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Article

Enhancing Chili Growth and Yield: The Synergistic Effects of Biochar and Inorganic Fertilizers on Soil Properties and Nutrient Use Efficiency

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Abstract: A pot experiment was conducted during the Kharif 1 season at Hajee Mohammad Danesh Science and Technology University, Dinajpur, to explore the synergistic effects of biochar and inorganic fertilizers on the growth, yield, soil properties, and nutrient use efficiency of chili (*Capsicum annum* L.). The study was structured in a Randomized Complete Block Design (RCBD) with five treatments: T_0 = Control (no fertilizer), T_1 = 100% recommended doses of NPK, T_2 = 100% biochar (10 t ha^{-1}), T_3 = 75% biochar + 25% NPK, T_4 = 50% biochar + 50% NPK, and T5 = 25% biochar + 75% NPK, replicated four times. Results indicated that combined treatments of biochar and NPK fertilizers significantly enhanced chili growth and yield attributes compared to individual applications. Among the treatments, T_4 (50% biochar + 50% NPK) recorded the highest values for most growth parameters, including plant height (38.6 cm), root length (10.50 cm), and number of leaves (78 $plant^{-1}$), as well as yield attributes like the number of fruits per plant (119), individual fruit weight (2.1 g), and total fruit weight (249.5 g). This treatment also improved soil properties, particularly pH, organic matter content, and available phosphorus, while enhancing nutrient use efficiency having strongly positive correlation. The findings suggest that a 50:50 combination of biochar and NPK fertilizers optimizes chili production by reducing chemical fertilizers with improved soil health through the enhancement of efficient nutrient uses and crop productivity, making it a promising strategy for sustainable agriculture.

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1. Introduction

Chili (*Capsicum annuum* L.) holds a significant place as one of the most important vegetable and spice crops worldwide, belonging to the genus Capsicum within the Solanaceae family (Muthukumar and Sathya, 2017). Revered not only for its culinary versatility but also for its nutritional and medicinal properties, chili is an indispensable spice in daily diets across many cultures (Paul and Eric, 2013). The fruit of chili plants is rich in trace elements, minerals, and nutrients, contributing to various health benefits, including the presence of carotenoids lipid-soluble pigments known for their antioxidant, anti-cancer, and anti-radiation properties (Arimboor et al., 2015; Subha et al., 2017;

Fernandez-Bedmar and Alonso-Moraga, 2016). Chili is a vital crop in Bangladesh, but its production is hampered by outdated practices and limited resources, leading to lower yields. In 2022-23, chili was cultivated on 97,125 hectares, yielding 662,000 metric tons (BBS, 2023). While inorganic fertilizers are essential for crop nutrition, their overuse degrades soil and leads to heavy metal accumulation in plant tissues, reducing crop quality (Maqbool et al. 2020; Shimbo et al., 2001; Abdiani et al., 2019). Additionally, excessive fertilizer use contributes to environmental pollution and biodiversity loss (Agbede, 2010). In developing countries, such agrochemicals pose significant risks to human and livestock health (Sharma & Singhvin, 2017). In contrast, biochar a carbon-rich product derived from the pyrolysis of organic material has recently gained attention as a promising soil amendment. It has the potential to enhance soil properties and improve agricultural productivity (Lehmann and Joseph, 2009). Biochar primarily comprises stable aromatic carbon compounds that resist degradation, making it a durable soil amendment compared to conventional organic inputs (Woolf, 2008). Its application in agriculture has been shown to improve soil structure (Jien et al. 2013), soil aggregate stability and porosity (Kimetu and Lehmann, 2010, Liang et al. 2006) increase nutrient cycling, and soil water retention (Harvey et al. 2012, Joseph et al. 2010), leading to improved crop yields (Lehmann and Joseph, 2009). Additionally, biochar's highly porous structure enhances plant-available water and reduces greenhouse gas emissions, contributing to climate change mitigation (Mishra et al., 2018; Woolf et al., 2010). Research findings have demonstrated that biochar can improve soil nutrient status, enhance cation exchange capacity, increase nutrient use efficiency and nutrient retention, and reduce soil acidity (Adekiya et al. 2020, Lehmann & Rondon, 2006, Ajayi et al. 2016). Despite its potential, research on the use of biochar in horticultural crops, particularly in chili cultivation, remains limited. This study aims to fill this gap by evaluating the synergistic effects of biochar and inorganic fertilizers on the growth, yield, soil properties, and nutrient use efficiency of chili plants. The objective is to determine the optimal combination of biochar and inorganic fertilizers that maximizes both growth and yield, thereby offering a sustainable solution for enhancing chili production in Bangladesh and beyond.

