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Rohan Khopade
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Gajanan Sawargaonkar
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Akash Paul
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Ramesh Singh
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

D Moses Shyam
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Santosh Kale
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Rakesh S
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Prasad J Kamdi
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Corresponding Author:
Ramesh Singh
International Crops Research
Institute for the Semi-Arid Tropics,
Patancheru, Hyderabad, Telangana,
India

Growth, yield, and morphological variability in tomato as influenced by improved management practices

Rohan Khopade, Gajanan Sawargaonkar, Akash Paul, Ramesh Singh, D Moses Shyam, Santosh Kale, Rakesh S and Prasad J Kamdi

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Abstract

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops worldwide, and requires efficient management practices to achieve higher productivity and sustainability. A field experiment was conducted over two consecutive years (2023-24 and 2024-25) to evaluate the effects of integrated crop management practices on tomato growth, yield attributes, and productivity. The study compared three distinct strategies: farmers' variety with farmers' practice (FV + FP), an improved cultivar with a fully integrated management module and biological consortia (IC + IPM + INM + BC), and an improved cultivar with a partial management module (IC + MM + Lime). The results revealed that integrated treatments significantly improved growth parameters compared with farmers' practices. The highest values for plant height (150.75 cm), number of leaves (103.00), and plant spread were recorded under the fully integrated IC + IPM + INM + BC treatment. While early flowering was observed in the farmers' practice (48.75 days), the integrated treatments exhibited a longer vegetative phase (61.25 days), contributing to enhanced biomass accumulation. Yield attributes, including the number of fruits per plant, fruit size, and average fruit weight, were significantly superior under the integrated module. The highest fruit yield (7727.22 kg ha⁻¹) was achieved with IC + IPM + INM + BC, representing a substantial increase over the farmers' practice (5811.57 kg ha⁻¹). Multivariate Analysis of Variance (MANOVA) confirmed a highly significant treatment effect (Wilks' Lambda = 0.0096, P < 0.001) that remained stable across both years. Principal Component Analysis (PCA) identified fruit weight, plant growth parameters, and fruit girth as the primary drivers of yield variation. Correlation analysis indicated strong positive associations between fruit yield and key traits, including plant height (r = 0.8739) and average fruit weight (r = 0.9035). The study concludes that the holistic integration of improved cultivars, balanced nutrient management (INM) and eco-friendly pest control (IPM) with biological consortia is essential for optimizing tomato productivity and ensuring long-term agricultural sustainability.

Keywords: Fruit traits, Integrated crop management, PCA, Sustainable agriculture, tomato, yield

1. Introduction

Tomato (*Solanum lycopersicum* L.) is among the most widely cultivated and economically important vegetable crops worldwide (Khopade *et al.*, 2025) ^[11]. It is valued for its high nutritional content, being a rich source of vitamins A and C, minerals, and antioxidants such as lycopene, which has been associated with reduced risk of chronic diseases (Li *et al.*, 2025; Motlhalamme *et al.*, 2025) ^[13, 14]. Globally, tomato plays a vital role in food security and agricultural economies, particularly in developing countries like India, where it is cultivated across diverse agro-climatic regions. Despite its importance, the productivity of tomato in many regions remains below potential due to several constraints, including imbalanced nutrient management, pest and disease incidence and the continued reliance on traditional farming practices (Nandhini *et al.*, 2024) ^[15].

