Research Article

Effect of Bioslurry-Based Integrated Nutrient Management on Yield and Quality of Tomato, Carrot, and Spinach

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Abstract | A field experiment was carried out from November 2018 to July 2019 at the horticulture field of Bangladesh Agricultural University (BAU) and the Bangladesh Livestock Research Institute (BLRI) to evaluate the integrated effects of bio-slurry and inorganic fertilizers on the growth, yield, and nutrient content of tomato, carrot, and spinach. The trial followed a randomized complete block design with six treatments: T_1 (100% chemical fertilizer), T_2 (75% chemical fertilizer + 25% bio-slurry), T_3 (50% chemical fertilizer + 50% bio-slurry), T_4 (25% chemical fertilizer + 75% bio-slurry), T_5 (100% bio-slurry), and T_6 (control). Results revealed that crop responses were stronger in BLRI soil, which had lower organic matter compared to BAU. Among the treatments, T_4 (25% chemical + 75% bio-slurry) consistently produced superior growth parameters, higher yields, and improved nutrient uptake across all three crops. Tomato exhibited higher fruit yield, carrot showed greater root length, diameter, and marketable yield, while spinach recorded significant increases in leaf number, size, and biomass. Integrated treatments also enhanced nitrogen, phosphorus, potassium, and sulphur uptake compared to sole applications. Overall, the study demonstrated that integrating bio-slurry with reduced chemical fertilizers significantly improved productivity and nutritional quality while reducing reliance on synthetic inputs. This indicates that bio-slurry-based integrated nutrient management is a sustainable and efficient approach for enhancing vegetable production and soil fertility in Bangladesh and similar agro-ecological regions.

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Introduction

In Bangladesh, a densely populated country with approximately 169.783 million inhabitants (BBS, 2023), agricultural productivity faces challenges exacerbated by land scarcity. In response to food scarcity concerns and to bolster vegetable output, the advent of the green revolution ushered in the widespread use of various inorganic fertilizers. However, this intensified agricultural activity has led to a phenomenon known as nutrient mining, characterized by the extraction of nutrients from the soil at an alarming rate, with cropping intensity soaring by 191% (BBS, 2023). Contributing factors include the adoption of high-yielding crop varieties, nutrient leaching, gaseous losses, soil erosion, and the imbalanced application of fertilizers, often without the addition of organic manure over time. The consequential nutrient depletion in the soil has manifested in deficiencies of essential elements such as nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Zn), and boron (B) over time (Islam, 2008; Jahiruddin and Satter, 2010). Alarmingly, nearly 45% of Bangladesh's cultivable land contains less than 1% organic matter (FRG, 2012), underscoring the urgent need for sustainable agricultural practices. The integration of organic manures with inorganic fertilizers to meet the nutritional demands of crops has emerged as an imperative practice to safeguard soil fertility while ensuring the sustainable cultivation of vegetable crops (Premsekhar and Rajashree, 2009; Heitkamp *et al*., 2011). Organic farming practices have gained momentum, driven by the imperative to mitigate and eliminate the harmful effects of synthetic chemicals and pesticides on the environment and human health.

In recent years, integrated nutrient management systems have gained traction in vegetable crop cultivation, commonly incorporating organic manure or bio-slurry. This approach reduces reliance on inorganic fertilizers while enhancing crop productivity. Notably, the global and local agricultural landscapes increasingly recognize the indispensable role of organic manure, as it not only reduces production costs but also contributes to long-term soil health. In conclusion, the adoption of integrated nutrient management practices, particularly the combination of organic manures with inorganic fertilizers, holds promise for sustaining agricultural productivity in Bangladesh and beyond. Embracing organic farming principles and prioritizing soil health are imperative steps toward achieving food security and environmental sustainability in the face of mounting agricultural challenges. In Bangladesh, carrot cultivation encompassed an area of 2625.88 ha during the 2022–2023 period, yielding a total production of 35270.61 metric tons (Mton) (BBS, 2023). Carrots (*Daucus carota* L.) are esteemed as a popular short-term root vegetable among Bangladeshi farmers. Tomatoes (*Solanum lycopersicum*) rank among the foremost vegetable crops cultivated globally, second only to potatoes and sweet potatoes in terms of cultivated area, yet leading in processing crops (FAO, 2010). In Bangladesh, tomato cultivation recorded a production of 469204.49 Mton, covering an area of 31138.40 ha (BBS, 2023). Spinach (*Spinacia oleracea*), a nutrient-rich green vegetable, is also prominently cultivated in Bangladesh. During the 2022–2023 growing season, spinach production reached an average yield of 63367.77 Mton, cultivated across 9934.29 ha (BBS, 2023). These statistics underscore the significance of carrot, tomato, and spinach cultivation in Bangladesh's agricultural landscape, highlighting their substantial contributions to food security and nutritional diversity within the country. The utilization of organic manure, specifically bio-slurry, emerges as an imperative strategy to sustain the production of carrot, tomato, and spinach crops. Bio-slurry, a byproduct of biogas plants, holds significant potential as a nutrient source for crop cultivation (Yu *et al*., 2010; Abubaker, 2012). It is derived from the anaerobic decomposition of various organic materials, primarily cow dung and poultry manure, within biogas digesters. During this fermentation process, approximately 25-30% of the organic matter is converted into biogas, leaving the remainder accessible as bio-slurry. While bio-slurry serves as a viable source of manure, it is insufficient to meet the nutritional requirements of crops solely through organic sources. Due to the gradual release of plant nutrients from organic matter, the capacity of organic sources to enhance agricultural yield is inherently limited. Studies indicate that only a fraction, ranging from One-fifth to one-half of the nutrients provided by manure are good, with the remainder being lost or immobilized over time (Miah, 1994). While this may suffice for soil fertility maintenance, it presents a notable constraint to maximizing plant nutrient uptake. To address this challenge, the integration of organic manures with synthetic fertilizers, known as integrated nutrient management, proves advantageous in carrot, tomato, and spinach agriculture. Integrated nutrient management has gained prominence in vegetable production as it optimizes nutrient utilization efficiency and promotes sustainable soil fertility practices. The ongoing experiment aims to ascertain the optimal admixture of organic and inorganic fertilizers to achieve the desired results in carrot, tomato, and spinach crops. Conducted in both the Bangladesh Agricultural University (BAU) horticulture field in Mymensingh and the Bangladesh Livestock Research Institute (BLRI) field in Savar, this study seeks to inform effective nutrient management strategies tailored to the specific needs and conditions of vegetable cultivation in Bangladesh.

Materials and Methods

Experimental site and soil characteristics

The experiment was carried out simultaneously at two distinct locations: the Horticulture Farm of Bangladesh Agricultural University (BAU) and the field of the Bangladesh Livestock Research Institute (BLRI), situated in Savar. Spanning from November 2018 to July 2019, the study aimed to explore the impacts of integrated nutrient management on the growth, yield, and quality of various winter vegetables, including root vegetables (carrot), fruit vegetables (tomato), and leafy vegetables (spinach). The geographical coordinates of the BAU experimental site are approximately 26°46'N latitude and 90° 24'E longitude, while BLRI is positioned at approximately 23.8820° N latitude and 90.2808° E longitude. Both locations share a comparable elevation, hovering around 18 m above sea level. The experimental sites are situated within a subtropical climate zone, characterized by distinctive climatic patterns. During the Rabi season (October to March), the climate is characterized by scant rainfall, low humidity, low air temperatures, and shorter daylight periods. Conversely, the Kharif season (April to September) experiences heavy rainfall, elevated humidity, higher temperatures, and relatively longer daylight periods. The BAU trial site is located on a medium highland within Agro-Ecological Zone 9 of the Old Brahmaputra Floodplain, featuring a non-calcareous dark gray floodplain (FAO and UNDP, 1988). These soil characteristics play a crucial role in shaping the agronomic practices and productivity potential of the experimental regions (Table 1).