2. Materials and Methods

Location and duration

The research was conducted to the Soil Science research field at Hajee Mohammad Danesh Science and Technology University, Dinajpur from February to June 2023.

Weather conditions

During the growing period of the crop, the weather conditions were recorded at the Meteorological Station of HSTU from the experimental site. Here are the details in Fig .

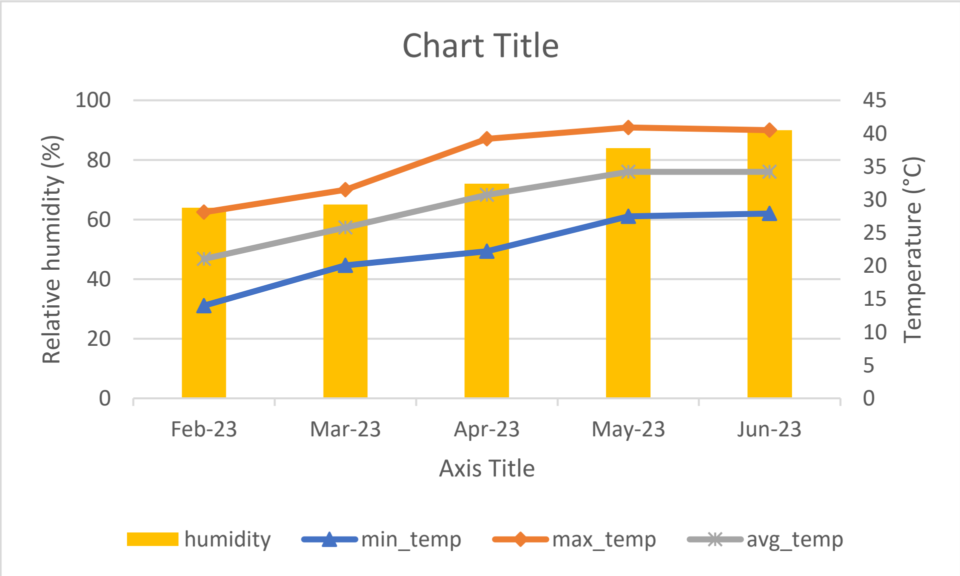

Fig. 1. Daily maximum, minimum, and average temperature and relative humidity during the experimental period.

Soil collection

The soil samples utilized in the pots were gathered from the top 15 cm layer of arable land located at the Soil Science Research Field, HSTU, in Dinajpur, Bangladesh. Weeds were removed before gathering the soil, which was then sun-dried for several days. After drying, the soil samples were ground and filtered through a 20-mesh sieve.

Soil properties

The land of the experimental plot was high, leveled, and well-drained (AEZ-1) and the soil was a non-calcareous brown floodplain. The soil was Ranisankail sandy loam series.

Table 1. Physico-chemical properties of pre-sown soil of the experimental field.
A. Physical properties of experimental field soil

Properties	Value (%)	Extraction method
Sand	60	-
Silt	27	-
Clay	11	-
Textural class	Sandy loam	Hydrometer method was employed and textural class was determined by following Marshall's Triangular coordinates as described in the USDA system

B. Chemical properties of experimental field soil

Properties	Analytical value	Critical value	Extraction methods
pH (1:1.25, Soil: H_2O)	6.67	-	Glass electrode type pH meter method. (soil-water ratio = 1:1.25)
Organic carbon	0.50		Wet oxidation method
Organic matter (%)	0.87	-	The method of wet oxidation was used and there after Van Bemmelen factor of 1.73 was employed for final calculations.
Total N (%)	0.021	0.08	By employing Micro-Kjeldahl apparatus
Available P (ppm)	24.94	10.00	Olsen method
Exchangeable K (me/100g soil)	8.00	0.12	By using Flame photometer
Available S (ppm)	12.03	10.00	Turbidity method using $BaCl_2$