One of the major challenges in tomato cultivation is the declining soil fertility caused by excessive and unbalanced use of chemical fertilizers. Continuous application of inorganic fertilizers without adequate organic supplementation leads to deterioration of soil health, reduced microbial activity and lower nutrient use efficiency (Singh *et al.*, 2023) ^[23]. In this context, Integrated Nutrient Management (INM) has emerged as a sustainable approach that combines organic and inorganic nutrient sources to maintain soil fertility and enhance crop

productivity. INM not only improves nutrient availability but also enhances soil structure and biological activity, thereby contributing to long-term agricultural sustainability (Fageria *et al.*, 2008; Gourkhede *et al.*, 2026, Khopade *et al.*, 2025) ^[5, 6, 11]. In addition to nutrient-related issues, pest and disease management remains a critical factor affecting tomato yield. The indiscriminate use of chemical pesticides has resulted in environmental pollution, pest resistance, and health hazards (Shanmugam *et al.*, 2024) ^[20]. Therefore, Integrated Pest Management (IPM) has been advocated as an eco-friendly approach that integrates biological, cultural and chemical methods to manage pests effectively while minimizing environmental impact. IPM strategies focus on pest monitoring, use of resistant cultivars, biological control agents, and need-based application of pesticides, ensuring both economic and ecological benefits (Kogan, 1998) ^[9].

Integration of INM and IPM into a unified management module represents a holistic approach to crop production. Such integrated crop management practices aim to optimize resource use efficiency, improve crop performance, and reduce environmental risks. Several studies have reported that the combined application of nutrient and pest management practices significantly enhances growth, yield attributes, and productivity of vegetable crops, including tomato (Singh *et al.*, 2023) ^[23]. Another important factor influencing tomato productivity is the choice of planting material. The use of improved cultivars (ICs) with higher genetic potential, better adaptability, and resistance to biotic and abiotic stresses is crucial for achieving higher yields. In contrast, farmers' varieties (FV) often exhibit lower productivity due to genetic limitations and lack of resistance traits. The adoption of improved cultivars, when combined with appropriate management practices, can substantially enhance crop performance.

In recent years, the use of biological consortia (BC) has gained importance as a component of sustainable agriculture. Biological consortia consist of beneficial microorganisms that enhance nutrient availability, improve soil microbial activity and promote plant growth through various mechanisms such as nitrogen fixation, phosphorus solubilization, and production of growth-promoting substances. The application of such microbial inputs has been shown to improve crop productivity while reducing dependency on chemical inputs (Vessey, 2003) ^[25]. Despite the availability of these improved technologies, their adoption at the farmer level remains limited, and farmers often continue to follow traditional farming practices (FP), which are less efficient and resource-intensive. There is a need to evaluate and demonstrate the benefits of integrated approaches under field conditions to promote their adoption (Owuor and Ochieng, 2026) ^[16].

Therefore, the present study was undertaken to assess the effect of integrated crop management practices involving management module (MM = INM + IPM), improved cultivars (IC), biological consortia (BC), and farmers' practices (FP) on growth, yield attributes, and productivity of tomato. The findings of this study are expected to provide valuable insights into sustainable tomato production and support the development of efficient crop management strategies.

2. Materials and Methods

2.1 Experimental Site and Design

The field experiment was conducted over two consecutive growing seasons (2023-24 and 2024-25) under open-field conditions to evaluate the effects of different crop management

practices on tomato productivity. Conducting the experiment across multiple years ensured that the results accounted for seasonal variability and environmental fluctuations. The experimental site was characterized by typical agricultural soil conditions suitable for tomato cultivation, and standard agronomic practices were followed throughout the crop growth period to maintain uniformity. The experiment was conducted using a randomized block design (RBD) with three treatments and three replications under field conditions. Each treatment was randomly allocated within each block to minimize the effect of field variability and to ensure unbiased comparison among treatments. A total of nine experimental plots were maintained. The design was adopted to control soil heterogeneity and improve the precision of treatment effects, thereby enabling reliable statistical interpretation. Each plot was maintained with uniform spacing, plant population, and management practices except for the treatment differences.

2.2 Treatments Details

The study consisted of three treatments combining crop management practices and planting materials. The treatments included: farmers' variety (Local) with farmers' practice (FV + FP); improved cultivar (Variety: Lakshmi) with an integrated management module and biological consortia (IC + MM + BC); and improved cultivar with a management module and soil amendment. The management module (MM) comprised integrated nutrient management (INM) and integrated pest management (IPM). These treatments were designed to evaluate the effectiveness of improved technologies compared to conventional farming practices.

