotypes.

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. T_0 Control (without biochar), T_1 2.5 t/ha biochar, T_2 5.0 t/ha biochar, T_3 7.5 t/ha biochar and T_4 10.0 t/ha biochar, G^{-1} BU Capsicum I and G^{-2} one capsicum line.

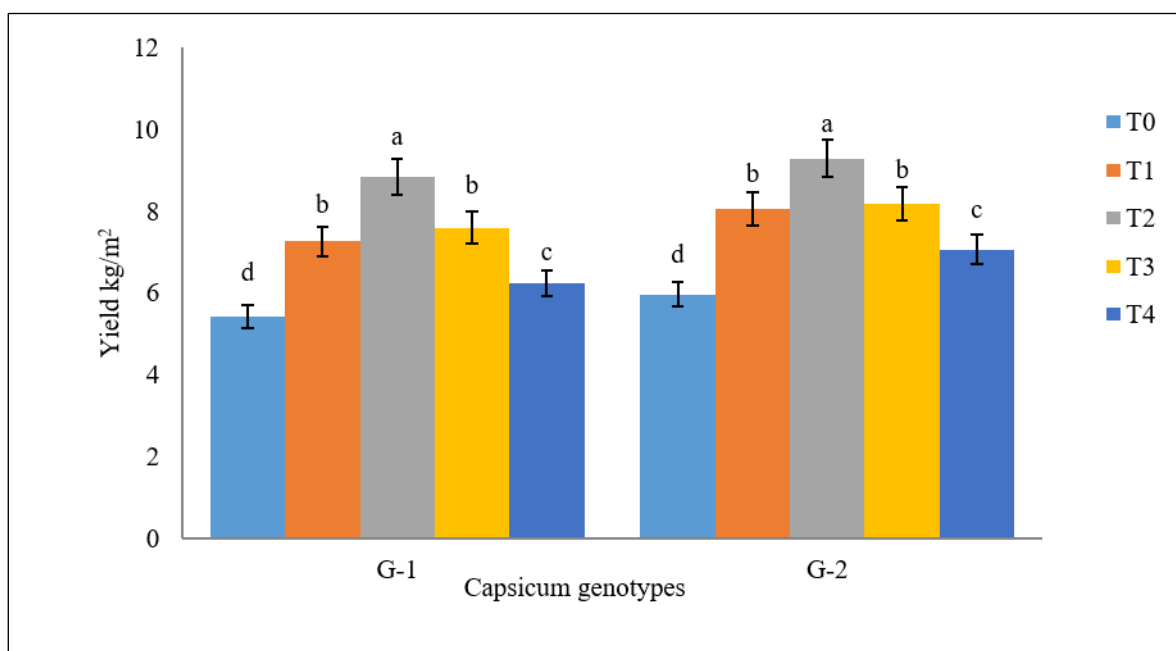


Figure 5: Effect of rice straw derived biochar on yield per meter square of capsicum genotypes.

The yield of capsicum was significantly influenced by various biochar treatment combinations (Figure 6). In comparison to untreated plots, all biochar-treated plots displayed increased yields. With 8.84 kg/m² for G-1 and 9.29 kg/m² for G-2, the T2 treatment (5.0 t/ha biochar) produced the highest yields. By comparison, the T0 treatment, which employed only chemical fertilizers and no biochar, produced the lowest yields, with G-1 and G-2 yielding 5.42 and 5.97 kg/m²,

respectively. But when charcoal treatment above 5.0 t/ha, capsicum output started to rapidly decrease. There was a significant ($p < 0.05$) difference in the total amount of capsicum produced by the two genotypes (G-1 and G-2) with and without biochar. Rice straw biochar's effect on capsicum production, however, did not appear to be genotype-dependent, as there was no evident interaction between genotypes and biochar treatments.

In a column figures having similar letter(s) do not differ significantly whereas figures with dissimilar letter(s) differ significantly. T_0 Control (without biochar), T_1 2.5 t/ha biochar, T_2 5.0 t/ha biochar, T_3 7.5 t/ha biochar and T_4 10.0 t/ha biochar, G^{-1} BU Capsicum I and G^{-2} one capsicum line.