Experimental treatments and design

The experiment consisted six treatments with three replications designed by complete block design (CBD). The treatment combinations were T_0 = Control (No fertilizer use), T_1 = 100% recommended doses of NPK, T_2 = 100% recommended doses of biochar, T_3 = 75% biochar + 25% NPK fertilizer, T_4 = 50% biochar + 50% NPK fertilizer, T_5 = 25% biochar + 75% NPK fertilizer. Urea, TSP, and MOP were applied at rates of 100, 60, and 80 kg ha-1, respectively, as per the Recommended Doses of Fertilizers (RDF), along with biochar at 10000 kg ha^{-1} (FRG, 2018). Total number of pots was 18 and 10 kg of soil was added per pot.

Pot preparation

The initial soil was collected from the Soil Science field of HSTU, Dinajpur. Then the soil sample was air-dried, grounded, and sieved for seven days. After that, the soil was ready to pour into the pot. For each plastic pot, 10 kg of collected soil was added. The pot width and length were 28, and 26.5 cm respectively and the weight of the pot was 500 g.

Planting materials

The study used BARI Marich-1 as the test crop, obtained from BRAC, a reputable seed and seedling producer in Basherhat, Dinajpur. At planting, the chili seedlings had an average height of 20 cm (n = 10).

Experimentation

The full doses of NPK fertilizer, biochar, and biochar-amended fertilizer were added to the respective pots 10 days before transplanting the seedlings. On 28th February 2023, thirty-day-old seedlings were carefully uprooted from the seedbed, and two seedlings were transplanted into each pot. After 10 days, one plant was carefully removed from each pot, leaving one for the experiment. Intensive care, including regular weeding and irrigation using a sprinkler can, ensured adequate growth and development. No pests or diseases were observed, so no control measures were necessary. The plants were harvested at full maturity, and their yield was meticulously recorde.

Data collection

Plant parameters

The data was recorded during the growing period and after harvesting i.e., plant height (cm), root length (cm), no. of leaves plant^{-1}, no. of flowers plant^{-1}, no. of fruits plant^{-1}, individual fruit weight (g), fruit diameter (cm), fruit length (cm) and otal fruit weight (g).

Agronomic Efficiency (AE) of fertilizers

The AE was determined by following the equation suggested by Shah et al. (2001).

AE of N = GYNA-GYN0/NR

Where,

GYNA = grain yield (kg ha^{-1}) after fertilizer addition,

GYN0 = grain yield (kg ha^{-1}) without fertilizer,

NR = rate of fertilizer addition (kg ha^{-1}).

Soil parameters:

At the Department of Soil Science, HSTU, Dinajpur, an in-depth analysis of soil samples extracted from the field both before harvesting and after transplanting was conducted. Various methods were employed to investigate the chemical characteristics of the soil, encompassing the use of the glass electrode pH meter, wet oxidation, Semi micro-Kjeldahl, Olsen, ammonium acetate extraction, $CaCl_2$ extraction, volumetric flask method, and core sampler method. These methods enabled the examination of crucial soil chemical properties, such as pH, organic matter, total nitrogen, available phosphorus, exchangeable potassium, and available sulfur. Initial and postharvest soil samples were collected before biochar application and after harvest. Initial and post-harvest soil samples were analyzed for soil's physical and chemical properties using standard methods.

Statistical analysis

The data were presented as mean values. Statistical analysis was conducted using Statistix 10 software. One-way analysis of variance (ANOVA) was performed, followed by Duncan's Multiple Range Test (DMRT) to identify significant differences among the treatments. Results were considered statistically significant at $p < 0.05$.

3. Results

Growth and yield of chili

Plant height, root length, no. of leaves plant^{-1}

The application of biochar and biochar-amended fertilizers had a significant impact on the growth parameters of chili plants, particularly plant height, root length, and leaf number (Table 2). Treatment T_1, which utilized 100% of the recommended doses of NPK, resulted in the tallest plants, reaching 39.70 cm. This was closely followed by T_4, which combined 50% biochar with 50% NPK, producing plants that were 38.6 cm tall. In contrast, the control treatment (T_0) resulted in the shortest plants, measuring only 25.02 cm. The marked increase in plant height observed in treatments involving biochar can be attributed to its role in enhancing nutrient uptake and increasing soil organic matter, which effectively reduces nitrogen leaching (Lehmann et al., 2011). These findings are consistent with previous research by Kim et al. (2013) and Khan et al. (2013, 2018), who also reported significant improvements in plant height due to biochar application.