2.3 Crop Establishment and Management

Healthy seedlings of both improved cultivar and farmers' variety were raised in well-prepared nursery beds under suitable conditions. Proper care was taken to ensure uniform germination and healthy seedling growth through timely irrigation and plant protection measures. Seedlings of 25–30 days old were transplanted into the main field. Transplanting was carried out during the evening hours to minimize transplanting shock and ensure better establishment of seedlings.

2.4 Land Preparation

The experimental field was prepared by thorough ploughing followed by harrowing to obtain a fine tilth suitable for transplanting. Well-decomposed farmyard manure was incorporated into the soil during the final land preparation to improve soil fertility and structure. The field was leveled properly and plots were laid out according to the experimental design with adequate bunds and irrigation channels.

2.5 Nutrient Management (INM Component)

Integrated nutrient management practices were followed in the respective treatments by combining organic and inorganic nutrient sources. Recommended doses of nitrogen, phosphorus and potassium fertilizers were applied. Nitrogen was applied in split doses, while phosphorus and potassium were applied as basal. Crops received fertilizer application at the rate of 150, 140, and 170 kg ha⁻¹ of urea, DAP, and MOP, respectively, along with basal application of zinc sulphate at 10 kg ha⁻¹ and borax at 5 kg ha⁻¹. Organic inputs such as farmyard manure were incorporated to enhance soil fertility and microbial activity. Biological consortia were also used to improve nutrient availability and overall plant growth.

2.6 Pest and Disease Management (IPM Component)

Integrated pest management practices were adopted to control pests and diseases in an eco-friendly manner. Regular monitoring of the crop was carried out to identify pest incidence at early stages. Biological control measures and cultural practices were emphasized, while chemical pesticides were applied only when necessary based on economic threshold levels. This approach minimized environmental impact while ensuring effective pest control.

2.7 Application of Biological Consortia (BC)

Biological consortia (*Azotobacter* + PSB) consisting of beneficial microorganisms were applied to enhance soil biological activity and nutrient availability. The consortia were applied through root dipping of seedlings prior to transplanting and through soil application near the root zone after establishment. These microorganisms facilitated nutrient solubilization, nitrogen fixation and plant growth promotion.

2.8 Intercultural Operations

All intercultural operations were carried out uniformly across treatments to ensure proper crop growth. Irrigation was provided at regular intervals based on crop requirements and prevailing weather conditions. Manual weeding was performed to maintain weed-free conditions. Staking and earthing up were carried out to support plant growth and improve aeration around the root zone.

2.9 Observations Recorded

All growth, phenological and yield parameters of tomato were recorded using standard procedures during the course of the experiment. Plant height (cm) was measured from the base to the tip of the main stem at final harvest using a measuring scale. The number of leaves per plant was obtained by counting all fully expanded leaves, while the number of branches per plant was recorded by counting primary branches arising from the main stem. Days to flowering was noted as the number of days from transplanting to the appearance of first flower in 50% of plants in each plot. The number of fruits per plant was determined by counting the total fruits harvested from selected plants. Fruit girth (cm) and fruit length (cm) were measured at the widest portion and from base to tip of the fruit, respectively, using a vernier caliper. Average fruit weight was calculated by dividing total fruit weight by number of fruits and expressed in grams:

$$\text{Average fruit weight (g)} = \frac{\text{Total fruit weight (g)}}{\text{Number of fruits}}$$

Total fruit yield per plot was recorded and converted to yield per hectare:

$$\text{Yield (kg acre}^{-1}\text{)} = \frac{\text{Yield per plot (kg)}}{\text{Plot area (m}^2\text{)}} \times 4000$$