Table 1: *Soil characteristics of BAU and BLRI*

Character-istics	BAU (Akter *et al.* 2018)	BLRI (Sultana *et al.* 2017)	Bio-slurry
Total N	0.91 g/kg	2.1 g/kg	21.6 g/kg
Available P	3.30 mg/kg	21.56 mg/kg	4.4 g/kg
Available K	0.17 mg/kg	103.25 mg/kg	0.25 mg/kg
Available S	6.46 mg/kg	94.73 mg/kg	4.9 g/kg
pH	6.4	7.44	-
OM	15.5 g/kg	32.5 g/kg	-

Treatment details and fertilizer application

The research employed a Randomized Complete Block Design (RCBD) with three replications to ensure statistical robustness and minimize variability. Within this experimental framework, each of the three winter vegetables—tomato, carrot, and spinach—underwent six distinct treatments at both the Bangladesh Agricultural University (BAU) and the Bangladesh Livestock Research Institute (BLRI) in Bangladesh. These treatments involved the application of chemical fertilizer, bioslurry as organic fertilizer, or various combinations thereof. The six treatments administered for each vegetable encompassed different fertilizer regimes, including sole application of chemical fertilizer, sole application of bio-slurry, and various combinations of the two. This comprehensive approach aimed to assess the individual and combined effects of chemical fertilizer and bio-slurry on the growth, yield, and quality attributes of tomato, carrot, and spinach crops across both experimental sites.

Table 2: *Recommended dose inorganic fertilizer and bio-slurry applied on different crops (FRG, 2018)*

Fertilizer		Amount (kg/ha)		
		Carrot	Tomato	Spinach
Inorganic fertilizer	Urea	90 -170	100 -195	40 -70
	TSP	30 - 50	30 - 50	15 - 25
	MoP	50-100	45-85	35-65
	Gypsum	50-85	30-55	30-55
Bio-slurry	Bio-slurry	10 t/ha	10 t/ha	10 t/ha

T_1 = 100% chemical fertilizer
T_2 = 75% chemical fertilizer + 25% bio-slurry
T_3 = 50% chemical fertilizer + 50% bio-slurry
T_4 = 25% % chemical fertilizer + 75% bio-slurry
T_5 = 100% bio-slurry
T_6 = Control

Fertilizers were applied by the Fertilizer Recommendation Guide (FRG, 2012) as shown in Table 2. Urea (181.88 kg ha^{-1}), triple superphosphate (TSP) (98.13 kg ha^{-1}), muriate of potash (MoP) (84.89 kg ha^{-1}), and gypsum (70.13 kg ha^{-1}) were used as N, P, K, and S sources, respectively, while 8.4 t ha^{-1} of bio-slurry was applied as organic fertilizer. During final land preparation, the full amount of P, K, S, and BS were administered as per treatments. One-third N was applied during final land preparation for carrot, one-half N for Tomato, and one-half N and K for spinach, while the remaining N was provided in equal splits for radish at 15 and 30 days after sowing (DAS), Tomato at 10 and 25 DAS, and spinach at 10 and 25 DAP (days after planting).

Planting/sowing and harvesting

The experiment included carrot (root), tomato (fruit), and spinach (leafy) vegetables—utilizing the Randomized Complete Block Design (RCBD). The experimental plots remained consistent throughout the trial period and were standardized to a unit plot size of 2 m by 1.8 m. During the Rabi season of 2018, carrot seeds were sown with a spacing of 100 mm x 100 mm, while seeds for tomatoes and spinach were sown with a spacing of 400 mm × 300 mm. These seeding patterns were meticulously adhered to across all experimental plots to ensure uniformity and facilitate accurate data collection. Throughout the trial, the experimental plots underwent regular maintenance activities, including weeding, mulching, watering, and pest control, as necessitated by crop growth and environmental conditions. Specialized intercultural operations such as earthing up for carrots and staking for tomatoes were conducted as required to optimize crop development and yield potential. Harvesting was conducted at the appropriate stages of crop maturity, varying according to the specific requirements of each vegetable type. This systematic approach to cultivation and management practices ensured consistency and reliability in the experimental results obtained for carrot, tomato, and spinach crops.

Data collection

Plant growth and yield data of vegetables

Plant height data at 30, 45, and 60 days after transplanting (DAT) were measured in mm for each of the vegetables. Additionally, different growth and yield parameters were recorded, which were converted into tons per ha.

Nutritional analysis of tomato, carrot, and spinach

The mineral content analysis of the vegetable plant samples involved the determination of N, P, K, and S using specific chemical methods. The protocols for each mineral analysis are outlined below:

N Content analysis:

N content was determined following the Kjeldahl method, as described by Bremner and Mulvaney (1982).In this method, plant samples were digested using a di-acid mixture composed of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a ratio of 2:1, according to the procedure outlined by Singh *et al.* (1999). Approximately 2 g of finely ground plant samples were digested with the di-acid mixture to obtain a solution for subsequent mineral content analysis.

P Content analysis:

The P content of the digest solution was determined by developing a phosphomolybdate blue complex with stannous chloride ($SnCl_2$. $2H_2O$). The absorbance of the resulting color complex was measured using a spectrophotometer (Model- T60, PG Instruments, UK) at a wavelength of 660 nm, as per the method outlined by Olsen and Sommers (1982).

K Content analysis:

The K content in the digest solution was determined using a flame emission spectrophotometer. The intensity of light emitted by K at a wavelength of 768 nm was measured, and the K concentration was calculated against known standards (Knudsen *et al.*, 1982).

S Content analysis:

The S content in the digested sample was estimated using a turbidity method. This involved the addition of 1 ml of acid seed solution to 0.5 g of barium chloride ($BaCl_2$), followed by measurement of turbidity at a wavelength of 420 nm using a spectrophotometer, according to the protocol outlined by (Anonymous, 1980).

These analytical methods enabled the accurate estimation of N, P, K, and S content in the vegetable plant samples, providing valuable insights into their nutritional composition and aiding in the evaluation of plant health and productivity

Data analysis:

Statistical analyses of the collected data were performed using Minitab 17 Statistical Software (Minitab Inc., 2000). An analysis of variance (ANOVA) was conducted using the General Linear Model technique, followed by mean comparisons using Duncan's Multiple Range Test (DMRT) at a significance level of $p < 0.05$.

Results and Discussion

Plant growth of tomato

Tomato plant growth responded differently to fertilizer treatments across the two experimental sites. At BAU, no significant differences in plant height were observed at 30 days after planting (DAP). However, at 60 DAP, significant differences emerged, with treatment T_4 producing the tallest plants (459.3 mm), while the control (T_6) produced the shortest (379.3 mm). Differences diminished after 90 DAP when plants entered the senescent stage. At BLRI, significant differences were evident at all growth stages (30, 60, and 90 DAP). Consistently, treatment T_4 produced the tallest plants (378.3, 592.0, and 865.7 mm at 30, 60, and 90 DAP, respectively), whereas the control (T_6) recorded the shortest plants (258.3, 397.0, and 560.3 mm). Overall, tomato growth was enhanced by fertilizer application, with treatment T_4 performing best at both sites (Table 3).Our findings confirm that fertilizer application significantly enhances tomato growth, with the tallest plants recorded under inorganic fertilizer (T_4) and the shortest in the unfertilized control. Similar results were reported by Kochakinezhad *et al.* (2012) and Tonfack *et al.* (2009), who showed that mineral and organic fertilizers improved plant height, fruit yield, and other growth traits compared to controls. Integrated fertilization, combining organic and inorganic sources, has been shown to maximize yield traits while improving fruit quality and soil fertility (Bilalis *et al*., 2018; Hashimi and Habibi, 2021; Wu *et al*., 2022). Recent meta-analyses (Yang *et al*., 2023; Fan *et al*., 2023) further confirm that such combinations enhance plant height, biomass, and nutrient efficiency. Overall, our results highlight that integrated nutrient management optimizes tomato growth while supporting long-term soil health and sustainability.