Root length showed notable differences across treatments, with T_2 (100% biochar) producing the longest roots at 11.20 cm, while T_4 exhibited strong performance with an average root length of 10.50 cm. The shortest roots were observed in the control treatment (T_0), measuring just 5.00 cm. These results emphasize the critical role of biochar in promoting root development, especially when combined with NPK fertilizers. Biochar's impact is particularly significant, as it not only supports root elongation but also enhances overall root architecture. According to Xiang et al. (2017), biochar application is particularly beneficial for root morphological development, as it alleviates nutrient and water deficiencies in plants. The increased root length observed in this study highlights biochar's ability to significantly expand the plant rhizosphere, enabling roots to access water and nutrients that would otherwise be out of reach, as corroborated by the findings of Eissenstat (1992) and Prendergast-Miller et al. (2014).

The number of leaves per plant was significantly impacted by the different treatments. Treatment T_1 recorded the highest leaf count with 80 leaves, followed closely by T_4 with 78 leaves, whereas the control treatment (T_0) had the fewest leaves at 65. These results underscore the effectiveness of biochar in sustaining robust growth parameters, even with reduced fertilizer application. Supporting this, (Rona et al. 2014) reported that the application of compost and biochar increases the number of leaves in cayenne pepper plants. Leaves are crucial as the primary site for photosynthesis. Additionally, (Rochman 2015), noted that organic fertilizers derived from urban waste can boost the number of chili plant leaves due to their high nutrient availability, particularly of N, P, K, and their low C/N ratio. Similarly, (Dan et al. 2017) observed that the combined use of organic and inorganic fertilizers significantly affects plant height and leaf count. These findings are consistent with the studies by Rakibuzzaman et al. (2019) and Haque et al. (2019), which also reported that biochar application significantly enhances plant growth.

No. of flowers plant^{-1}, No. of fruits plant^{-1}, Individual fruit weight, Fruit diameter, Fruit length and Total fruit weight

The combined application of biochar and inorganic (NPK) fertilizers significantly enhanced the reproductive performance and yield of chili plants. Treatments T_1 (100% NPK) and T4 (50% biochar + 50% NPK) increased the number of flowers per plant, with T_4 producing 120 flowers and T_1 yielding 119, both leading to a higher fruit set of 119 and 117 fruits per plant, respectively. These treatments also improved individual fruit weight, with T_4 achieving an average of 2.1 g and T_1 at 1.9 g, outperforming the control (T_0), which had only 80 fruits and a weight of 1.4 g. The treatments notably influenced fruit dimensions, with T_1 (100% recommended doses of NPK) and T_4 (50% biochar + 50% NPK) yielding the largest fruits. T_1 produced fruits with an average diameter of 2.75 cm and a length of 6.0 cm, while T_4 resulted in fruits with a slightly larger diameter of 2.80 cm and a length of 6.5 cm. These values are considerably higher than those observed in the control group (T_0), where the average fruit diameter was 2.30 cm and the length was 4.5 cm. The observed increase in fruit size under T_1 and T_4 suggests that both biochar and NPK fertilizers play complementary roles in enhancing the physical attributes of chili fruits. Biochar's ability to improve soil structure (Ding et al., 2016; Manya`, 2012; Xu et al., 2012), increase water retention (Van et al., 2009), and enhance nutrient availability (Lehmann et al., 2011) likely contributed to the observed improvements in fruit size, while the NPK fertilizers provided essential nutrients in a readily available form, boosting plant growth and fruit development. These findings are consistent with previous research by Haque et al. (2019), Mahato et al. (2020), and Kul et al. (2022), which demonstrated the positive impact of biochar and NPK fertilizers on the growth and productivity of various crops. T_4 was particularly effective, resulting in the highest total fruit weight of 249.5 g per plant, followed by T_1 with 224.33 g, while the control recorded just 110 g. The significant increase in total fruit weight ($p < 0.05$) underscores the benefit of integrating biochar with NPK fertilizers, both in yield quantity and fruit quality. These findings align with studies by Rakibuzzaman et al. (2019), Mahato et al. (2020), and Astika et al. (2022), which reported similar improvements with combined organic and inorganic fertilization. Additionally, Wisnubroto et al. (2017) found that biochar and fertilizer interactions significantly influence dry biomass and fruit yield in red chili. Yilangai et al. (2014) also suggested that biochar improves nutrient retention and plant growth, supporting the superior performance of the T4 treatment in this study.