2.10 Statistical Analysis

The recorded data were subjected to statistical analysis using standard procedures. Descriptive statistics such as mean, standard deviation and standard error were computed to summarize the data. Pearson's correlation analysis was performed to evaluate relationships among growth and yield parameters. Analysis of variance (ANOVA) was conducted under the randomized block design framework to test the significance of treatment effects. Where significant differences were observed, mean separation was performed using Tukey's honestly significant difference test. Additionally, a multivariate analysis of variance (MANOVA) was conducted to assess the

combined effect of treatments across multiple variables. Principal component analysis (PCA) was also performed to identify major contributing traits and reduce data dimensionality. All analyses were conducted using appropriate statistical software, and results were interpreted at standard levels of significance.

3. Results and Discussion

3.1 Effect of Treatments on Growth Parameters

The growth parameters of tomato were significantly influenced by different treatment combinations, indicating the effectiveness of improved management practices over conventional methods (Table 1). Among the treatments, IC + IPM + INM + BC recorded the highest values for all growth parameters, with plant height of 150.75 cm, number of leaves per plant 103.00, and number of branches per plant 2.58. This treatment also exhibited a comparatively higher number of days to flowering (61.25 days), suggesting prolonged vegetative growth and better crop establishment. The treatment IC + MM + Lime showed moderate performance, recording plant height of 136.04 cm, number of leaves per plant of 79.48, number of branches per plant of 1.94, and days to flowering of 54.59 days. This indicates that partial adoption of improved practices enhanced growth compared to conventional methods but was inferior to the fully integrated approach.

The lowest growth parameters were observed under FV + FP, with plant height of 95.92 cm, number of leaves per plant of 56.08, and number of branches per plant of 1.58, along with earlier flowering (48.75 days). The reduced vegetative growth under this treatment may be attributed to poor nutrient availability, higher pest incidence and absence of improved cultivar and biological inputs.

The superior performance of IC + IPM + INM + BC can be attributed to the synergistic effect of improved cultivar, balanced nutrient supply through integrated nutrient management (INM), reduced pest pressure through integrated pest management (IPM) and enhanced rhizospheric activity due to biological consortia (BC). These factors collectively improved nutrient uptake, photosynthetic efficiency and plant vigor, resulting in enhanced vegetative growth. The improved cultivar also contributed due to its superior genetic potential. These findings are in close agreement with Singh *et al.*, (2023) ^[23], who reported significant improvement in vegetative growth of tomato under integrated nutrient management practices. Similarly, Vessey (2003) ^[25] emphasized that plant growth-promoting microorganisms enhance root growth and nutrient uptake, thereby improving plant development. The enhanced growth under integrated treatments may also be attributed to improved soil physical properties and increased enzymatic activity, as reported by Fageria *et al.*, (2008) ^[5]. The reduction in days to flowering under integrated treatments may be attributed to optimal nutrient availability and reduced biotic stress, which accelerated physiological processes and crop development. Early flowering is advantageous because it extends the reproductive phase, leading to better yield realization. The delayed flowering observed under farmers' practices may be due to nutrient imbalances and higher pest incidence, which can slow plant growth. These results are consistent with Kumar *et al.*, (2017) ^[10] and Porras *et al.*, (2022) ^[18] who reported that integrated nutrient and pest management significantly reduced days to flowering in vegetable crops.

3.2 Effect of treatments on Yield Attributes and Yield

The yield attributes and fruit yield of tomato were markedly influenced by different treatment combinations, clearly reflecting the advantage of integrated crop management

practices (Table 1). Among the treatments, IC + IPM + INM + BC recorded the highest performance for almost all yield parameters, with 29.75 fruits per plant, fruit girth of 23.03 cm, fruit length of 6.68 cm, and average fruit weight of 85.67 g. Consequently, this treatment also produced the highest fruit yield of 7727.22 kg ha⁻¹.

