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Research

Multivariate Evaluation of Integrated Nutrient Management Effects on Growth and Yield Determinants of Summer Squash (*Cucurbita pepo* L.) under Sustainable Production Systems in Nepal

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Abstract

Summer squash (*Cucurbita pepo* L.) is a short-duration, high-value vegetable crop of increasing importance in Nepal; however, its productivity is frequently constrained by imbalanced fertilizer use and declining soil fertility. This study evaluated the effects of organic, inorganic, and integrated nutrient management practices on growth, flowering, and yield of summer squash under subtropical conditions of Nepal. The experiment was conducted during March–June 2024 at the Directorate of Agricultural Research, Tarahara, Sunsari, Nepal, using a Randomized Complete Block Design with eight treatments and three replications. Treatments comprised bio-fertilizer, poultry manure, vermicompost, farmyard manure (FYM), Jeevamrit, recommended NPK (235:176:117 kg ha^{-1}), integrated application of half recommended NPK combined with FYM, and an unfertilized control. Analysis of variance revealed significant treatment effects for all vegetative, flowering, and yield parameters. The integrated application of ½ NPK + FYM produced the most balanced and superior performance, resulting in higher leaf number, greater lateral branching, earlier flowering, increased fruit size, higher fruit number, and maximum fruit yield (46.07 t ha^{-1}), closely followed by sole NPK application. The control consistently recorded the lowest growth and yield. Regression and multivariate analyses (PCA and clustering) indicated that yield improvement was primarily driven by fruit number, individual fruit weight, and vegetative vigor, while delayed flowering was negatively associated with productivity. Overall, the findings demonstrate that integrated nutrient management, particularly the combined use of half recommended NPK with FYM, enhances growth–yield relationships and offers a productive and sustainable nutrient strategy for summer squash cultivation under similar agro-climatic conditions.

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Statement of Sustainability: This study provides important insights into the role of integrated nutrient management in improving the growth and productivity of summer squash under sustainable cultivation systems. The findings support the development of balanced and eco-friendly nutrient strategies that enhance soil health and promote stable crop performance. These outcomes enable farmers and agricultural stakeholders to adopt sustainable production practices that strengthen food security and contribute to SDG 2 – Zero Hunger.

1. Introduction

Summer squash (*Cucurbita pepo* L.), locally known as "hariyo farsi" in Nepal, is an important vegetable crop belonging to the family Cucurbitaceae, which includes economically significant crops such as cucumber, pumpkin, bottle gourd, and bitter gourd. The crop is characterized by rapid growth, a short maturity period, and high yield potential, making it well suited for intensive and short-season vegetable production systems. Owing to its wide adaptability across diverse agro-ecological zones, summer squash is increasingly cultivated in both the Terai and mid-hill regions of Nepal under open-field as well as protected cultivation systems (Kumar & Sharma, 2018; Gurau & Ray, 2024). Its rising market demand and the possibility of multiple harvests within a short production cycle have made it an attractive crop for income generation and livelihood improvement among smallholder farmers (Pandit et al., 2025; Subedi et al., 2024).

From a nutritional perspective, summer squash is valued for its high dietary fiber content, low caloric value, and richness in essential vitamins, particularly vitamins A and C, along with moderate levels of mineral salts (Bhatt et al., 2011; Hossen et al., 2025). These attributes contribute substantially to household nutrition and dietary diversification, especially in rural communities. Recent studies have further highlighted the presence of bioactive and antioxidant compounds in cucurbit crops, enhancing their recognized health-promoting properties (Acharya et al., 2024; Das et al., 2024). With increasing awareness of nutritional security and healthy dietary practices, demand for nutrient-dense vegetables such as summer squash is expected to rise steadily in Nepal.

Despite its agronomic and nutritional significance, the productivity of summer squash in Nepal remains relatively low, averaging approximately 14.3 t ha^{-1}, which is slightly below the global average of 15.83 t ha^{-1} (Chapagain et al., 2022; Mahara et al., 2024). This yield gap is largely attributed to declining soil fertility, imbalanced fertilizer application, and inefficient nutrient management practices (Mehata et al., 2023; Khanuma et al., 2021). In many vegetable-growing regions, excessive and indiscriminate use of chemical fertilizers has led to nutrient imbalance, reduced soil organic matter, deterioration of soil structure, and suppression of beneficial soil microorganisms (Antonious et al., 2022; Bhattarai et al., 2024). Over time, such practices compromise soil health and decrease nutrient-use efficiency, ultimately limiting crop productivity. Conversely, exclusive reliance on organic nutrient sources, although environmentally sustainable, often fails to meet the high nutrient demand of fast-growing crops like summer squash. Organic inputs such as farmyard manure, poultry manure, vermicompost, and liquid formulations like Jeevamrit release nutrients gradually and may not supply sufficient nutrients during critical growth and reproductive stages (Farhan et al., 2021; Ritika, 2024). As a result, suboptimal vegetative growth, delayed flowering, reduced fruit set, and lower yields are frequently observed under intensive cultivation systems (Sarhan et al., 2011; Shareef et al., 2022). Therefore, achieving a balance between high productivity and long-term soil sustainability remains a key challenge in summer squash production systems.