Table 2. Effect of biochar and inorganic fertilizers on growth and yield of chilli

Treatments	Plant height (cm)	Root length (cm)	No. of leaves plant^{-1}	No. of flowers plant^{-1}	No. of fruits plant^{-1}	Individual fruit weight (g)	Fruit diameter (cm)	Fruit length (cm)	Total fruit weight (g)
T_0	25.02 e	5.00 e	65.00 e	82.00 c	80 e	1.4 c	2.30 d	4.5 d	110.00 d
T_1	39.70 a	9.96 bc	80.00 a	119.00 a	117 a	1.9 ab	2.75 ab	6.0 ab	224.30 b
T_2	36.00 c	11.20 a	70.00 d	99.00 d	98 d	1.8 ab	2.76 ab	5.5 bc	176.40 c
T_3	35.00 d	9.29 c	74.67 c	106.00 c	104 c	1.7 bc	2.69 b	5.2 c	178.40 c
T_4	38.6 ab	10.50 ab	78.00 b	120.00 a	119 a	2.1 a	2.80 a	6.5 a	249.50 a
T_5	37.3 b	7.20 d	77.00 b	112.00 b	110 b	1.6 bc	2.60 c	5.8 b	179.20 c
CV (%)	**2.78**	**7.21**	**1.15**	**2.63**	**2.28**	**12.34**	**1.80**	**5.94**	**1.39**

Treatment combinations were T_0 = Control (No fertilizer use), T_1 = 100% recommended doses of NPK, T_2 = 100% recommended doses of biochar, T_3 = 75% biochar + 25% NPK fertilizer, T_4 = 50% biochar + 50% NPK fertilizer, T_5 = 25% biochar + 75% NPK fertilizer.

Chemical properties of the post-harvest soil of chilli

Soil pH

The application of biochar and NPK fertilizer significantly influenced the pH of post-harvest soils ($p < 0.01$) (Table 3). The highest soil pH (6.60) was recorded in treatment T_2, which received 100% of the recommended dose of biochar, highlighting biochar's substantial ability to raise soil pH. Treatments incorporating biochar (T_3, T_4, T_5) also demonstrated a positive impact on soil pH compared to the control (T_0). Among these, T_3 (75% biochar + 25% NPK) and T_4 (50% biochar + 50% NPK) achieved relatively higher pH values of 6.43 and 6.30, respectively. In contrast, the control treatment (T_0) exhibited the lowest pH (5.73), indicating that the absence of fertilizer leads to reduced soil pH. Numerous studies (Hanpattanakit et al. 2021, Nurhidayati et al. 2014) have similarly documented an increase in soil pH following biochar application, attributing this effect to the high pH of biochar, which boosts soil base saturation, reduces exchangeable aluminum levels, and neutralizes soil protons (Zhang et al. 2017). Supporting this, research by Yu et al. (2022), Murtaza et al. (2021), and Pandian et al. (2016) also confirmed that the addition of biochar to soil effectively raises soil pH.

Organic matter content

The application of biochar and NPK fertilizers had a significant impact on soil organic matter (OM) content ($p < 0.01$) (Table 3). The highest OM levels were recorded in treatments T_2, T_3, and T_4, which received 100%, 75%, and 50% biochar, respectively, with OM content values of 0.59%, 0.57%, and 0.57%. These treatments exhibited substantial increases in OM content compared to the control, with T_2, T_3, and T_4 showing increases of approximately 40.48%, 35.71%, and 35.71%, respectively. These results underscore the crucial role of biochar in enhancing soil organic matter. In contrast, the control treatment (T_0) had the lowest OM content at 0.42%, followed by T_1 (100% NPK) with 0.47%, indicating that inorganic fertilizers are less effective than biochar in boosting soil organic matter. This finding is consistent with Nigussie et al. (2012), who reported that biochar and NPK fertilizers significantly influence soil organic matter content. Similarly, El-Naggar et al. (2019) observed increases in OM content ranging from 42% to 72% in sandy soils and 32% to 48% in loam soils following biochar application.