In comparison, IC + MM + Lime showed moderate performance, recording 17.81 fruits per plant, a fruit girth of 19.36 cm, fruit length of 5.90 cm, and an average fruit weight of 65.72 g, resulting in a fruit yield of 6634.26 kg ha⁻¹. Interestingly, while the FV + FP treatment recorded a higher number of fruits per plant (19.42) than the Lime-based treatment, it produced the lowest values for fruit length (5.15 cm), average fruit weight (58.58 g), and overall fruit yield (5811.57 kg ha⁻¹). This indicates that without integrated management, although fruit numbers may persist, the quality and cumulative biomass (yield) are significantly compromised.

The higher yield under IC + IPM + INM + BC can be attributed to the combined effects of improved cultivar, balanced nutrient supply, effective pest management, and enhanced soil microbial activity. These factors collectively improved flowering, fruit set, and fruit development, resulting in higher fruit numbers and larger fruit, ultimately increasing yield. The improvement in yield attributes under integrated treatments can be attributed to better nutrient uptake, efficient assimilate partitioning, and reduced pest damage. Biological consortia further enhanced nutrient solubilization and uptake, thereby improving fruit development. The improved cultivar also contributed due to its higher yield potential and better adaptability. These findings are consistent with those of Adesemoye *et al.* (2010)^[1], who reported that microbial inoculants significantly improve yield components by enhancing nutrient efficiency and plant health. Similar results were reported by Chumyani *et al.* (2012)^[3], who observed increased fruit size and weight under integrated nutrient management. Similarly, Fageria *et al.* (2008)^[5] and Kogan (1998)^[9] highlighted the importance of integrated nutrient management and integrated pest management in reducing yield losses and improving crop performance, ultimately enhancing crop productivity by improving nutrient use efficiency.

3.3 Correlation Analysis among Growth, Yield Attributes, and Yield

Correlation analysis revealed strong, positive associations among growth parameters, yield attributes, and fruit yield in

tomato, indicating their interdependence in determining crop productivity (Table 2). Fruit yield showed a very strong positive correlation with plant height ($r = 0.8739$) and days to flowering ($r = 0.8971$), indicating that taller plants with longer growth duration contributed significantly to higher yield. Similarly, yield was strongly correlated with the number of leaves per plant ($r = 0.8783$) and number of branches per plant ($r = 0.8347$), suggesting that enhanced vegetative growth improves photosynthetic efficiency and assimilate production, ultimately leading to increased productivity. The strong interrelationship among vegetative traits such as plant height, number of leaves and number of branches observed in the present study is in accordance with earlier findings, where improved vegetative growth resulted in better assimilate production and translocation to reproductive parts (Vessey, 2003; Fageria *et al.*, 2008)^[25, 5]. Among yield attributes, fruit yield exhibited a strong positive correlation with average fruit weight ($r = 0.9035$) and fruit length ($r = 0.8058$), indicating that larger and heavier fruits contributed directly to higher yield. A moderate to strong positive correlation was observed with the number of fruits per plant ($r = 0.6973$) and fruit girth ($r = 0.6380$), suggesting their supportive role in yield improvement. The interrelationship among growth traits was also strong, with plant height and number of leaves ($r = 0.9310$) showing a very high positive correlation. Similarly, the number of leaves was strongly associated with average fruit weight ($r = 0.8972$), indicating that better foliage development enhances assimilate supply for fruit growth. Days to flowering showed strong positive correlations with most growth and yield parameters, particularly with plant height ($r = 0.8670$) and fruit yield ($r = 0.8971$), suggesting that an extended vegetative phase under improved management contributes to higher biomass accumulation and yield. The strong positive associations among these parameters highlight the importance of integrated crop management practices for simultaneously improving growth and yield components. Several researchers have reported that plant height and number of leaves are positively correlated with fruit yield, as these traits enhance photosynthetic capacity and biomass accumulation, ultimately improving productivity (Singh 2020; El Hjouji *et al.*, 2025)^[24, 4]. The significant positive relationship observed between average fruit weight and fruit yield is also supported by previous studies, which indicated that fruit weight is one of the most important yield-determining components in tomato (Singh *et al.*, 2018)^[22].

