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RESEARCH ARTICLE

YIELD RESPONSE AND N USE EFFICIENCY OF ZERO-TILLED CAPSICUM TO NITROGEN VARIATIONS IN THE COASTAL SOIL OF GANGES DELTA

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ABSTRACT

Nitrogen (N) is the most vital component for the productivity and profitability of crops, particularly in N-deficient soil. The use efficiency of N mostly depends on its judicious application and availability. Thus, the experiment was conducted in the farmer's field of the southwestern coastal region during winter (2024-'25) to investigate the growth, yield response and N use efficiency (NUE) of capsicum to various N rates under zero-tillage conditions. The factorial experiment comprised two capsicum varieties (Astha and BARI Misti Morich-2) and five rates of N (0, 90, 120, 150 and 180 kg ha^{-1}). The experimental design was a factorial randomized complete block design and replicated three times. The individual effect of variety and N showed significant influence on growth, yield and profitability, yet their interaction was not significant. The growth, yield attributes, yield, total soluble solids, profitability, and NUE of Astha were substantially higher than BARI Misti Morich-2, where the yield, net income, and NUE were enhanced by 13%, 43%, and 13%, respectively. Among the N rates, application of N at180 kg ha^{-1} produced the highest yield, which was increased by 4 to 71% from 150 to 90 kg N ha^{-1} yet the yield was statistically similar with 150 kg N ha^{-1}. Total soluble solids were substantially increased with the increased rate of N, but vitamin C content initially increased from 0 to 120 kg N ha^{-1} then gradually declined with the higher N rates beyond 150 kg ha^{-1}. The net income declined by 1.09 to 7.35 times from 120 to 90 kg N ha^{-1} compared to 180 kg N ha^{-1}, yet there was no significant variation between 150 and 180 kg N ha^{-1} while in control treatment the net income was negative. The NUE was higher in the lower rates and then gradually decreased with the higher rates, where the NUE declined by 3 to 15% from the application of 120 to 180 kg N ha^{-1} compared to 90 kg N ha^{-1}. The results of this experiment suggested that the Astha variety is suitable with the application of 150 kg N ha^{-1} under zero tillage conditions in the southwestern coastal soil of Bangladesh.

KEYWORDS

Capsicum annuum, N use efficiency, Quality attributes, Profitability, Coastal soil

1. INTRODUCTION

Capsicum (*Capsicum annuum* L.) is a significant and valuable year-round vegetable crop and is cultivated in almost all country of the world, particularly in temperate countries (Greenleaf, 1986; Mahmud et al., 2017). Popularly, it is also identified as bell pepper or green pepper (Srikanth et al., 2019). It is extensively grown in Mexico and South America, yet it is native to South America (Ahmed et al., 2022). In Bangladesh, capsicum has been considered an important commercial crop in recent years due to its high value and demand, but not so much acquainted by the people and the farmers (Jahan et al., 2022; Shukla et al., 2011). Folate, vitamin C, vitamin E, and vitamin A are all abundant in capsicum (Phillips et al., 2006; Wahyuni et al., 2011). Green capsicums are abundant in vitamin C, potential antioxidant that fortifies the body's defense against illnesses, vitamin A, a lipid-soluble vitamin and significant antioxidant that helps reduce the risks to health caused by free radicals, protein, carbohydrates and unsaturated fatty acids (Lal et al., 2014). An edible quantity of one hundred grams of capsicum has 0.3 g of fat, 4.3 g of carbohydrates, 1.3 g of protein, and 24 kcal of energy (Haque et al., 2019).

The coastal region of Bangladesh is the most stress-prone area, which hinders the cropping and productivity of crops. In this region, cropping in the winter and succeeding dry season is mainly restricted due to the constraints of excessive soil wetness due to poor drainage system, soil salinity, scarcity of fresh irrigation water and sometimes uncertain pre-monsoon rainfall (Bell et al., 2019; Paul et al., 2020; Sarker et al., 2023). For crop plants, salinity is among the most important stressors (Kaymakanova, 2009). Pepper production is decreased by salinity (Navarro et al., 2002). Slow and patchy seed germination, abrupt wilting, stunted growth, marginal burn on leaves (particularly lower, older leaves), leaf yellowing, leaf fall, limited root development, and abrupt or gradual plant mortality are all signs of saline in the soil (Carpici et al., 2009; Haque et al., 2014).

Pepper needs a sufficient quantity of most major and minor nutrients. However, nitrogen and phosphorus are the nutrients that are most frequently used in pepper. The application of plant nutrients, particularly nitrogen, is essential for high-yield cultivation. Since nitrogen is one of the most mobile plant nutrients in soil, managing nitrogenous fertilizer is crucial to agriculture. The yield generated per unit of available nitrogen is known as nitrogen use efficiency (NUE), and it is an essential indicator in agriculture (Litke et al., 2019). Numerous factors, including the growing season's weather, the type, rate, and timing of nitrogenous fertilizer application, might have an impact on NUE (Haile et al., 2012). Most of the land in this SW coastal region is kept fallow after the harvest of monsoon rice. There is a scope to incorporate capsicum in the existing cropping pattern. Few researches regarding capsicum cultivation have been conducted in the farmer's field of SW coastal Bangladesh. Capsicum, as a new crop in the farmer's field of southwestern coastal Bangladesh needs to be investigated to determine which variety will perform better and

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what would be the appropriate rate of N under zero tillage conditions. Therefore, this study has been conducted with the aim of evaluating the effect of variety and N rates on growth, productivity, NUE, and profitability of capsicum under zero tillage in the southwestern coastal soil of Bangladesh.