In this context, integrated nutrient management (INM) has emerged as a practical and sustainable strategy to address these limitations. INM promotes the combined use of organic manures, inorganic fertilizers, and biofertilizers to optimize nutrient availability, enhance soil physical and biological properties, and improve crop productivity (Mehata et al., 2023; Sah et al., 2024). Organic amendments contribute to improved soil structure, water-holding capacity, and microbial activity, whereas inorganic fertilizers provide readily available nutrients required for rapid plant growth. Biofertilizers further enhance nutrient-use efficiency through mechanisms such as biological nitrogen fixation and phosphorus solubilization (Kulkarni & Gargelwar, 2019; Pathma & Sakthivel, 2012). Several studies on cucurbit crops have reported positive effects of integrated nutrient management on growth, flowering, and yield attributes (Kaur & Rattan, 2021). However, yield formation in summer squash is a complex process governed by the interaction of multiple vegetative, phenological, and reproductive traits rather than a single factor. Most previous research has relied primarily on univariate statistical approaches, which may not adequately capture these complex trait interactions. Multivariate analytical techniques, including principal component analysis (PCA), correlation analysis, clustering, and regression modeling, offer robust tools to simultaneously evaluate multiple traits, identify key yield determinants, and visualize treatment responses in an integrated framework (Ghimire et al., 2023; Pandit et al., 2025). Despite their analytical advantages, such approaches have rarely been applied in nutrient management studies on summer squash under Nepalese conditions.

Therefore, the present study was undertaken to address this knowledge gap by conducting a comprehensive multivariate assessment of integrated nutrient management practices and their effects on vegetative growth, flowering behavior, and yield determinants of summer squash under sustainable cultivation systems in Nepal. The specific objectives were to evaluate the performance of different organic, inorganic, and integrated nutrient sources and to identify key growth and reproductive traits contributing to yield improvement using advanced multivariate analytical techniques.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted during the summer season (March–June 2024) at the Directorate of Agricultural Research (DoAR), Tarahara, Sunsari, under NARC, Koshi Province, Nepal. The experimental site is located in the eastern Terai at an altitude of approximately 130 m above sea level, with geographic coordinates of 26°70′45″ N latitude and 87°28′11″ E longitude (Figure 1). The area is characterized by a subtropical climate, receiving an average annual rainfall of about 1435.3 mm, with maximum and minimum temperatures of 39.2°C and 11.8°C, respectively. The site provided suitable agro-climatic conditions for evaluating the growth and yield response of summer squash under different nutrient management practices.