Table 1: Descriptive statistics (Mean, standard deviation, standard error, and coefficient of variation) of growth, phenological, and yield parameters of tomato under different treatments

Treatment	Statistic	Plant Height	No. of leaves plant ⁻¹	No. of branches plant ⁻¹	Days to flowering	Number of fruits per plant	Fruit girth (cm)	Fruit length (cm)	Average Fruit weight (g)	Fruit yield (kg acre ⁻¹)
FV+FP	Mean	95.92	56.08	1.58	48.75	19.42	19.35	5.15	58.58	5811.57
	SD	9.95	8.63	0.51	2.86	3.75	2.27	0.67	3.70	623.71
	SE Mean	2.87	2.49	0.15	0.83	1.08	0.66	0.19	1.07	180.05
	CV (%)	10.37	15.38	32.52	5.88	19.33	11.73	13.00	6.32	10.73
IC+MM+BC	Mean	150.75	103.00	2.58	61.25	29.75	23.03	6.68	85.67	7727.22
	SD	10.86	17.74	0.51	3.17	4.47	0.93	0.56	17.10	454.53
	SE Mean	3.14	5.12	0.15	0.91	1.29	0.27	0.16	4.93	131.21
	CV (%)	7.21	17.22	19.93	5.17	15.04	4.06	8.38	19.96	5.88
IC+INM+Lime	Mean	136.04	79.48	1.94	54.59	17.81	19.36	5.90	65.72	6634.26
	SD	9.04	5.79	0.13	4.67	1.33	1.78	0.56	5.12	504.54
	SE Mean	2.61	1.67	0.04	1.35	0.38	0.51	0.16	1.48	145.65
	CV (%)	6.64	7.29	6.49	8.56	7.46	9.19	9.51	7.78	7.61
Average	Mean	127.57	79.52	2.03	54.86	22.32	20.58	5.91	69.99	6724.35
	SD	25.42	22.59	0.59	6.28	6.33	2.44	0.86	15.48	948.93
	SE Mean	4.24	3.76	0.10	1.05	1.06	0.41	0.14	2.58	158.15
	CV (%)	19.93	28.40	29.01	11.44	28.36	11.87	14.53	22.11	14.11

Table 2: Correlation coefficients among growth, phenological and yield parameters of tomato

	Plant Height	No. of leaves plant ⁻¹	No. of branches plant ⁻¹	Days to flowering	No. of fruits plant ⁻¹	Fruit girth (cm)	Fruit length (cm)	Average Fruit weight (g)	Fruit yield (kg ha ⁻¹)
Plant Height	1								
No. of leaves plant ⁻¹	0.931	1							
No. of branches plant ⁻¹	0.7498	0.8183	1						
Days to flowering	0.8670	0.8689	0.7515	1					
Number of fruits plant ⁻¹	0.6198	0.7423	0.6828	0.6221	1				
Fruit girth (cm)	0.5060	0.6037	0.6091	0.6149	0.6409	1			
Fruit length (cm)	0.8230	0.8089	0.6597	0.8015	0.7439	0.4672	1		
Average Fruit weight (g)	0.7626	0.8972	0.8373	0.7798	0.7651	0.6985	0.6391	1	
Fruit yield (kg ha ⁻¹)	0.8739	0.8783	0.8347	0.8971	0.6973	0.638	0.8058	0.9035	1

3.4 Statistical Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) indicated that the treatment had a highly significant effect on tomato growth and yield ($P < 0.001$), with an F-value of 75.94 (Table 3). This confirms that the variation between management practices, specifically the superiority of the integrated approach (IC + IPM + INM + BC), is statistically robust. The year was also a significant source of variation ($F = 8.83$, $P = 0.0059$), suggesting that seasonal factors influenced overall performance.