Yield Contributing Characters and Yield of Tomato

The effects of bio-slurry based integrated nutrient management (BS-INM) on tomato growth and yield-contributing characters were assessed at two locations: Bangladesh Agricultural University (BAU) and Bangladesh Livestock Research Institute (BLRI). At BAU, the number of flowers per cluster did not differ significantly among treatments T_1 to T_6, indicating that flower initiation at this site was not strongly influenced by the type or proportion of chemical and organic fertilizers applied (Table 4). In contrast, at BLRI, significant differences in the number of flowers per cluster were observed ($p < 0.05$). Treatments T_1 to T_5 produced statistically similar numbers of flowers per cluster, while the control plot (T_6) consistently recorded the lowest value (24.33 flowers per cluster), highlighting the critical role of nutrient management in enhancing flower production under field conditions at BLRI. Regarding flower and fruit clusters per plant, treatment T_4 (25% chemical fertilizer + 75% bio-slurry) consistently produced the highest number of flower clusters (11.60 at BAU; 8.50 at BLRI) and fruit clusters (11.60 at BAU; 8.50 at BLRI), whereas the control plot (T_6) produced the lowest number (3.73 at BAU; 4.70 at BLRI). These results indicate that increasing the proportion of bio-slurry in the nutrient management regime positively influences reproductive development, likely through improved nutrient availability and soil fertility. Comparable observations have been reported by Islam *et al.* (2017) and Ferdous *et al.* (2018), who noted that integrated application of organic and inorganic fertilizers significantly enhanced tomato truss and fruit numbers per plant. Fruit morphological traits also responded differently to the treatments. At BAU, the highest fruit length was observed in T_3 (57.3 mm), while T_2 recorded the maximum fruit diameter (47.8 mm). Conversely, the control (T_6) produced the lowest fruit length (52.1 mm) and diameter (41.5 mm). At BLRI, treatment T_4 exhibited superior fruit length (65.8 mm) and diameter (79.0 mm), with T_6 again recording the minimum. These results suggest that nutrient-rich conditions provided by BS-INM promote cell division and elongation, resulting in larger fruits. Similar effects of integrated nutrient management on fruit size and weight have been documented (Tonfack *et al*., 2009; Wu *et al*., 2022; Hashimi and Habibi, 2021). The number of fruits per plant varied significantly at BLRI, with T_4 producing the highest fruit number (41.90 fruits per plant), followed by T_3 (31.43 fruits per plant). Treatments T_1, T_2, and T_5 were statistically similar, while T_6 had the lowest number (8.47 fruits per plant). At BAU, fruit number did not differ significantly among treatments, suggesting that factors such as microclimate or soil fertility may modulate the expression of yield traits more strongly at BLRI. Fruit weight was highest in T_4 at both sites (75.90 g) and lowest in T_6 (45.83 g). The percentage of dry matter in fruits, however, did not differ significantly among treatments at either location, indicating that fertilizer regimes influenced fruit size and weight more than compositional traits (Table 4).

The application of BS-INM substantially influenced tomato yield, with pronounced differences between BAU and BLRI. At BAU, the highest yield was observed in T_2 (28.32 t/ha), approximately 180% higher than the control (T_6), while at BLRI, T_4 achieved the highest yield (16.41 t/ha), representing a 333% increase over T_6. Treatments T_3, T_2, T_1, and T_5 at BLRI resulted in yield increases of 239.5%, 191%, 176%, and 167.5% compared to the control, respectively (Figure 1). The higher response at BLRI may be attributed to variations in soil fertility, texture, and microclimatic conditions, emphasizing the interaction between nutrient management and site-specific environmental factors. The superior performance of treatments integrating bio-slurry with chemical fertilizers (T_2, T_3, and T_4) can be explained by the synergistic effects of organic and inorganic nutrients. Organic amendments such as bio-slurry provide slow-release nutrients, enhance microbial activity, and improve soil structure, while chemical fertilizers supply immediately available nutrients, thereby ensuring nutrient availability throughout the crop growth period. This observation is consistent with prior studies by Kochakinezhad *et al.* (2012), Gao *et al.* (2023), and Wu *et al.* (2022), which reported higher tomato growth, yield, and fruit size under integrated nutrient management compared to sole organic or inorganic fertilizers. The observed increases in flower and fruit clusters, fruit size, and yield corroborate findings by Islam *et al.* (2017), who reported enhanced growth and fruit production in Roma VF tomatoes with integrated organic and inorganic fertilization. Similarly, Ferdous *et al.* (2018) found that combining cow dung bio-slurry with synthetic fertilizers produced higher numbers of fruits and greater fruit weight than either source alone. Studies by Yang *et al.* (2023) and Fan *et al.* (2023) further support the notion that organic-inorganic fertilizer combinations significantly improve yield and morphological characteristics, including fruit diameter, number of fruits per plant, and plant height. While the highest yield at BAU was achieved with 75% chemical fertilizer + 25% bioslurry (T_2), BLRI showed optimum performance at 25% chemical fertilizer + 75% bioslurry (T_4), indicating that site-specific conditions, including soil fertility and management history, influence the optimal proportion of organic and chemical fertilizers. These findings align with the conclusions of Li *et al.* (2023) and Wu *et al.* (2022), who emphasized the importance of adjusting nutrient management strategies according to local conditions to maximize tomato productivity. Overall, the results demonstrate that bio-slurry based integrated nutrient management enhances tomato growth, yield, and fruit quality more effectively than single-source fertilizers, with significant benefits in both quantitative and qualitative traits. These findings underscore the potential of integrated nutrient management as a sustainable and efficient approach to increase tomato productivity while maintaining soil health, aligning with global trends in organic-inorganic fertilization strategies (Ahmed *et al.*, 2022; Hui-Lian *et al.*, 2024).

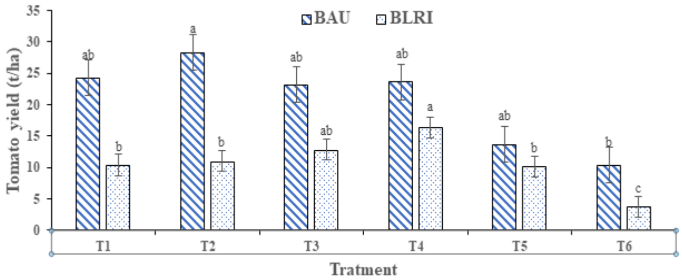

Figure 1: *Effect of bio-slurry based integrated nutrient management system on tomato yield (t/ha) at BAU and BLRI*
(T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Table 3: *Effect of bioslurry-based integrated nutrient management system on plant height of tomato at different days after sowing at BAU and BLRI*

Treat-ment	Plant height at 30 DAS (mm)	Plant height at 60 DAS (mm)	Plant height at 90 DAS (mm)
Location 1: BAU			
T_1	278.0 ± 20.8a	434.0 ± 10.4ab	688.0 ± 43.9a
T_2	300.7 ± 12.7 a	460.7 ± 17.3a	745.3 ± 17.8a
T_3	287.3 ± 7.1a	434.7 ± 7.0ab	674.7 ± 23.4a
T_4	280.7 ± 11.6a	459.3 ± 15.9a	700.7 ± 49.6a
T_5	284.0 ± 8.3a	454.0 ± 12.2a	693.3 ± 57.3a
T_6	270.0 ± 11.1a	379.3 ± 8.1b	674.0 ± 15.1a
Location 2: BLRI			
T_1	350.2 ± 10.9ab	531.0 ± 68.2ab	751.0 ± 30.4b
T_2	296.0 ± 18.0bc	479.0 ± 24.9ab	759.0 ± 21.2b
T_3	322.0 ± 24.7ab	516.7 ± 8.1ab	822.3 ± 13.4ab
T_4	378.3 ± 17.9a	592.0 ± 18.1a	865.7 ± 8.7a
T_5	306.3 ± 6.5abc	467.3 ± 19.6ab	750.0 ± 23.4b
T_6	258.3 ± 1.7c	397.0 ± 8.0b	561.3 ± 22.0c