2. Materials and Methods

2.1 Location and soil of the experimental site

The study was carried out at the farmer's field of Pankhali (22^0 38′ N, 89^0 30′ E with an elevation of ~3–4 meter above the mean sea level), Dacope, Khulna, Bangladesh, (typical coastal area) situated in the agro-ecological zone of the Ganges Tidal Floodplain (AEZ-13). The experimental period in the field was January to March 2025. The weather prevailed in the study area from March to June was hot and humid, while cool and dry during November to February.

The daily maximum and minimum temperatures throughout the growing season ranges were 17.4-39 °C and 11.5-27.1 °C, respectively, where the average lowest minimum (14.06 °C) and highest maximum (33.41 °C) temperatures was noticed in the month of January and March, respectively (Figure 1). The cumulative rainfall all over the growing season was 9 mm (Figure 1).

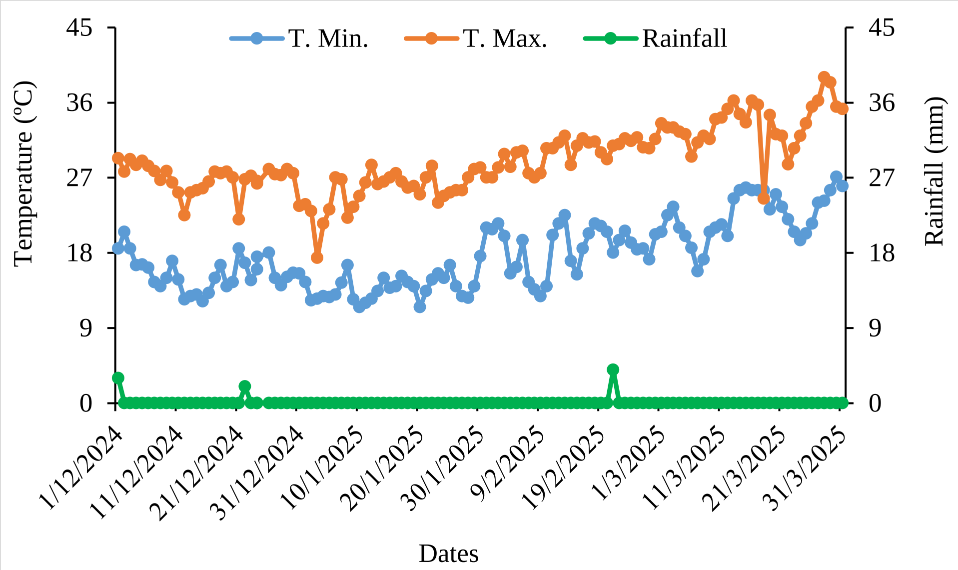

Figure 1: Temperature and rainfall patterns in the experimental area during the growing season.

2.2 Experimental design, layout and treatments

The experiment consisted of two capsicum varieties (Astha and BARI Misti Morich-2) and five levels of nitrogen (N) (0, 90, 120, 150 and 180 kg ha^{-1}), which were arranged following a factorial randomized complete block design (RCBD) and replicated three times. The unit plot size of the experiment was 10 m^2 (5.0 m length and 2.0 m wide), maintaining a spacing of 1.5 m and 1.0 m between replication to replication and plot to plot, respectively.

2.3 Seedling raising and transplant of seedlings

After harvesting the previous monsoon rice crop, the field was almost in a saturated condition and conventional tillage was totally impossible. Thus, the seedlings (28 days old) were transplanted under zero tillage conditions (just making a hole using local implements and then placing the seedlings in the hole after which the hole was covered using dry soil). The zero tillage method facilitated minimal soil disruption, consistent with conservation agriculture principles designed to improve soil health and water retention.

2.4 Fertilizer and crop management

Urea, triple super phosphate (TSP), muriate of potash (MoP) gypsum and zinc sulphate ($ZnSO_4$) were used as the source of N, P, K, S and Zn. The rate of TSP, MoP, gypsum and ZnSO4 was 350, 250, 110 and 5 kg ha^{-1}, respectively, whereas N fertilizer was applied as per the treatment. During transplanting, the prescribed amount (as per treatment) of urea, TSP, MoP, gypsum and ZnSO4 was applied in the hole around the seedling. The second and third split of urea and MoP was applied at 25 and 50 days after transplanting (DAT), respectively.

Following each split fertilizer application, light irrigation was immediately supplied. Two manual weeding was carried out at 20 and 40 DAT. Other intercultural operations like irrigation and plant protection measures were conducted as and when required and kept unique in all the plots.