4 DISCUSSION

4.1 Performance of soil properties

According to the study's findings, applying rice straw biochar (RSB) greatly improves a number of soil characteristics, such as pH, soil organic carbon (SOC), nitrogen (N), phosphorus (P), sulfur (S), and cation exchange capacity (CEC). Prior studies have demonstrated a beneficial relationship between biochar and increases in soil SOC and pH [43]. Biochar works particularly well to improve acidic soils since it typically has a high pH [44]. However, its benefits may diminish in soils where the pH exceeds the optimal range, possibly due to the high pH nature of the biochar. The study also identified a notable increase in soil CEC in plots treated with biochar compared to untreated controls. This enhancement can be attributed to biochar's large surface area, which becomes even more pronounced at higher pyrolysis temperatures, thereby improving CEC [45]. These results are consistent with earlier studies highlighting biochar's role in enhancing soil quality [46,47,48]. For example, Shafie et al. [46] reported that biochar application boosts SOC, soil pH, and CEC, while Lehmann et al. [47] and Liang et al. [48] observed comparable improvements in these properties in biochar-amended soils. Moreover, biochar has been shown to reduce nitrogen losses, likely due to its capacity to enhance soil CEC [49] or its ability to suppress nitrate transformations from fertilizers [50]. The observed increases in soil phosphorus and sulfur levels in this study could be attributed to the rise in soil pH caused by applying high-pH biochar. Additionally, biochar's role in promoting microbial activity may further contribute to the enrichment of these soil nutrients.

4.2 Performance on plant growth and yield contributing characters

Rice straw biochar (RSB) has a well-established positive impact on plant growth and related metrics. In comparison to untreated controls, this study showed significant improvements in plant height, fruit weight, length, and number of fruits per plant in plots treated with biochar. The enhanced soil fertility brought about by the use of biochar is responsible for these gains. Likewise, prior studies have demonstrated that biochar promotes plant development, especially in low-fertility soils [51–54]. It has been demonstrated that applying rice straw biochar improves soil fertility, which supports enhanced plant growth and yield-related characteristics. However, an intriguing observation was the decrease in the number of fruits per plant with higher biochar application rates. This decline could be explained by a reduction in nutrient availability, potentially caused by an increase in microbial populations that utilize soil nutrients for their growth. At higher application levels, biochar may form organic-nutrient complexes, further limiting the availability of certain nutrients for plant uptake. These results align with those of Pariari and Khan [55], who observed an increase in fruit length in *Capsicum annuum* when organic amendments were used alongside chemical fertilizers, compared to using chemical fertilizers alone.

4.3 Performance on capsicum yield

Experimental results indicated that capsicum yields were significantly influenced by improved soil nutrient status and enhanced soil properties resulting from biochar application. All plots treated with biochar demonstrated higher yields compared to untreated controls. Similarly, Yang et al. [56] reported that biochar application increases crop yields, while David and John [57] emphasized that biochar enhances nutrient retention, highlighting the effectiveness of integrated nutrient management over the sole use of conventional fertilizers for achieving optimal yields. However, a decline in capsicum yield was observed when biochar application exceeded 5.0 t/ha. This reduction may be due to an increase in microbial populations that utilize soil nutrients as their own source, thereby reducing nutrient availability for plants. As a result, nutrient deficiencies may occur, leading to decreased yields. These observations align with Lehmann and Rondon [54], who reported positive crop responses to biochar additions up to 55 t/ha, with growth reductions observed only at very high application rates. Similarly, Biederman and Harpole [32] noted yield declines at excessive biochar levels. Asai et al. [58] also found that rice yields were highest with 4 t/ha of biochar, while higher rates of 8 or 16 t/ha produced yields comparable to those of unamended soils. These findings are consistent with other studies [20,34] that observed limited improvements in yield and nutrient availability when biochar was used on its own. This is likely because biochar is carbon-rich but low in nutrients. Research suggests that biochar's positive effects on crop production are more evident when combined with mineral fertilizers [20,24,34,47,58]. The observed improvements in nutrient efficiency following biochar application have primarily been attributed to enhanced nutrient retention, reducing

nutrient losses; better soil properties, including increased water-holding capacity, reduced soil compaction, and a liming effect that facilitates contaminant immobilization or nutrient mobilization; and improved soil biological characteristics, such as a more conducive root environment and increased microbial activity that promotes nutrient availability.

5 CONCLUSION

This study demonstrated that applying rice straw biochar to soil significantly improved soil properties, notably increasing acidic soil pH from 5.99 to approximately neutral (6.35). It also resulted in a notable rise in soil organic carbon (0.98%), cation exchange capacity (6.13 Cmol+/kg), and microbial activity. The application of rice straw biochar enhanced capsicum production, with a treatment rate of 5 t/ha proving to be the most effective in significantly boosting capsicum growth and yield.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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The authors declare no conflicts of interest regarding this manuscript.

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