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Table 4: *Effect of bio-slurry based integrated nutrient management system on yield contributing character of tomato at BAU and BLRI*

Treatment	Number of flowers cluster^{-1}	Flower clusters plant^{-1}	Fruit clusters plant^{-1}	Fruit length (mm)	Fruit diameter (mm)	No. of fruit plant^{-1}	Fruit individual weight (g)	% Dry matter of fruits
Location 1: BAU								
T_1	48.13 ±5.92a	6.40 ± 0.99ab	6.40 ± 0.99ab	51.2 ± 1.9a	43.8 ± 2.6a	17.33 ± 3.04a	48.20 ± 0.50b	2.06 ± 0.19a
T_2	45.27 ± 5.07a	6.07 ± 0.74ab	6.07 ± 0.74ab	55.5 ± 2.0a	47.8 ± 1.8a	19.40 ± 1.86a	51.30 ± 4.77b	2.13 ± 0.16a
T_3	40.73 ± 1.45a	4.53 ± 0.88ab	4.53 ± 0.88ab	57.3 ± 2.7a	47.1 ± 1.6a	13.87 ± 2.60a	61.50 ± 3.93ab	1.92 ± 0.20a
T_4	43.73 ± 4.80a	11.60 ± 3.50a	11.60 ± 3.50a	52.8 ± 1.0a	44.3 ± 1.0a	16.60 ± 6.77a	75.90 ± 3.09a	2.96 ± 0.53a
T_5	39.07 ± 1.51a	4.93 ± 0.83ab	4.93 ± 0.84ab	52.3 ± 1.0a	44.3 ± 1.2a	8.07 ± 2.40a	60.47 ± 1.31ab	2.45 ± 0.41a
T_6	32.47 ± 1.90a	3.73 ± 0.77b	3.73 ± 0.77b	52.1 ± 0.5a	41.5 ± 0.3a	8.00 ± 1.21a	45.83 ± 3.97b	2.54 ± 0.09a
Location 2: BLRI								
T_1	46.00 ± 8.02a	6.30 ± 0.35bc	6.30 ± 0.35bc	55.2 ± 2.4ab	75.0 ± 2.5ab	24.90 ± 1.63c	48.20 ± 0.50b	7.20 ± 0.39a
T_2	51.33 ± 4.33a	6.07 ± 0.35bc	6.07 ± 0.35bc	54.8 ± 1.3ab	67.3 ± 1.2bc	25.43 ± 0.35c	51.30 ± 4.77b	6.72 ± 0.60a
T_3	57.17 ±1 .30a	6.93 ± 0.12ab	6.93 ± 0.12ab	63.0 ± 4.0a	74.3 ± 1.2ab	31.43 ± 0.89b	61.50 ± 3.93ab	7.44 ± 0.49a
T_4	61.70 ± 1.23a	8.50 ± 0.45a	8.50 ± 0.45a	65.8± 3.5a	79.0 ± 2.7a	41.90 ± 1.73a	75.90 ± 3.09a	6.41 ± 0.64a
T_5	47.50 ± 0.29a	5.93 ± 0.58bc	5.93 ± 0.58bc	53.3 ± 2.9ab	60.3 ± 1.5c	23.23 ± 0.62c	60.47 ± 1.31ab	6.52 ± 0.63a
T_6	24.33 ± 1.20b	4.70 ± 0.26c	4.70 ± 0.26c	42.3 ± 1.5b	50.3 ± 0.3d	8.47 ± 0.29d	45.83 ± 3.97b	7.63 ± 0.18a

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Table 5: *Effect of bio-slurry based integrated nutrient management system on mineral uptake of tomato at BAU and BLRI*

Treatment	N (g/kg)	P (g/kg)	K (g/kg)	S (g/kg)
Location 1: BAU				
T_1	26.2 ± 0.3b	7.3 ± 0.5a	25.8 ± 3.9a	1.7 ± 0.1a
T_2	27.2 ±0.8b	7.8 ± 0.4a	22.0 ± 7.0a	1.4 ± 0.1a
T_3	27.7 ± 0.1b	8.8 ± 0.2a	33.7 ± 3.7a	1.3 ± 0.1a
T_4	30.3 ± 0.7a	7.7 ± 1.1a	24.5 ± 2.6a	1.6 ± 0.3a
T_5	25.9 ± 0.4b	8.6 ± 0.2a	31.0 ± 0.1a	1.3 ± 0.1a
T_6	23.0 ± 0.9c	8.4 ± 0.3a	30.9 ± 1.5a	1.4 ± 0.04a
Location 2: BLRI				
T_1	26.2 ± 0.3a	5.0 ± 0.5a	17.9 ± 0.9a	0.4 ± 0.1ab
T_2	28.1 ± 0.4a	6.1 ± 8.3a	19.6 ± 2.3a	0.5 ± 0.1ab
T_3	26.5 ± 0.6a	6.7 ± 1.5a	17.2 ± 1.5a	0.3 ± 0.07b
T_4	28.4 ± 1.4a	6.9 ± 0.8a	16.4 ± 1.4a	0.8 ± 0.1a
T_5	28.0 ± 1.5a	5.7 ± 0.1a	15.5 ± 0.9a	0.7 ± 0.03ab
T_6	26.1 ± 0.3a	5.9 ± 0.3a	15.3 ± 1.2a	0.8 ± 0.1a

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Mineral uptake by Tomato

The uptake of essential mineral nutrients (N, P, K, and S) by tomato fruits was significantly influenced by the application of different fertilizer treatments in both Bangladesh Agricultural University (BAU) and Bangladesh Livestock Research Institute (BLRI) experimental plots (Table 5). At BAU, treatment T_4 recorded the highest N uptake (30.3 g/kg), T_3 had the highest P (8.8 g/kg) and K (33.7 g/kg) uptake, and T1 had the highest S content (1.7 g/kg), representing increases of 31.74%, 4.76%, 9.06%, and 21.43%, respectively, over the control. Similarly, at BLRI, T_4 exhibited the highest N (28.4 g/kg) and P (6.9 g/kg) uptake, T_2 had the highest K (19.6 g/kg), and S uptake was highest in T_2 and T_3 (0.8 g/kg), corresponding to increases of 8.81%, 16.65%, 28.10%, and 166.67%, respectively, compared to the control. The enhanced nutrient uptake in bio-slurry and integrated fertilizer treatments is attributed to the combined effects of immediate nutrient availability from inorganic fertilizers and the gradual nutrient release from organic sources. These findings are consistent with previous studies, which demonstrated that integrated organic–inorganic nutrient management significantly improves tomato N, P, and K uptake by enhancing soil fertility and microbial activity (Ahmed *et al*., 2022; Wu *et al*., 2022; Hashimi and Habibi, 2021). Organic fertilizers alone have been reported to improve fruit nutrient composition, particularly S and K, through slow nutrient release and stimulation of soil enzymatic activities (Li *et al*., 2023; Fan *et al*., 2023). The variation in K and S uptake across

Table 6: *Effect of bio-slurry based integrated nutrient management system on growth of carrot at BAU and BLRI*