Moreover, Adekiya et al. (2020) demonstrated that incorporating 30 Mg ha^{-1} of hardwood biochar led to increases in OM content by 77%, 18%, and 9%, compared to the unamended control and treatments with 10 Mg ha^{-1} and 20 Mg ha^{-1} of biochar over two years. Yang and Lu (2020) also found that biochars derived from rapeseed stalks and rice straw significantly increased soil organic matter content.

Total N

The treatments did not result in significant variation in total nitrogen content (Table 3). The highest total nitrogen level of 0.02% was observed in T_4 (50% biochar + 50% NPK), which was similar to T_1 (100% NPK) and T_3 (75% biochar + 25% NPK), both also at 0.02%. This indicates that a balanced combination of biochar and NPK fertilizers can enhance soil nitrogen content. In contrast, the control (T0) had the lowest nitrogen content at 0.01%. These findings are consistent with Haque et al. (2019), who reported that combining biochar with NPK fertilizers significantly affects total soil nitrogen. However, De et al. (2019) observed that biochar alone had a minimal impact on nitrogen content. Additionally, the incorporation of biochar with NPK fertilizer and manure reduced apparent ammonification and ammonium loss by temporarily adsorbing NH_4^+ onto the biochar surface (Steiner et al., 2010; Widowati et al., 2011; Awasthi et al., 2016). Biochar also contributes a small amount of nitrogen to the total nitrogen pool, as noted by Cui et al. (2017).

Available P

The available phosphorus content varied significantly among the treatments (Table 3). T_4 (50% biochar + 50% NPK) recorded the highest available P content (93.12 ppm), followed by T_1 (100% NPK) with 86.67 ppm. This suggests that biochar, particularly when combined with NPK, can substantially increase the availability of phosphorus in the soil. The control (T_0) showed the lowest available P (36.42 ppm), highlighting the importance of fertilization in enhancing phosphorus availability. This result was in agreement with Adekiya et al. (2020) who observed that the increased available phosphorus in plots treated with both biochar and NPK fertilizers is due to the high phosphorus content in the NPK fertilizer. The enhanced phosphorus levels can also be attributed to the phosphorus contributions from biochar ash, manure, and inorganic fertilizer, which collectively boost the soil's phosphorus pool (Apori & Byalebeka, 2021).

Exchangeable K

There were significant differences in exchangeable potassium (K) content in post-harvest soil, with $p < 0.01$ indicating a strong statistical significance (Table 3). Among the treatments, T_4 (50% biochar + 50% NPK) exhibited the highest exchangeable potassium content at 12.03 meq/100 g soil, suggesting that the synergistic combination of biochar and NPK notably enhances potassium availability in the soil. T_1 (100% NPK) also showed a considerable potassium content at 10.25 meq/100 g, whereas the control (T_0) had the lowest value of 6.85 meq/100 g, highlighting the substantial impact of both biochar and NPK on soil potassium levels. These findings are consistent with Haque et al. (2019), who observed that biochar and NPK fertilizer applications positively influenced exchangeable K in soil. The improvement in soil chemical properties due to biochar application is attributed to its capacity to absorb soluble organic matter and inorganic nutrients (Theis & Rillig, 2009). The increase in K content in soils treated with biochar can be explained by the presence of cation exchange sites on the biochar surface, which enhances potassium retention and availability (Jones et al. 2012; Sohi et al. 2010; Lehmann et al., 2003).

Available S

The study revealed that the available sulfur (S) content in post-harvest soil was significantly influenced by different treatments (Table 3), with the highest sulfur content observed in the T_4 treatment (50% biochar + 50% NPK) at 17.84 ppm. This suggests that combining biochar with NPK fertilizers is particularly effective in enhancing sulfur availability. The increased sulfur content in biochar-amended soils can be attributed to biochar's large surface area and numerous exchange sites, which reduce nutrient leaching and improve nutrient retention (Haque et al., 2019). Additionally, biochar may promote the activity of sulfate-reducing bacteria, further contributing to the improved sulfur levels by facilitating the conversion of sulfate into plant-accessible forms (DeLuca et al. 2019). The results align with previous findings, indicating that the integration of biochar with inorganic fertilizers can effectively enhance soil sulfur levels and improve overall soil fertility (Schulz & Glaser, 2012).