2.5 Data collection and calculation

Data on growth parameters (plant height, number of leaves), phenological (first flowering and fruit formation) and yield attributes (fruit length, fruit diameter, individual fruit weight), were taken from the arbitrary selected five plants in each plot. For fresh fruit yield calculation, fruit weight from each plot was compiled and then converted to t ha^{-1}. Leaf greenness was measured using a portable leaf chlorophyll content meter (SPAD 502 plus; Konica Minolta, Japan). The total soluble solid was determined using a handy Brix Refractometer (Model: 45-03; Brand: B & S, UK). Vitamin C content use efficiency of N [agronomic N efficiency (ANE) and partial N use efficiency (PNUE)], net income and benefit-cost ratio (BCR) were measured and or calculated using the below formulae-

Vitamin C (mg 100^{-1} gm) $= e \times \frac{db}{ca} \times 100$ (Nagy et al., 2015)

Where, a= weight of capsicum, b= volume made with meta phosphoric acid, c= volume of aliquot taken for estimation, d= dye factor and e= average burette reading for sample

$$AE = \frac{\text{Yield of capsicum in N added plot (kg/ha)} - \text{Yield of capsicum in no N added plot(kg/ha)}}{\text{Amount of N applied (kg/ha)}}$$

(Sarker et al., 2025)

$$NUE = \frac{\text{Yield of capsicum in N added plot (kg/ha)}}{\text{Amount of N applied (kg/ha)}}$$ (Sarker et al., 2025)

Net income= $Gross\ income\ (Tk) - Total\ cost\ of\ production\ (Tk)$

$$BCR = \frac{\text{Gross income (Tk)}}{\text{Total cost of production (Tk)}}$$ (Sarker et al., 2023)

2.6 Statistical analysis

The collected, measured and calculated data were tabulated, compiled and analyzed following analysis of the variance technique (two-way ANOVA) using the statistical computer package 'Statistix 10'. The comparison among the means was separated by all pair-wise comparison following Tukey's HSD test at 95% confidence level. The computer program Microsoft Excel was used for regression analysis and to prepare the graphs.

3. Results

3.1 Effect of variety, N rates and their interaction on growth parameters of capsicum

Growth parameters (plant height and leaf number $plants^{-1}$) differed significantly among the varieties and nitrogen (N) rates individually, but there was no significant variation observed in their interaction (Table 1). On different days after transplanting (DAT) the highest plant height and leaf number $plant^{-1}$ were obtained from the Astha variety while, the lowest was found in BARI Misti Morich-2. In the case of N rates, the application of N at 180 kg ha^{-1} resulted the highest at different DAT, which was statistically similar to 150 kg ha^{-1} whereas, the lowest was found in no N added treatment. In their interaction, the effect of variety and N rates at different days after transplanting numerically showed the highest plant height was found in Astha with 180 kg N ha^{-1}, while the lowest was recorded from BARI Misti Morich-2 with no N added treatment. Similar results were found in leaf number.

Table 1: Effect of variety and variety, nitrogen rates and their interaction on growth parameters of capsicum grown under zero tillage in the coastal soil of southwestern Bangladesh.

Treatment		Plant height (cm)				Leaf number			
Variety	**Nitrogen rate (kg ha-1)**	**30 DAT**	**40 DAT**	**50 DAT**	**60 DAT**	**30 DAT**	**40 DAT**	**50 DAT**	**60 DAT**
Astha	No N added	17.76	18.92	22.63	26.04	9.67	10.78	15.33	16.67
	90	21.72	25.81	31.55	35.95	12.00	15.78	19.44	20.67
	120	28.05	29.75	35.98	41.20	13.78	17.78	21.89	22.00
	150	30.66	34.08	39.39	47.55	14.89	18.78	23.44	26.33
	180	31.50	36.48	41.39	49.77	16.00	19.33	24.66	27.67
BARI Misti Morich 2	No N added	13.76	18.24	23.90	29.03	8.33	12.33	14.22	11.89
	90	19.72	24.05	28.25	33.22	11.33	14.67	18.33	20.11
	120	25.71	27.75	31.54	36.97	13.00	15.67	19.33	22.22
	150	27.66	31.13	35.10	39.27	14.22	17.33	22.00	23.22
	180	29.83	32.35	36.12	39.75	14.98	18.00	23.33	24.22
Significance level									
Variety (V)		**	*	**	**	*	*	*	**
Nitrogen rate (N rate)		**	**	**	**	**	**	**	**
Variety and N rate		ns	ns	ns	ns	ns	ns	ns	ns
LSD0.05		5.71	8.51	7.97	8.93	2.52	4.10	4.88	6.22

Here, *LSD, ns, ** and *** represents least significance difference, non-significant, significant at 5% level and significance at 1% level, respectively.

Notably, the leaf chlorophyll content index and leaf area varied significantly among the varieties and nitrogen rates independently; however, no significant variation was detected from their interaction (Table 2). At different DAT, the highest leaf chlorophyll content index was achieved from Astha while the lowest was found in BARI Misti Morich-2. Similarly, Astha showed a larger leaf area throughout every observation date. Considering N rates, application of N at 180 kg ha^{-1} resulted in the highest leaf chlorophyll content index and leaf area, which was statistically similar to 150 kg ha^{-1} whereas the lowest was found in the no N added treatment. Although the interaction effect was not significant numerically the highest leaf chlorophyll content index and largest leaf area were found in Astha variety with 180 kg N ha^{-1}, while the lowest were recorded from BARI Misti Morich-2 with no N added treatment.

Table 2: Effect of variety, nitrogen rates and their interaction on leaf chlorophyll content index and leaf area of capsicum grown under zero tillage in the coastal soil of southwestern Bangladesh.