Treatment	Number of leaves plant^{-1}	Plant height at 30 DAS (mm)	Plant height at 60 DAS	Plant height at 90 DAS
Location 1: BAU				
T_1	10.13 ± 0.33a	118.0 ± 5.0a	238.7 ± 5.5a	464.7 ± 13.9a
T_2	9.03 ± 0.23a	124.7 ± 7.7a	242.7 ± 19.6a	491.0 ± 0.5a
T_3	9.27 ± 0.74a	118.7 ± 2.4a	239.3 ± 19.6a	424.0 ± 16.8a
T_4	9.53 ± 1.14a	116.0 ± 3.1a	224.7 ± 12.7a	448.0 ± 21.2a
T_5	8.67 ± 0.27a	115.3 ± 1.3a	222.7 ± 5.8a	347.3 ± 4.8b
T_6	10.13 ± 0.33a	118.0 ± 5.0a	238.7 ± 5.5a	464.7 ± 13.9a
Location 2: BLRI				
T_1	9.40 ± 0.31b	162.0 ± 3.1a	463.2 ± 37.2abc	596.0 ± 13.0a
T_2	9.50 ± 0.12 b	170.0 ± 0.1a	372.0 ± 51.4bc	576.7 ± 43.0a
T_3	9.50 ± 0.17 b	171.3 ± 1.3a	414.5 ± 36.8ab	566.7 ± 46.5a
T_4	10.77 ± 0.15a	179.3 ± 22.3a	523.1 ± 33.7a	671.3 ± 77.0a
T_5	9.10 ± 0.21 b	132.7 ± 14.6a	473.4 ± 46.5ab	632.0 ± 13.5a
T_6	9.40 ± 0.31b	162.0 ± 3.1a	463.2 ± 37.2abc	596.0 ± 13.0a

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Table 7: *Effect of bio-slurry based integrated nutrient management system on yield contributing character of carrot at BAU and BLRI*

Treatment	Root length (mm)	Diameter of root (mm)	Fresh weight of leaves plant^{-1} (g/plant)	% Cracked root	% Dry matter leaves	% Dry matter root	Fresh weight root/plant (g/plant)	Gross yield of carrot/plant (kg/plant)
Location 1: BAU								
T_1	135.1 ± 52.a	34.9 ± 0.9a	42.0 ± 4.18a	16.71 ± 7.63a	18.84 ± 1.49a	9.48 ± 0.31a	72.40 ± 6.25a	3.80 ± 0.03a
T_2	124.2 ± 9.0a	34.7 ± 0.1a	36.57 ± 0.64a	3.043 ± 0.80a	19.15 ± 3.01a	8.35 ± 1.54a	73.50 ± 0.15a	1.94 ± 0.95a
T_3	130.1 ± 5.2a	34.1 ± 1.7a	34.93 ± 3.48a	17.66 ± 8.45a	18.68 ± 3.41a	8.56 ± 0.91a	64.33 ±0.51ab	2.35 ± 1.03a
T_4	124.9 ± 1.21a	32.1 ± 1.9ab	42.27 ± 4.01a	19.79 ± 6.30a	21.24 ± 0.22a	8.71 ± 0.50a	61.8 ± 10.8ab	2.80 ± 0.70a
T_5	119.8 ± 0.35a	29.8 ± 1.0ab	13.50 ± 0.30b	3.15 ± 2.25a	22.58 ± 0.74a	10.22 ± 0.66a	39.20 ± 0.60ab	1.74 ± 0.63a
T_6	110.5 ± 0.03a	27.3 ± 0.4b	12.87 ± 1.59b	1.75 ± 1.75a	13.91 ± 4.41a	7.50 ± 1.50a	39 ± 4.66b	1.50 ± 0.55a
Location 2: BLRI								
T_1	139.7 ± 2.9ab	37.1 ± 0.6ab	45.53 ± 1.40b	8.33 ± 0.68a	18.38 ± 2.42a	11.05 ± 0.52a	75.67 ± 2.19b	2.86 ± 0.07a
T_2	134.7 ± 3.9ab	37.7 ± 0.7a	44.33 ± 0.48bc	6.13 ± 1.45ab	16.43 ± 0.27a	10.94 ± 0 .12a	79.17 ± 1.76ab	2.85 ± 0.10a
T_3	137.8 ± 1.5ab	37.9 ± 0.1a	41.0 ± 0.40c	5.10 ± 0.61abc	18.10 ± 0.64a	11.03 ± 0 .29a	75.00 ± 1.86b	2.95 ± 0.09a
T_4	149.0 ± 8.3a	38.4 ± 1.0a	51.63 ± 0.69a	3.53 ± 0.42bc	19.99 ± 2.44a	11.34 ± 0 .05a	86.33 ± 2.07a	3.17 ± 0.05a
T_5	123.0 ± 2.1bc	34.5 ± 0.3b	31.33 ± 1.00d	3.77 ± 0.68bc	16.02 ± 0.61a	15.44 ± 0 .17a	52.37 ± 1.73c	2.29 ± 0.09b
T_6	107.7 ± 3.4c	27.7 ± 0.7c	15.57 ± 0.23e	1.67 ± 0.26c	17.85 ± 0.82a	9.69 ± 0.39a	33.97 ± 0.72d	1.30 ± 0.03c

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

treatments and locations suggests site-specific responses influenced by initial soil fertility, organic matter content, and microbial activity. The remarkable increase in S uptake at BLRI (up to 166.67% over control) highlights the efficiency of bio-slurry and organic amendments in supplying secondary nutrients often limiting in conventional systems (Heeb *et al*., 2006; Turhan and Özmen, 2021). Overall, the application of bio-slurry-based integrated nutrient management not only enhanced tomato fruit yield but also improved nutritional quality by increasing N, P, K, and S concentrations. These results emphasize the importance of integrating organic and inorganic fertilizers to optimize nutrient uptake, maintain soil fertility, and achieve high-quality tomato production.

Carrot

Growth of carrot

The growth of carrot plants was significantly influenced by different fertilizer treatments in both experimental plots, although the magnitude and timing of effects varied between BAU and BLRI (Table 6). At BAU, no significant differences in plant height were observed at 30 and 60 DAS. However, at 90 DAS, treatment T_2 produced the tallest plants (491.0 mm), likely due to the combined effect of rapid nutrient availability from inorganic fertilizers and slow-release bio-slurry. The shortest plants at maturity were recorded in treatment T_5 (347.3 mm), which differed significantly from other treatments. In contrast, the number of leaves per plant did not differ significantly among treatments in the BAU plot. At BLRI, significant differences in plant height wereobserved at 60 DAS, with treatment T_4 producing the tallest plants (523.1 mm), representing a 61.21% increase over the control (324.7 mm). At 30 and 90 DAS, plant height differences were not significant. The number of leaves per plant was also significantly affected, with T_4 yielding the highest leaf count (10.77), a 43% increase over the control. Lower leaf numbers were observed in treatment T_5 (9.10). These results suggest that integrated application of bio-slurry with inorganic fertilizers enhances vegetative growth, particularly during peak growth stages, by improving nutrient availability and retention. Similar trends have been reported in previous studies. Amartey *et al*. (2022) and Valšíková-Frey *et al*. (2021) found that combinations of organic and inorganic fertilizers significantly enhanced carrot plant height, canopy development, and root yield compared to sole fertilizer or control treatments. Manure and NPK application increased vegetative growth and root yield (Zdravković *et al*., 1996; Zdravković *et al*., 2004) while Nikmatullah *et al*. (2021) demonstrated that foliar organic fertilization improved leaf development and overall plant growth. Foliar and organic amendments, along with integrated nutrient management, also enhance leaf number, chlorophyll content, and nutrient uptake, which collectively promote higher growth rates during critical developmental stages (Kwiatkowski *et al*., 2013; Ishwar *et al*., 2024). Therefore, the results indicate that bio-slurry-based integrated nutrient management can optimize carrot vegetative growth, particularly during the 60–90 DAS period, by providing a balanced supply of nutrients and improving plant architecture. Treatment T_4 consistently showed superior performance in leaf number and peak growth height, highlighting the benefits of combining organic and inorganic nutrient sources for improved carrot production.