However, the interaction between treatment and year was non-significant ($F = 0.22$, $P = 0.8001$), indicating that the treatments performed consistently across both years of the study. The block effect was significant ($F = 25.80$, $P < 0.001$), reflecting variability due to the experimental layout and justifying the use of a randomized design to isolate treatment effects.

Thus, the ANOVA results confirm that treatment effects were the primary source of variation, validating the impact of integrated management practices on tomato productivity. These results align with findings from Kumar *et al.*, (2022) [12], who reported significant increases in yield components under integrated nutrient management and Pandey and Chandra (2013) [17], who showed marked improvements in tomato growth parameters under integrated practices compared to traditional farmers' practices. The high R-squared value of 0.8657 further confirms that the model accounted for the majority of the observed variation, lending high credibility to these findings.

Table 3: Analysis of variance (ANOVA) of treatment, year and their interaction effects on growth and yield parameters of tomato.

Number of obs = 36 R-squared = 0.8657 Root MSE = 382.023 Adj R-squared = 0.8379					
Source	Partial SS	df	MS	F	Prob>F
Model	27283941	6	4547323.4	31.16	0.0000
Treatment	22164347	2	11082174	75.94	0.0000
Year	1288225	1	1288225	8.83	0.0059
Treatment#Year	65612.551	2	32806.276	0.22	0.8001
Block	3765755.9	1	3765755.9	25.80	0.0000
Residual	4232304.8	29	145941.55		
Total	31516245	35	900464.15		

3.5 Post-hoc Comparison of Treatments (Tukey HSD Test)

To further identify specific differences in management practices, a Tukey HSD post hoc test was conducted on fruit yield (Table 4). The results revealed that all pairwise comparisons between the three treatments were statistically significant, as none of the 95% confidence intervals included zero.

The most substantial yield difference was observed between IC + IPM + INM + BC (Treatment 2) and FV + FP (Treatment 1), with a significant positive contrast of 1915.65 kg ha⁻¹. Similarly, IC + MM + Lime (Treatment 3) significantly outyielded the

conventional practice by 822.69 kg ha⁻¹. Furthermore, the comparison between the two improved practices (Treatment 3 vs 2) showed a significant negative contrast of -1092.96 kg ha⁻¹, indicating that the partial adoption of improved practices was significantly less effective than the fully integrated suite.

Table 4: Tukey's Honestly Significant Difference (HSD) post-hoc test for pairwise comparisons of treatment effects on tomato fruit yield.

Yield	Contrast	Std. err.	Tukey [95% conf. interval]	
Treatment				
2 vs 1	1915.648	217.3288	1382.368	2448.928
3 vs 1	822.6852	217.3288	289.405	1355.965
3 vs 2	-1092.963	217.3288	-1626.243	-559.6827

These results are in close agreement with those of Pandey and Chandra (2013) [17], who observed that integrating biofertilizers and improved nutrient management resulted in 29–34% yield increases over traditional methods in tomato. Similar significant differences between integrated and conventional modules were reported by Jacob (2019) [8], who highlighted that the synergistic effect of IPM creates a superior yield-contributing environment compared to farmers' practices alone. Additionally, Sharma *et al.*, (2010) [21] demonstrated through analysis that integrated nutrient management consistently forms a distinct statistical group with the highest mean yields, while conventional practices remain significantly inferior due to imbalanced inputs and poor pest control.

These findings collectively emphasize that while any improvement over conventional methods is beneficial, the maximum yield potential of tomato is achieved only through the holistic integration of improved cultivars, bio-inputs, and balanced nutrient management.

3.6 Multivariate Analysis of Variance (MANOVA)

Multivariate analysis of variance (MANOVA) was performed to evaluate the collective effect of treatments on multiple dependent variables simultaneously, including growth parameters, phenological traits, yield attributes, and fruit yield (Table 5).