Treatment		Leaf chlorophyll content index				Leaf area (cm2)		
Variety	**Nitrogen rate (kg ha-1)**	**30 DAT**	**40 DAT**	**50 DAT**	**60 DAT**	**40 DAT**	**50 DAT**	**60 DAT**
Astha	No N added	37.27	38.21	39.64	38.88	27.95	35.86	43.30
	90	49.81	55.61	57.01	54.39	44.44	53.51	63.45
	120	52.18	58.35	58.56	56.79	48.49	64.47	68.04
	150	56.03	59.56	60.59	58.45	53.60	66.49	72.56
	180	58.87	62.04	62.81	61.82	57.63	70.31	76.14
BARI Misti Morich 2	No N added	35.98	36.48	37.87	36.93	25.98	30.49	37.35
	90	48.01	53.07	55.04	52.72	38.13	49.15	57.65
	120	50.59	56.66	57.24	55.41	42.88	57.74	62.83
	150	53.51	57.74	59.50	57.66	46.78	61.55	66.28
	180	55.52	59.81	61.86	59.96	49.63	65.26	70.56
Significance level								
Variety (V)		*	ns	ns	ns	**	**	**
Nitrogen rate (N rate)		**	**	**	**	**	**	**
Variety and N rate		ns	ns	ns	ns	ns	ns	ns
LSD0.05		7.80	9.61	8.46	7.71	7.99	12.91	11.16

Here, *LSD, ns,* * and ** represents least significance difference, non-significant, significant at 5% level and significance at 1% level, respectively.

3.2 First flowering and first fruiting

First flowering and fruiting varied significantly among the variety, nitrogen rates, and their interaction (Figure 2). In BARI Misti Morich-2, early flowering and fruiting were reported, which were significantly different from the variety Astha. In case of interaction, the longest time for flowering and fruiting was recorded in the no N added treatment for Astha and BARI Misti Morich-2, while the earliest flowering and fruiting was recorded at 180 kg N ha^{-1} for both varieties.

3.3 Yield attributes

The varieties and nitrogen rates showed substantial differences in fruit length, fruit diameter, and fresh fruit weight, but no significant variation was seen when the varieties and N rates were combined (Table 3). The highest fruit length (7.05 cm), fruit diameter (15.33 cm) and fruit weight (61.15 g) were found in Astha and in BARI Misti Morich-2. In the case of N rates, application of N at 180 kg ha^{-1} resulted in the highest fruit length, fruit diameter and fresh fruit weight, which was statistically similar to 150 kg ha^{-1} whereas the lowest was found in the control. Fruit length, fruit diameter, and fruit weight were numerically highest in Astha with 180 kg N ha^{-1} and lowest in BARI Misti Morich-2 with no N added treatment when it came to the interaction impact of variety and N rates.

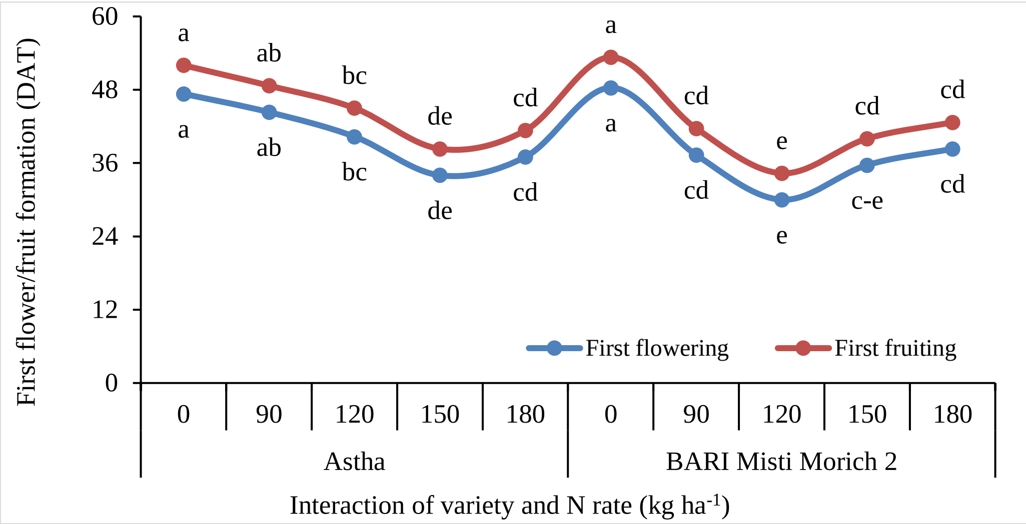

Figure 2: Effect of variety, N rates and their interaction on first flowering and first fruiting of capsicum. Here, DAT indicate days after transplanting

Table 3: Effect of variety and variety, nitrogen rates and their interaction on fruit length, fruit diameter and fruit weight of capsicum grown under zero tillage in the coastal soil of southwestern Bangladesh.