Table 8: *Effect of bio-slurry based integrated nutrient management system on mineral uptake of carrot at BAU and BLRI*

Treat-ment	N (g/kg)	P (g/kg)	K (g/kg)	S (g/kg)
Location 1: BAU				
T_1	20.3 ± 0.3d	9.7 ± 0.46a	16.2 ± 0.3a	0.9 ± 0.04b
T_2	22.8 ± 0.7bc	6.5 ± 0.5ab	16.4 ± 0.7a	1.0 ± 0.08b
T_3	25.0 ± 0.3ab	6.5 ± 2.5ab	16.4 ± 1.5a	1.2 ± 0.1ab
T_4	27.3 ± 0.4a	7.2 ± 0.4ab	17.6 ± 0.2a	2.1 ± 0.7a
T_5	25.5 ± 0.7a	4.6 ± 0.4ab	16.7 ± 0.5a	1.5 ± 0.4a
T_6	22.5 ± 0.3cd	0.5 ± 0.08b	17.1 ± 0.6a	0.8 ± 0.08b
Location 2: BLRI				
T_1	11.8 ± 0.9a	5.9 ± 0.3a	13.3 ± 0.8a	1.5 ± 0.7a
T_2	8.1 ± 0.3b	9.0 ± 3.70a	1.49 ± 0.8a	1.5 ± 0.5a
T_3	10.7 ± 0.7ab	8.5 ± 0.7a	1.35 ± 0.6a	1.2 ± 0.1a
T_4	7.7 ± 0.01b	9.9 ± 1.4a	1.56 ± 2.2a	1.3 ± 0.2a
T_5	8.1 ± 0.4b	6.1 ± 1.6a	1.35 ± 3.4a	1.4 ± 0.1a
T_6	9.5 ± 0.7ab	8.4 ± 2.1a	0.84 ± 1.2a	0.9 ± 0.3a

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

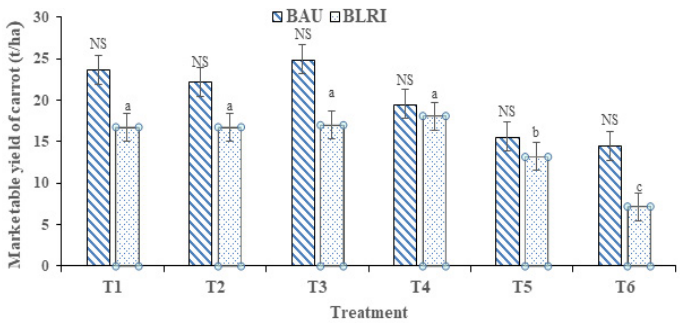

Figure 2: *Effect of bio-slurry based integrated nutrient management system on marketable yield of carrot (t/ha) at BAU and BLRI*

(T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Table 9: *Effect of bio-slurry on plant height of spinach at different days after sowing at BAU and BLRI*

Treatment	Plant height at 30 DAS (mm)	Plant height at 45 DAS (mm)	Plant height at 60 DAS (mm)
Location 1: BAU			
T_1	136.7 ± 7.9a	208.7 ± 16.2ab	322.0 ± 37.6ab
T_2	146.7 ± 11.8a	209.3 ± 26.9ab	317.3 ± 48.3ab
T_3	142.0 ± 7.6 a	210.7 ± 7.1ab	326.0 ± 8.3ab
T_4	155.3 ± 11.3a	279.7 ± 61.8a	437.3 ± 94.3a
T_5	134.0 ± 7.2a	145.3 ± 7.5ab	164.7 ± 20.2b
T_6	123.3 ± 20.7a	128.0 ± 23.1b	138.0 ± 18.9b
Location 2: BLRI			
T_1	135.0 ± 5.1ab	225.0 ± 3.6b	324.0 ± 12.3b
T_2	125.0 ± 14.0ab	218.8 ± 10.7b	329.3 ± 15.2b
T_3	146.7 ± 12.4ab	232.3 ± 6.7b	350.7 ± 3.2b
T_4	165.0 ± 8.7a	319.7 ± 8.8a	453.2 ± 10.9a
T_5	115.9 ± 10.1ab	169.5 ± 9.0c	198.5 ± 5.4c
T_6	93.0 ± 16.9b	155.4 ± 11.2c	185.7 ± 13.7c

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Table 10: *Effect of bio-slurry based integrated nutrient management system on yield contributing character of spinach at BAU and BLRI*

Treatment	No. of leaves plant^{-1}	Leaf length (mm)	Leaf breadth (mm)
Location 1: BAU			
T_1	8.80 ± 0.42ab	187.3 ± 13.6ab	55.8 ± 4.8ab
T_2	8.67 ± 0.24ab	195.7 ± 13.9ab	56.4 ± 5.1ab
T_3	9.25 ± 0.07a	166.0 ± 30.1ab	54.0 ± 3.1ab
T_4	9.27 ± 0.71a	231.3 ± 36.4a	69.5 ± 9.7a
T_5	7.93 ± 0.37ab	119.8 ± 12.1b	37.5 ± 1.3b
T_6	7.27 ± 0.33b	92.0 ± 22.7b	34.7 ± 7.7b
Location 2: BLRI			
T_1	8.53 ± 0.44ab	189.7 ± 7.6ab	55.2 ± 6.0ab
T_2	8.63 ± 0.35ab	202.0 ± 7.2ab	59.1 ± 4.8a
T_3	9.17 ± 0.08a	202.0 ± 8.9ab	55.5 ± 0.5ab
T_4	9.63 ± 0.27a	230.3 ± 17.2a	72.0 ± 4.6a
T_5	8.17 ± 0.38ab	156.0 ± 11.5b	53.4 ± 3.2ab
T_6	7.33 ± 0.24b	746.0 ± 3.8c	37.0 ± 1.2b

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at $p < 0.05$ according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Yield contributing character and yield of carrot

The application of different combinations of organic and inorganic fertilizers significantly influenced carrot growth, yield, and quality at both the Bangladesh Agricultural University (BAU) and Bangladesh Livestock Research Institute (BLRI) experimental plots (Tables 7, Figure 2). Baseline soil fertility was comparable between sites, ensuring that observed differences were attributable to fertilizer treatments rather than initial soil variability. At BAU, treatment T_1 (100% chemical fertilizer) produced the highest root length (153.1 mm) and root diameter (34.9 mm), indicating that rapid nutrient availability from chemical fertilizers promoted superior early root growth. The control plot (T_6) yielded the shortest and thinnest roots (110.5 mm and 27.3 mm, respectively). The highest fresh leaf weight per plant was recorded in T_4 (42.27 g), which also showed the highest percentage of cracked roots (19.79%), indicating a potential negative effect of excessive or imbalanced nutrient supply on root quality. Treatments T_5 and T_6 produced the highest dry matter content in roots and leaves, suggesting that slower nutrient release from organic sources favors carbohydrate accumulation. Fresh root weight per plant was maximized in T_2 (73.50 g), representing an 88.46% increase over the control, while marketable yield per hectare was highest in T_3 (24.88 t/ha), a 71.59% increase over T_6. These results suggest that integrating chemical fertilizers with bio-slurry enhances vegetative growth and yield, but careful management is required to minimize quality-reducing disorders such as root cracking. At BLRI, T_4 (25% chemical fertilizer + 75% bio-slurry) consistently outperformed other treatments, producing the highest root length (149.0 mm), root diameter (38.4 mm), fresh leaf weight per plant (51.63 g), and marketable yield (18.10 t/ha). In contrast, T_1 showed the highest cracked root percentage (8.33%), highlighting that higher chemical fertilizer levels can increase physiological defects. Treatments T_4 and T_5 also achieved the highest dry matter percentages in leaves (19.99%) and roots (15.44%), indicating improved nutrient assimilation and carbohydrate accumulation under integrated nutrient management. Overall, trends across both sites were similar: moderate chemical fertilizer combined with bio-slurry (T_3 and T_4) provided the best balance between yield enhancement and reduction of quality-reducing defects. The results were consistent with recent studies showing that integrated nutrient management improves carrot growth, yield, and quality (Amartey *et al*., 2022; Valšíková-Frey *et al*., 2021; Ishwar *et al*., 2024). These findings underscore that bio-slurry-based integrated fertilization can enhance nutrient use efficiency, promote dry matter accumulation, and improve carrot yield while minimizing adverse quality traits such as cracked roots.