The results indicated a highly significant multivariate effect of treatments (Wilks' Lambda = 0.0096; $F = 24.54$; $P < 0.001$), confirming that the combined response of all measured parameters was significantly influenced by the different treatment combinations. Among the treatments, IC + IPM + INM + BC consistently recorded higher mean values across the variable set, including plant height, number of fruits per plant, and fruit yield, indicating its overall superiority. In contrast, FV + FP showed lower mean values, reflecting the limitations of conventional practices. The IC + MM + Lime treatment exhibited intermediate performance, indicating partial

improvement.

Table 5: Multivariate analysis of variance (MANOVA) showing the effect of treatments on combined growth and yield parameters of tomato

Source	W = Wilks' lambda P = Pillai's trace		L = Lawley-Hotelling trace R = Roy's largest root			
	Statistic	df	F(df1, df2) =	F	Prob>F	
Model	W	0.0076	3	27.0	70.7	11.29 0.0000 a
	P	1.9960		27.0	78.0	5.74 0.0000 a
	L	19.6022		27.0	68.0	16.46 0.0000 a
	R	12.7091		9.0	26.0	36.72 0.0000 u
Residual		32				
Treatment	W	0.0096	2	18.0	48.0	24.54 0.0000 e
	P	1.7953		18.0	50.0	24.37 0.0000 a
	L	19.3014		18.0	46.0	24.66 0.0000 a
	R	12.7086		9.0	25.0	35.30 0.0000 u
Year	W	0.7688	1	9.0	24.0	0.80 0.6183 e
	P	0.2312		9.0	24.0	0.80 0.6183 e
	L	0.3008		9.0	24.0	0.80 0.6183 e
	R	0.3008		9.0	24.0	0.80 0.6183 e
Residual		32				
Total		35				

e = exact, a = approximate, u = upper bound on F

Notably, the multivariate test for the Year effect was non-significant (Wilks' Lambda = 0.7688; P = 0.6183), suggesting that the combined expression of growth and yield traits remained stable across the two years of the study.

The significant multivariate test statistics (Wilks' Lambda, Pillai's Trace, and Lawley-Hotelling Trace) indicate that the observed differences across traits were statistically robust and interrelated. The strong contribution of yield-related parameters, such as average fruit weight and number of fruits, further strengthened the multivariate significance. These findings align with Hair *et al.*, (2019) [7], who emphasized the importance of MANOVA in detecting treatment effects across correlated variables. Similar multivariate responses have been reported by Agyeman *et al.*, (2021) [2], underscoring the utility of MANOVA in capturing treatment effects on complex, interdependent trait sets in tomato improvement programs.

4. Conclusion

The present study demonstrated that integrated crop management practices significantly improved the growth, yield attributes and productivity of tomato. Among the treatments, the combination of improved cultivar (IC) with management module (MM = Integrated Nutrient Management + Integrated Pest Management) and biological consortia (BC) recorded the best performance across all parameters. This treatment enhanced vegetative growth, promoted early flowering and improved fruit characteristics, ultimately resulting in higher yield. The superior performance of IC + MM + BC can be attributed to the synergistic effects of balanced nutrient supply, effective pest control, and improved soil biological activity. Biological consortia played a crucial role in enhancing nutrient availability and promoting plant growth, thereby contributing to increased productivity. The treatment involving IC + MM + Lime also showed improvement over farmers' practice, indicating the importance of integrated nutrient and pest management. In contrast, the farmers' variety under farmers' practice (FV + FP) recorded the lowest growth and yield, highlighting the limitations of traditional cultivation methods. The study also revealed positive associations between growth parameters and yield, emphasizing the importance of maintaining good plant

vigor for higher productivity. Overall, the findings suggest that the adoption of integrated approaches combining improved cultivars, nutrient management, pest management and biological inputs is essential for sustainable tomato production. Therefore, the use of IC + MM + BC can be recommended as an effective strategy to enhance yield, improve soil health and ensure long-term agricultural sustainability.

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