Treatment		Fruit length (cm)	Fruit diameter (cm)	Fruit weight (g)
Variety	Nitrogen rate (kg ha-1)			
Astha	No N added	4.68	8.82	40.08
	90	6.63	13.71	52.91
	120	7.48	15.97	62.11
	150	8.09	18.82	73.82
	180	8.36	19.34	76.85
BARI Misti Morich 2	No N added	4.42	8.40	36.82
	90	6.48	12.50	47.90
	120	7.06	15.20	53.64
	150	7.83	18.03	69.37
	180	7.97	18.84	71.79
Significance level		0.89	0.95	0.94
Variety (V)		**	*	*
Nitrogen rate (N rate)		**	**	**
Variety and N rate		ns	ns	ns
LSD0.05		0.77	2.72	15.76

Here, *LSD, ns,* * and ** represents least significance difference, non-significant, significant at 5% level and significance at 1% level, respectively.

3.4 Yield

Varieties and nitrogen rates separately showed substantial differences in capsicum fruit production, while the combination of varieties and N rates did not show any significant variation (Figure 3). The variety Astha produced the maximum (9.39 t ha^{-1}) yield, demonstrating better performance between the evaluated types. On the other hand, BARI Misti Morich-2 produced 8.30 t ha^{-1}. With increasing N dosages, the output increased further, peaking (11.76 t ha^{-1}) at 150 kg N ha^{-1} and reaching its highest (12.21 t ha^{-1}) yield at 180 kg N ha^{-1}. Regarding the interaction effect in the Astha variety, the control treatment produced the lowest (4.28 t ha^{-1}). At 180 kg N ha^{-1}, the maximum yield (12.94 t ha^{-1}) was noted.

3.5 Total soluble solids (TSS) and vitamin-C content

Variety improves the quality attributes of capsicum (Table 4). The highest (10.90 ºbrix) TSS value was found in the Astha variety, which was significantly higher than that of the BARI Misti Morich 2. However, the vitamin C levels of the varieties did not differ significantly (Table 4). Vitamin C levels in Astha (129.55 mg 100 g^{-1}) were numerically higher than BARI Misti Morich-2 (122.31 mg 100 g^{-1}). The total soluble solids (TSS) was raised by intermediate nitrogen levels. Quality attributes of capsicum are impacted by different N application rates under zero tillage (Table 4). The concentration of TSS varied significantly between the N treatments. The lowest (5.42 ºbrix) TSS was in no N added treatment and the highest (13.33 ºbrix) was in 180 kg N ha^{-1}. However, there were no significant differences in vitamin C concentration among the N treatments. The interaction effects were not significant for either vitamin C content or TSS.

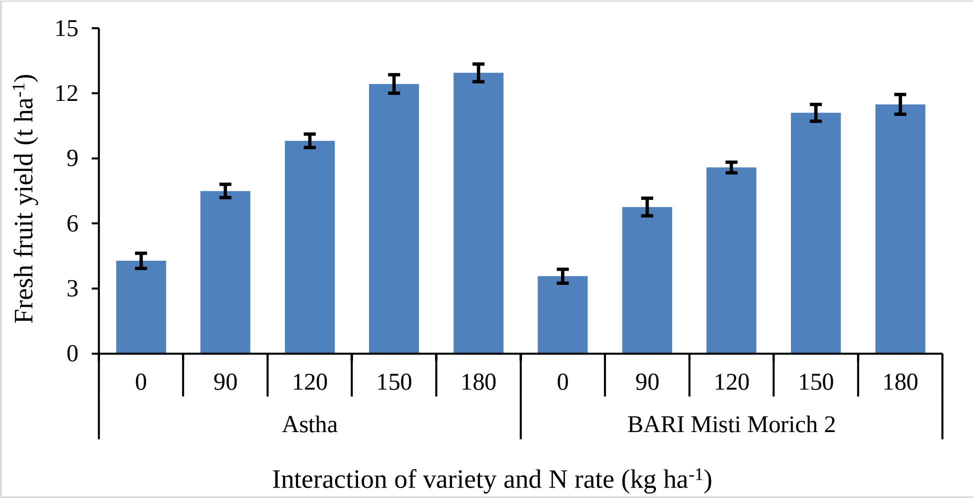

Figure 3: Effect of variety, N rates and their interaction on yield of capsicum grown under zero tillage condition in the coastal soil of southwestern Bangladesh

Table 4: Effect of variety and variety, nitrogen rates and their interaction on quality attributes of capsicum grown under zero tillage in the coastal soil of southwestern Bangladesh.

Treatment		Total Soluble Solids	Vitamin C content
Variety	**Nitrogen rate (kg ha-1)**		
Astha	No N added	5.83	124.68
	90	9.67	133.07
	120	12.00	140.37
	150	13.17	130.92
	180	13.83	118.70
BARI Misti Morich 2	No N added	5.00	111.49
	90	8.33	122.01
	120	10.17	131.57
	150	11.67	129.66
	180	12.83	116.80
Significance level			
Variety (V)		**	ns
Nitrogen rate (N rate)		**	**
Variety and N rate		ns	ns
LSD0.05		2.45	39.68

Here, *LSD, ns,* and **** represents least significance difference, non-significant and significance at 1% level, respectively.