Mineral uptake of carrot

Carrot uptake of N, P, K, and S was significantly influenced by organic and inorganic fertilizer combinations, with site-specific differences between BAU and BLRI (Table 8). At BAU, T_4 (25% chemical fertilizer + 75% bio-slurry) recorded the highest N (27.3 g/kg), K (17.6 g/kg), and S (2.1 g/kg) uptake, while T_1 (100% chemical fertilizer) had the highest P uptake (9.7 g/kg). These represented increases of 21–546% over the control (T_6). At BLRI, T_1 had the highest N (11.8 g/kg), T_4 the highest P (9.9 g/kg) and K (15.6 g/kg), and T_1/T_2 the highest S (1.5 g/kg). Overall, N and P were most responsive to fertilization, K uptake was relatively stable, and S uptake showed site-dependent variation. Integrated application of moderate chemical fertilizer with bio-slurry (T_3, T_4) generally enhanced N, K, and S uptake, whereas sole chemical fertilizer favored P uptake. These findings align with previous reports that combined organic and inorganic fertilization improves nutrient assimilation, dry matter accumulation, and yield in carrot (Amartey *et al*., 2022; Valšíková-Frey *et al*., 2021; Ishwar *et al*., 2024). Site variation underscores the influence of soil properties on nutrient response. Overall, bio-slurry-based integrated nutrient management effectively enhances carrot nutrient uptake while reducing risks of imbalance from sole chemical fertilization.

Spinach

Plant growth of spinach

Spinach (*Spinacia oleracea* L.) growth was significantly influenced by fertilizer treatments at both BAU and BLRI experimental plots. At BAU, plant height showed no significant differences at 30 DAS, but differences became significant at 60 and 90 DAS. Treatment T_4 consistently produced the tallest plants (155.3 mm at 30 DAS, 279.7 mm at 60 DAS, and 437.3 mm at 90 DAS), representing increases of 26%, 118.5%, and 216.88% over the control (T_6). At BLRI, T_4 also achieved the highest heights (165.0 mm at 30 DAS, 319.7 mm at 60 DAS, 453.2 mm at 90 DAS), exceeding the control by 77.42%, 106%, and 142.43%. The control treatment consistently recorded the lowest plant height at all stages, underscoring the strong effect of bio-slurry and integrated organic-inorganic treatments (Table 9). These results align with previous studies indicating that organic fertilizers enhance spinach growth by improving nutrient availability, chlorophyll content, and soil microbial activity (Türkkan and Kibar, 2022; Sharma *et al*., 2024; Balkrishna *et al*., 2025). Similarly, combined organic and inorganic amendments have been shown to increase plant height, leaf number, and biomass accumulation in spinach and water spinach (Kurakula *et al*., 2021; Pohan, 2021; Quddus *et al*., 2024). The superior performance of T_4 is likely due to synergistic effects on nutrient uptake and soil fertility, highlighting the importance of integrated nutrient management for sustainable crop production. In conclusion, T_4 significantly enhanced spinach growth at all stages, demonstrating the effectiveness of bio-slurry-based fertilizer management for improving plant height, productivity, and soil health, consistent with global findings on organic and integrated fertilization strategies.

Table 11: *Effect of bio-slurry based integrated nutrient management system on mineral uptake of spinach at BAU and BLRI*

Treatment	N (g/kg)	P (g/kg)	K (g/kg)	S (g/kg)
Location 1: BAU				
T_1	26.0 ± 0.07c	6.5± 0.4a	23.6 ± 6.7a	4.4 ± 0.07a
T_2	29.8 ± 0.1b	11.8 ± 6.0a	30.8 ± 7.9a	3.0 ± 0.4a
T_3	31.8 ± 1.1b	5.9 ± 0.2a	24.7 ± 5.6a	3.5 ± 0.5a
T_4	37.1 ± 0.6a	5.2 ± 1.0a	20.9 ± 6.3a	3.3 ± 0.5a
T_5	23.1 ± 0.2d	7.3 ± 0.7a	28.2 ± 5.6a	5.2 ± 0.06a
T_6	22.5 ± 0.2d	4.2 ± 0.8a	34.3 ± 0.8a	0.44 ± 0.02a
Location 2: BLRI				
T_1	2.60 ± 0.006bc	0.58 ± 0.04ab	2.02 ± 0.12b	0.28 ± 0.03a
T_2	3.14 ± 0.087ab	0.68 ± 0.08ab	2.04 ± 0.04b	0.24 ± 0.01a
T_3	2.62 ± 0.105bc	0.75 ± 0.09a	2.60 ± 0.12a	0.27 ± 0.05a
T_4	3.68 ± 0.04a	0.67 ± 0.02ab	2.30 ± 0.14ab	0.26 ± 0.03a
T_5	2.72 ± 0.32bc	0.58 ± 0.02ab	2.12 ± 0.06ab	0.24 ± 0.01a
T_6	2.26 ± 0.08c	0.42 ± 0.06b	2.60 ± 0.12a	0.21 ± 0.01a

Mean ± Standard Deviation (SD) followed by non-similar letters within a parameter are significantly different at p < 0.05 according to Tukey's test (T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

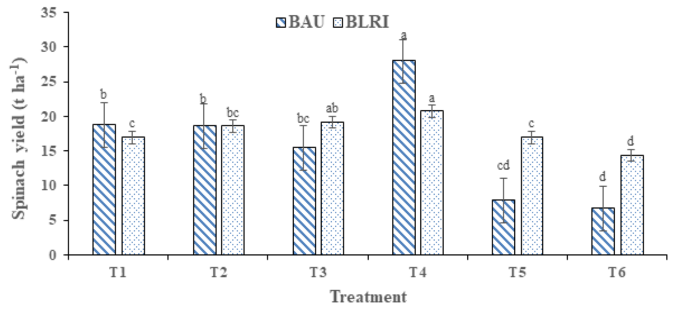

Figure 3: *Effect of bio-slurry based integrated nutrient management system on spinach yield of (t/ha) at BAU and BLRI*

(T_1 = 100% chemical fertilizer, T_2 =75% chemical fertilizer + 25% bio-slurry, T_3 = 50% chemical fertilizer + 50% bio-slurry, T_4 = 25% chemical fertilizer + 75% bio-slurry, T_5 = 100% bio-slurry, T_6 = Control)