Table 3. Effect of biochar and inorganic fertilizers on soil chemical properties

Treatments	pH	OM (%)	Total N (%)	Available P (ppm)	Exchangeable K (meq/100 g soil)	Available S (ppm)
T_0	5.73 b	0.42 d	0.01	36.42 f	6.85 e	11.80 d
T_1	6.00 ab	0.47 c	0.02	86.67 b	10.25 b	16.67 b
T_2	6.60 a	0.59 a	0.01	65.75 c	7.65 d	15.00 c
T_3	6.43 ab	0.57 a	0.02	45.18 e	7.60 d	16.88 b
T_4	6.30 ab	0.57 a	0.02	93.12 a	12.03 a	17.84 a
T_5	5.86 b	0.50 b	0.02	61.24 d	10.15 c	14.45 c
CV (%)	6.70	3.04	5.25	0.73	0.46	2.66

Treatment combinations were T_0 = Control (No fertilizer use), T_1 = 100% recommended doses of NPK, T_2 = 100% recommended doses of biochar, T_3 = 75% biochar + 25% NPK fertilizer, T_4 = 50% biochar + 50% NPK fertilizer, T_5 = 25% biochar + 75% NPK fertilizer. .

Agronomic efficiency/ Nutrient use efficiency

Agronomic efficiency (AE) is crucial for assessing how well fertilizers enhance crop yield. In this study, treatment T_4 (50% biochar + 50% NPK fertilizer) achieved the highest nutrient use efficiency, with a fruit yield of 249.50 g per plant and AE values of 6.34 g pot^{-1} for urea, 11.63 g pot^{-1} for TSP, and 8.72 g pot^{-1} for MOP. This highlights the effectiveness of combining biochar with inorganic fertilizers to boost nutrient efficiency. Treatment T_3 (75% biochar + 25% NPK fertilizer) also showed significant improvements in AE over both the control group (T0) and the full NPK treatment (T_1), with AE values of 6.18 g pot^{-1} for urea, 11.33 g pot^{-1} for TSP, and 8.50 g pot^{-1} for MOP. While T_4 was the most efficient, T_3 also provided notable benefits in nutrient use efficiency. The control group (T_0), which received no fertilizers, exhibited no measurable AE. These results suggest that biochar enhances nutrient use efficiency by improving soil nitrate retention and reducing nitrate losses, consistent with the findings of Cao et al. (2019), Liu et al. (2021), and Cong et al. (2023). Additionally, biochar at higher soil concentrations not only affects nutrient availability for plant growth but also improves overall soil fertility (DeLuca et al. 2019).

Table 4. Effects of biochar and inorganic fertilizers on nutrient use efficiency/ agronomic efficiency (AE)

Treatments	FYNA (g plant^{-1})	FYNO (g plant^{-1})	NR (g pot^{-1})			AE of fertilizer (g pot^{-1})		
			Urea	TSP	MOP	Urea	TSP	MOP
T_0	110.00	110.00	0	0	0	0.00 d	0.00 d	0.00 d
T_1	222.00		44	24	32	2.55 c	4.58 c	3.50 c
T_2	176.40		0	0	0	0.00 d	0.00 d	0.00 d
T_3	178.00		11	6	8	6.18 b	11.33 b	8.50 b
T_4	249.50		22	12	16	6.34 a	11.63 a	8.72 a
T_5	179.20		33	18	24	2.10 c	3.84 c	2.88 c
						12.5	**7.66**	**8.42**

FYNA= Fruit yield with the addition of fertilizer, GYN0= Fruit yield without fertilizer, NR= rate of fertilizer addition (kg ha^{-1}).