3.6 Nitrogen use efficiency (NUE) and agronomic efficiency (AE)

NUE differed significantly across the cultivars (Figure 4). Astha reported the greatest value (79.97 kg kg^{-1}), and BARI Misti Morich-2 recorded the lowest value. In contrast, AE did not vary significantly between the varieties. Though numerically the highest (46.13 kg kg^{-1}) AE was reported in Astha, followed by BARI Misti Morich-2 (42.82 kg kg^{-1}). NUE and AE were significantly influenced by N rates (Figure 4). The highest (79.24 kg kg^{-1}) NUE was achieved with 90 kg N ha^{-1}, and the lowest was found with 180 kg N ha^{-1}. The highest AE (52.26 kg kg^{-1}) was reported with the application of N at 150 kg ha^{-1}, while the lowest was found with 90 kg N ha^{-1}. The interaction between varieties and nitrogen rates has no significant effect on either NUE or AE (Figure 4).

3.7 Net income and benefit cost ratio

Significantly, the highest net income (111414.00 BDT) and benefit cost ratio (1.42) were recorded in Astha variety, whereas the lowest net income (77756.00 BDT) and benefit cost ratio (1.30) were found in BARI

Misti Morich 2 (Figure 5). In the case of N rates, 180 kg N ha-1 substantially resulted in the highest net income (225398.00 BDT) and benefit cost ratio (1.85) which was statistically at par with 150 kg N ha-1 while the lowest (net income: -96428.00 BDT; BCR: 0.62) was obtained in no N added treatment. In the interaction effect of variety and N rates there was no significant effect was found.

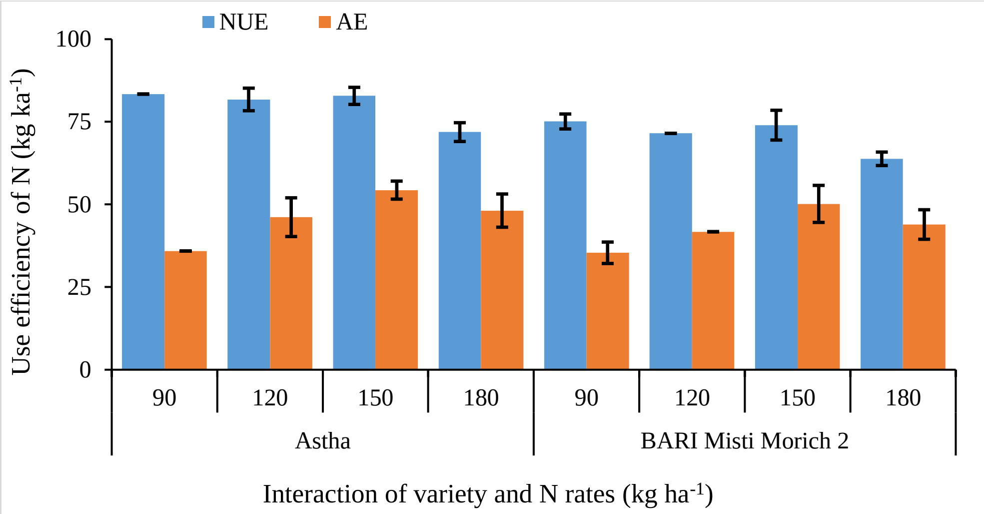

Figure 4: Effect of variety, N rates and their interaction on NUE and AE of capsicum grown under zero tillage in the coastal soil of southwestern Bangladesh.

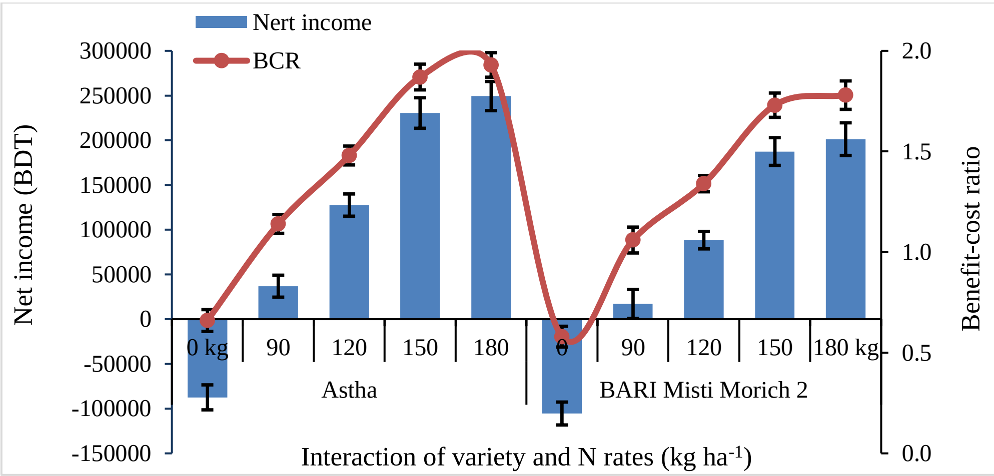

Figure 5: Effect of variety, N rates and their interaction on net income and BCR of capsicum grown under zero tillage in the coastal soil of southwestern Bangladesh

3.8 Functional relationship between yield and yield attributes

The correlation of fruit yield and individual fruit weight was found positive and significant in the growing season (Figure 6). The linear relationship between fruit yield and individual fruit weight could be clarified at 99% as per the equation of $y = 0.2289x - 4.5488$. The fruit yield of capsicum increased with the increase of individual fruit weight.