Spinach yield and yield contributing character

The spinach yield and its contributing parameters were significantly influenced by different fertilizer treatments in both experimental sites, Bangladesh Agricultural University (BAU) and Bangladesh Livestock Research Institute (BLRI) (Figure 3, Table 10). At BAU, treatment T_4 produced the highest number of leaves per plant (9.27), leaf length (231.3 mm), leaf breadth (69.5 mm), and spinach yield (27.9 t/ha), representing increases of 27.51%, 151.41%, and 322.73% over the control (T_6). Similarly, at BLRI, T_4 yielded the highest number of leaves (9.63), leaf length (230.3 mm), leaf breadth (72.0 mm), and yield (10.65 t/ha), showing increases of 31.38%, 208.71%, and 144.33% compared to T_6. In both locations, the control treatment (T_6) consistently showed the lowest values, confirming the positive impact of integrated nutrient management on spinach productivity. The results indicate that combining organic and inorganic fertilizers, particularly bio-slurry-based treatments like T_4, enhances spinach growth by improving nutrient availability, leaf development, and photosynthetic capacity. These findings align with previous studies where organic amendments, such as vermicompost, cow manure, poultry manure, and bio-slurry, significantly increased spinach yield, leaf number, and plant height compared to control or solely inorganic fertilizers (Türkkan and Kibar, 2022; Kurakula *et al*., 2021; Pohan, 2021). The synergistic effect of organic and inorganic inputs likely improved soil structure, microbial activity, and nutrient uptake efficiency, supporting higher biomass accumulation and yield (Quddus *et al*., 2024; Sharma *et al*., 2024). Additionally, the literature highlights that organic fertilizers contribute to sustainable spinach production by reducing heavy metal accumulation, enhancing micronutrient availability, and maintaining soil fertility (Türkkan and Kibar, 2022; Rejeki *et al*., 2023). The observed superior performance of T_4 could be attributed to a balanced supply of macronutrients (N, P, K, S) and improved soil physico-chemical properties, consistent with findings of Miah *et al*. (2021) and Tshikalange *et al*. (2022) in both spinach and water spinach under organic amendments. Interestingly, while both experimental sites showed a similar trend, the absolute yield values differed, with BAU recording higher yields than BLRI. This variation could be associated with differences in soil fertility, microclimatic conditions, or experimental management practices, reinforcing the need to tailor fertilizer strategies to local conditions for maximum efficiency (Noor *et al*., 2022; Balkrishna *et al*., 2025). Overall, the results underscore the importance of integrated nutrient management combining bio-slurry, organic fertilizers, and inorganic nutrients in optimizing spinach growth, yield, and nutrient uptake. Treatment T_4 consistently outperformed other treatments, suggesting it as the most effective strategy for sustainable spinach production while maintaining soil health and reducing dependency on chemical fertilizers.

Mineral uptake of spinach

The analysis revealed significant effects of fertilizer treatments on spinach mineral content in both experimental locations (Table 11). At the BAU experimental plot, the highest nitrogen (N) content (37.1 g/kg) was observed in treatment T_4, while phosphorus (P) was maximized in T_2 (11.8 g/kg). Potassium (K) accumulation was greatest in T_6 (34.3 g/kg), and sulphur (S) content was highest in T_5 (5.2 g/kg). The control treatment consistently recorded the lowest mineral concentrations across all parameters. At the BLRI site, treatment T_4 also yielded the highest N content (36.8 g/kg). The highest P (7.5 g/kg) and K (13.0 g/kg) were found in treatment T_3, whereas sulphur (2.8 g/kg) was maximized under T_1. Similar to BAU, the control treatment showed the lowest mineral content. Overall, the results indicate that different fertilizer treatments significantly influenced the accumulation of N, P, K, and S in spinach leaves at both experimental sites, though the treatment-specific responses varied. The present study demonstrates that integrated nutrient management systems significantly enhanced spinach mineral content compared to control plots, though the best-performing treatments differed by site. Treatment T_4 consistently improved N content across both BAU and BLRI, suggesting that balanced organic–inorganic combinations promote nitrogen mineralization and uptake efficiency. This observation agrees with Kurakula *et al*. (2021), who reported improved nutrient use efficiency in spinach with FYM and vermicompost combined with reduced NPK. Phosphorus and potassium responses varied across sites, with BAU favoring T_2 (P) and T_6 (K), while BLRI favored T_3 for both nutrients. These differences may be attributed to variations in soil properties and organic matter decomposition rates, which influence nutrient release. Similar findings were reported by Pohan (2021) in water spinach and Tshikalange *et al*. (2022) in spinach, where organic fertilizers enhanced P and K accumulation under field conditions. Sulphur content showed contrasting results, being highest in T_5 (BAU) and T_1 (BLRI). This suggests that organic amendments play a role in S availability, consistent with Miah *et al*. (2021), who found that nutrient amendments improved macronutrient uptake in spinach grown in acidic soil but that S dynamics were strongly influenced by soil pH and amendment type. The results are further supported by studies highlighting the positive role of organic fertilizers on spinach growth and quality. For instance, Türkkan and Kibar (2022) found that cattle manure significantly enhanced N, P, and S contents while reducing heavy metals. Similarly, Sharma *et al*. (2024) emphasized that combinations of Azotobacter and organic fertilizers improved nutrient accumulation and soil fertility. In the present study, treatments incorporating organic amendments (e.g., T_4 and T_5) also enhanced mineral uptake, confirming their contribution to sustainable nutrient management. Recent innovations in organic fertilization align with these findings. Saba *et al*. (2023) demonstrated that keratin hydrolysate fertilizers from chicken feathers increased spinach nutrient density, while Rejeki *et al*. (2023) showed that black soldier fly (BSF) compost enhanced nutritional quality without heavy metal risks. Such bio-based approaches highlight the potential of organic nutrient sources to complement inorganic fertilizers for improved crop nutrition. Taken together, the findings indicate that bio-slurry-based integrated nutrient management strategies can substantially improve spinach mineral content while reducing reliance on chemical fertilizers. However, the variability in nutrient responses between BAU and BLRI underscores the need for site-specific recommendations. Further studies are warranted to explore nutrient interactions, optimize amendment combinations, and evaluate long-term soil fertility impacts.

Conclusions and Recommendatoins

The combined application of bio-slurry and inorganic fertilizers substantially improved the growth, yield, and mineral composition of tomato, carrot, and spinach. Among the treatments, T_4 (25% chemical fertilizer + 75% bio-slurry) emerged as the most effective, delivering higher productivity and improved nutrient uptake across the crops while reducing quality-reducing disorders such as root cracking in carrot. The results confirm that bio-slurry-based integrated nutrient management not only enhances crop performance but also contributes to long-term soil fertility and sustainability. Therefore, adopting integrated fertilizer strategies can serve as a practical solution for sustainable vegetable production in Bangladesh and other regions facing similar challenges of soil fertility depletion and high dependency on chemical fertilizers.

Data Availability

Data are available on request

Geolocation

BAU is located Mymensingh, Bangladesh having altitude 24.7585° N and longitude 90.4062° E. Similarly, BLRI is located Savar, Bangladesh having altitude 23.8703° N and a longitude 90.3715° E.

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Novelty Statement

This research is novel because it evaluates bio-slurrybased nutrient management across three vegetable types and two soil conditions, offering rare comparative insights. It also identifies an optimal bio-slurry–chemical fertilizer ratio that boosts yield and nutritional quality while reducing chemical fertilizer use.

Author's Contribution

Md. Tariqul Islam and M Ashraful Islam: Were responsible for research concept, literature review, methodology, manuscript writing, data collection and analysis and data interpretation
M Hossain Sumon: Conducted statistical analyses and edited the manuscript
Jobaida Shovna Khanam and J Nasrin Sultana: Conducted fieldwork, such as planting and maintaining the trials, assisting in data collection, and providing practical support throughout the project.
M Ashraful Islam: Read and agreed to the published version of the manuscript.

Use of Artificial Intelligence Tools
No artificial intelligence (AI) tools, including software, algorithms, or machine learning models, were utilized by any of the contributing authors during the research process. Additionally, none of the ideas, protocols, writings, data, results, or sections of this submission were generated or enhanced through the use of AI tools.

Conflicts of interest:
All the authors stated that they have no conflicting interests.

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