Heatmap Correlation

The correlation heatmap illustrates strong positive relationships among various growth parameters and yield components in chili plants. Notably, plant height (PH) exhibits strong correlations with the number of leaves (NL, 0.91), number of fruits per plant (NFPP, 0.94), and total fruit weight (TFW, 0.90), indicating that taller plants tend to produce more leaves, fruits, and overall yield. Similarly, the number of leaves shows a strong correlation with the number of fruits (0.97) and total fruit weight (0.88), suggesting that plants with more foliage are more productive. Fruit characteristics, including length (FL), diameter (FD), and individual fruit weight (IFW), also positively correlate with each other and with total fruit weight, highlighting the interconnected nature of these traits in influencing overall yield. Overall, the traits generally show moderate to strong positive correlations with one another, indicating that enhancing one trait could beneficially influence others, leading to improved crop performance. These findings are consistent with the earlier studies by Islam et al. (2017a, 2021a,b, 2023), Islam et al. (2024), Sayed et al. (2024), Mahendra et al. (2020) and Wangmo. et al. (2022)

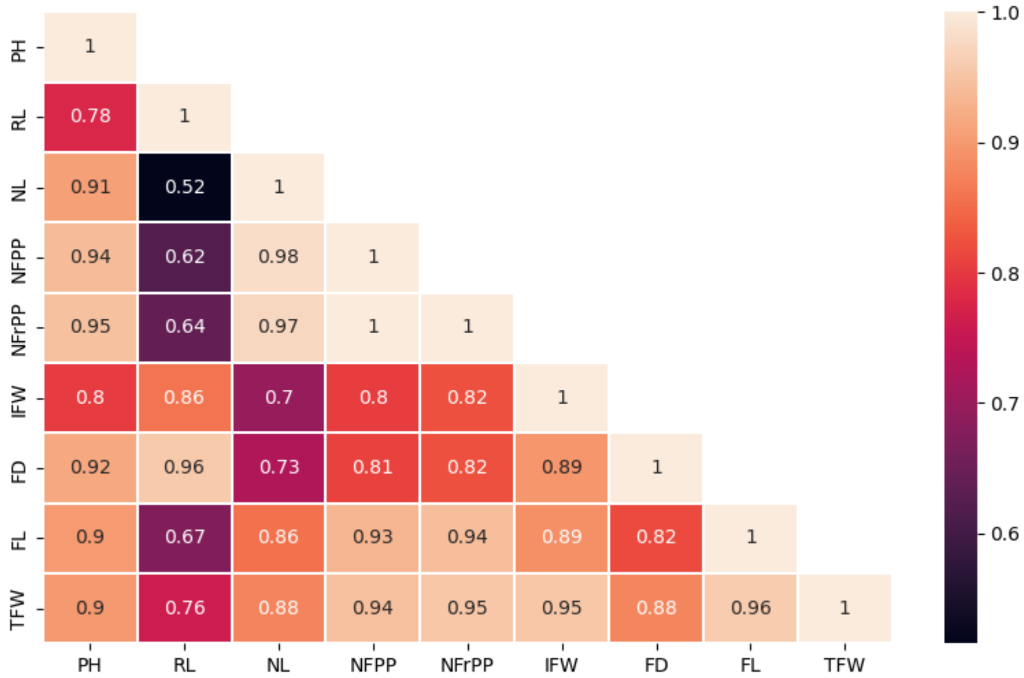

Fig: Heatmap showing the Pearson correlation coefficients between various agronomic traits. The color intensity indicates the strength of the correlation, with lighter colors representing stronger positive correlations. (PH= Plant height; RL= Root length ; NL= Number of leaf; NFPP= No. of flowers plant-1; NFrPP= No. of fruit plant-1; IFW= Individual fruit weight; TFW= Total fruit weight; FW= Fresh weight of the plant ; FD = Fruit diameter; FL = Fruit Length)

4. Conclusion

The study highlights the synergistic effects of biochar and inorganic fertilizers on chili growth, yield, and soil properties. The application of biochar, both alone and in combination with reduced doses of inorganic fertilizers, demonstrated substantial improvements in soil nutrient retention, plant growth, and overall yield. The results suggest that using 50% biochar along with 50% of the recommended doses of NPK fertilizers is an effective strategy for maximizing chili production while minimizing the environmental impact of fertilizer overuse. This approach not only maintains high crop productivity but also enhances soil health, offering a sustainable solution for chili cultivation in Bangladesh. Consequently, adopting this integrated nutrient management practice can lead to long-term agricultural sustainability and improved economic returns for farmers. Further research is recommended to explore the long-term impacts of biochar application across different soil types and climatic conditions to solidify its role in sustainable agriculture.

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