The variation of fruit yield from 3.93 to 12.21 t ha-1 due to an increase of the individual fruit weight from 38.45 to 74.32 g. The strong positive linear relationship indicates that fruit yield in capsicum is largely driven by individual fruit weight, confirming that heavier fruits contribute directly to higher productivity. Similar yield–component relationships have been widely reported in Capsicum annuum under improved nutrient management.

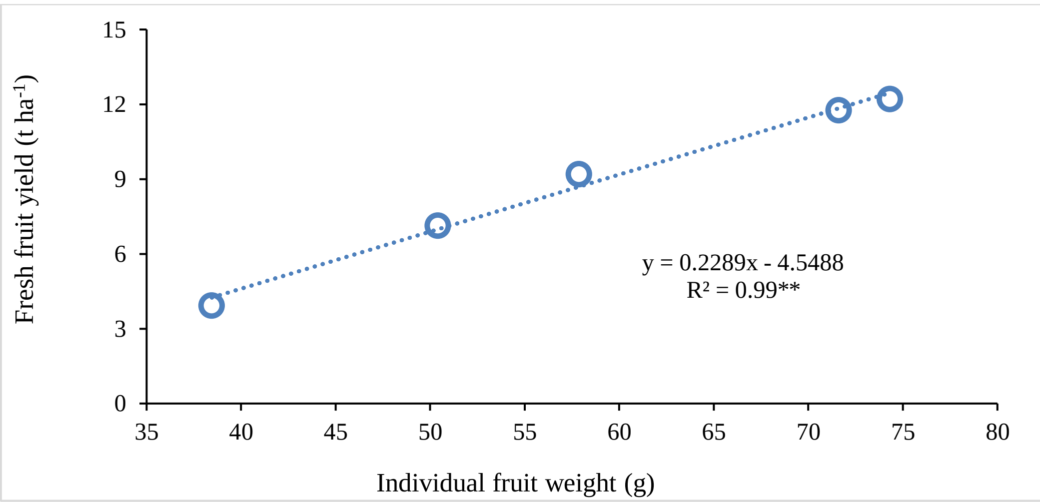

Figure 6: Functional relationship between fruit yield and individual fruit weight of capsicum

4. Discussion

4.1 Effects of N on growth parameters

Growth parameters of capsicum significantly varied with the variation of nitrogen rate where the growth rate gradually enhanced with the higher rate of N yet there was no significant variation with the 20% reduced rate of N (Table 1). The increase in plant height and leaf number with higher N is likely due to enhanced protein synthesis, which drives cell division and elongation, supporting vegetative growth (Iqbal et al., 2009; Tajul et al., 2013; Mahmud et al., 2020; Liu et al., 2019). Application of nitrogenous fertilizer positively impacted on leaf chlorophyll content index which may be attributed higher biomass accumulation and boosted the crop growth (Hokmalipour and Darbandi, 2011). N is an important element of the chlorophyll molecule that makes its synthesis easier. Increased nitrogen levels are generally associated with improvements in the leaf chlorophyll content index, which can enhance photosynthetic efficiency and overall plant growth and finally yield (Muñoz-Huerta et al., 2013). Additionally, N promotes chlorophyll synthesis, cell division, and leaf area expansion which enhances photosynthesis and plant growth and increases biomass production (Xu et al., 2012; Iqbal et al., 2006; Law-Ogbomo and Egharevba., 2009). The quick and vigorous cell division within the plant leaves results in larger leaf blades, which may be the cause of the increase in the number of leaves with higher nitrogen levels (Nadeem et al., 2009). Similarly, enhanced N level may stimulate cell division, which ultimately contributes to consistent growth in stem diameter (Mahdi et al., 2011). The significant varietal differences in growth parameters, quality attributes and yield components reveal the role of genotype (Sing et al., 2020). Among the two varieties, the enhanced growth parameters in Astha variety may be due to the genetic makeup and wider adaptability.

4.2 Effects of N on yield attributes and yield

In the current research, the yield attributes improved with the enhanced rate of N yet statistically similar results was noticed in both 150 and 180 kg N ha^{-1} (Table 3). Sufficient N supply encourages canopy growth, increased assimilate production for fruit set, and higher leaf greenness (SPAD). Boosting N at the ideal rate increased pepper yield and plant vigor, which is consistent with the known benefits of N for fruit formation and vegetative growth (Nahida et al., 2024). However, yield gains plateaued after reaching the optimum. In coastal Bangladesh, adding N at a rate higher than advised did not further boost bell pepper yield (Nahida et al., 2024). At the expense of reproductive development, excess N frequently results in luxuriant vegetative growth. In fact, increased foliage, fruit diseases (such as blossom-end rot), and decreased fruit-set have all been associated with heavy N application in pepper (Bar-Tal et al., 2001; Stefanelli et al., 2010). This imbalance was reflected in the tendency for greater N to postpone flowering and the first harvest. The observed patterns mirror physiological mechanisms, while moderate N ensures sufficient assimilates for fruiting, whereas oversupply leads to unbalanced growth and inhibited fruit formation (Bar-Tal et al., 2001; Stefanelli et al., 2010). Higher fruit length, diameter and weight in Astha indicate varietal superiority, while increased yield attributes with higher nitrogen rates reflect the role of N in enhancing photosynthesis and assimilating translocation to fruits (Grasso et al., 2022). Higher application rates of N enhance the availability of nitrogen, which explains the variations in yield across nitrogen levels (Aslam et al., 2011; Shehzad et al., 2012; Ayub et al., 2013). In comparison to other N treatments, the 180 kg N ha^{-1} treatment produced the best biomass production, and the biomass yield in the N treatments increases significantly with greater N application (Johnston, 2000; Mahmud et al., 2003; Nasiri et al., 2010; Haque et al., 2016).

4.3 Effects of N on quality attributes

The optimal N application optimizes fruit quality (Zhang et al., 2019). In the present study, at 180 kg N ha^{-1}, total soluble solids (TSS) increased by 137% compared to the control treatment in the Astha variety and by 157% for Bari Misti Morich- 2 (Table 4). The beneficial impact of nitrogen on fruit quality is supported by its function in promoting cell division and protein synthesis (Ahmed et al., 2015; Meena et al., 2016). This improvement is attributed to nitrogen's role in promoting cell division, protein synthesis, and photosynthetic efficiency, which increases assimilate production for conversion into sugars and other soluble compounds (Grasso et al., 2022; Taiz et al., 2015; Stefanelli et al., 2010). Fruit biochemical composition, including soluble sugars and soluble solids, also improved by balanced nitrogen nutrition (Rubatzky and Yamaguchi, 2012). However, because of dilution effects and increased vegetative growth that modifies the carbon–nitrogen balance within the plant, excessive nitrogen fertilizer tends to lower the content of vitamin C in fruits (Lee and Kader, 2000). When compared to the control, vitamin C in the Astha variety rose by 7–13% at moderate nitrogen levels (90–120 kg N ha^{-1}), but it slightly decreased at higher nitrogen levels. BARI Misti Morich-2 showed a similar pattern, with vitamin C rising by 9–18% at moderate nitrogen levels but falling at the highest nitrogen level (Table 4).

4.4 Effects of N on the use efficiency of N

NUE, which measures how well crops use available nitrogen for growth and production, is generally defined as the yield or biomass generated per unit of nitrogen provided or absorbed by the plant (Xu et al., 2012). In the current investigation, NUE in both capsicum types exhibited a decreasing tendency as nitrogen treatment rates increased (Figure 4). When compared to the no nitrogen condition, nitrogen fertilization greatly improved yield and growth characteristics. However, as nitrogen input increased, NUE declined. For example, the Astha variety showed a 13.8% decrease in NUE at the highest nitrogen level, with NUE falling from 83.39% at 90 kg N ha^{-1} to 71.89% at 180 kg N ha^{-1}. A similar pattern was seen in BARI Misti Morich-2, suggesting that plants used applied nitrogen less efficiently when nitrogen availability exceeded. This study's decreasing trend of NUE with rising nitrogen rates is in line with other research on horticultural crops like capsicum. According to a study, raising nitrogen rates considerably increased capsicum output, but at the same time decreased nitrogen use efficiency because yield increases were proportionally less than nitrogen application increases (Timilsina and Khanal, 2024). Similarly, a group researcher found that while vegetative growth increased, excessive nitrogen fertilization decreased nutrient utilization efficiency in pepper production (Zhang et al., 2019). Plants can more efficiently use applied nitrogen for growth and fruit production when there is an adequate supply of nitrogen because it fosters leaf development and photosynthetic capacity (Guo et al., 2024; Anas et al., 2020).

4.5 Effects of N on the cost of production and profitability

Nitrogen application substantially improved the economic performance of capsicum compared with the control treatment. In the present study, both varieties showed negative net income and a benefit–cost ratio (BCR) below 1.0 in the absence of nitrogen, indicating that production without N fertilization was not economically viable under coastal soil conditions (Figure 5). For Astha, net income increased by 359.3% and 383.9% at 150, and 180 kg N ha^{-1}, respectively, compared with the control. Similarly, BCR increased by 72.7%, 124.2%, 175.8%, and 192.4% at the respective nitrogen levels. For BARI Misti Morich 2, net income increased by 277.8%, and 291.1% at 150, and 180 kg N ha^{-1}, respectively, compared with the control, while BCR increased by 79.7%, 127.1%, 193.2%, and 201.7%. Increased yield results in larger gross returns and better farmer profitability. However, excessive nitrogen application may lower economic efficiency since fertilizer costs rise with increasing nitrogen inputs, even though higher nitrogen rates boosted production and financial returns. Therefore, striking the ideal balance between fertilizer expense and yield gain is necessary for nitrogen fertilization to be economically beneficial (Zhang et al., 2010; Liang et al., 2023). The necessity of a sufficient supply of nitrogen for productive capsicum production is further highlighted by the negative economic return seen in the no-nitrogen treatment. The results of this study indicate that moderate nitrogen treatment levels can balance fertilizer costs and yield improvement, increasing profitability and guaranteeing sustainable capsicum production in coastal soil conditions.

5. Conclusion

Growth, yield attributes, yield, and fruit quality of capsicum were all highly impacted by variety and N rate, and all the data gathered increased dramatically with increasing N levels, while the no N added treatment showed a sharp decline. Irrespective of variety, the performance of Astha was relatively better compared to BARI Misti Morich-2. From the findings of this study, Astha variety is suitable with the N rate of 150 kg ha^{-1} under zero tillage condition in the coastal soil of southwestern Bangladesh.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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