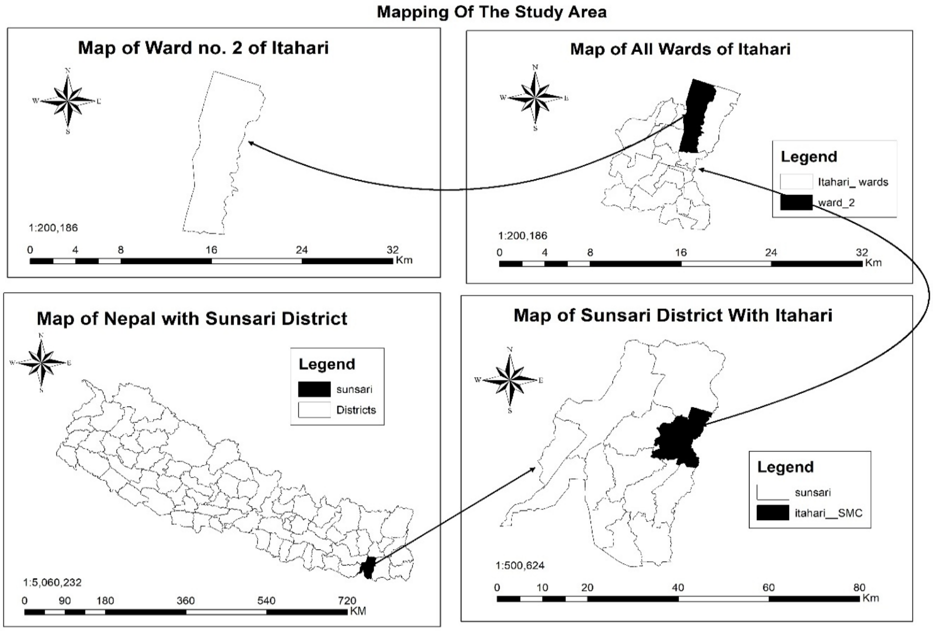

Figure 1. Map of Nepal showing geographical location of experimental site.

2.2. Soil Sampling and Laboratory Analysis

The detailed results of the soil analysis are summarized in Table 1. Before sowing, composite soil samples were collected from the 0–25 cm depth and analyzed using standard methods. The experimental soil was clay loam, slightly acidic (pH 6.57), with moderate organic matter (2.76%) and total nitrogen (0.18%), high available phosphorus (75.56 ppm), and low available potassium (49.34 ppm). These baseline properties provided a suitable basis for evaluating the effects of different nutrient management practices on summer squash.

Table 1. Physico-chemical properties of experimental soil and analytical methods used.

S. N.	Parameters	Results	Methods
1	Textural class	Clay loam	Bouyoucos Hydrometer
2	Organic matter content	2.76 %	Walkley and Black
3	Available Nitrogen	0.18%	Kjeldahl Digestion
4	Available Phosphorous	75.56 ppm	Olsen
5	Available Potassium	49.34 ppm	Ammonium acetate extraction
6	pH	6.57	Potentiometric 1:2.5

2.3. Experimental Setup and Cultural Practices

The field experiment was conducted following a Randomized Complete Block Design (RCBD) comprising eight treatments replicated three times, resulting in 24 experimental plots. The experimental area covered 159.74 m^2, with individual plots measuring 2.6 m × 1.6 m. Adequate spacing was maintained to avoid treatment interference, with 1 m between replications and 60 cm between adjacent plots. Treatments were allocated randomly within each block using the lottery method, ensuring uniform representation of all treatments across replications. The study utilized the summer squash variety Sondo V. Seeds were soaked in clean water for 24 hours to enhance germination, shade-dried for 3 hours, and sown in plastic nursery cups containing a sterilized 1:1:1 mixture of soil, vermicompost, and coco-peat. Seedlings were raised under shaded conditions and transplanted into the field, followed immediately by irrigation. Land preparation was carried out after harvesting the preceding crop through deep ploughing and repeated harrowing to obtain a fine tilth. Crop residues were removed, plots were levelled, and slightly raised beds with drainage furrows were prepared to facilitate proper water management. Irrigation was applied 2–3 times per week during vegetative and flowering stages and once weekly after 20 DAT, depending on rainfall and soil moisture conditions. To minimize weed competition, manual weeding was performed twice during the crop growth period. All experimental plots were managed uniformly in accordance with recommended agronomic practices throughout the growing season.

2.4. Treatments Details

To evaluate the influence of different nutrient management practices on summer squash, a total of eight treatments involving organic, inorganic, and integrated fertilizer sources, along with a control, were imposed in the experiment. These treatments included bio-fertilizer, poultry manure, vermicompost, farmyard manure, Jeevamrit, NPK, and a combined application of half NPK with half FYM, each applied at their respective doses. The treatment details and notations used for analysis are presented in Tables 2 and 3.

Table 2. List of treatments along with doses and their notations.

Treatments	Dose	Notations
Bio-fertilizer	60 kg ha^{-1}	T1
Poultry manure	39.3 Mt ha^{-1}	T2
Vermicompost	39.3 Mt ha^{-1}	T3
$\frac{1}{2}$ (NPK + FYM)	$\frac{1}{2}$ (NPK + FYM)	T4
Farmyard manure	58.95 Mt ha^{-1}	T5
Jeevamrit	1L per plant	T6
NPK	235: 176: 117 kg ha^{-1}	T7
Control	-	T8

Table 3. Application of different treatments details at basal dose and at 30. 45 & 60 DAT.

Treatments	Before transplanting	30 DAT	45 DAT	60 DAT
T1	14.67 gm/plant bio-fertilizer was kept in the field days before transplanting	-	-	-
T2	1.31 kg/plant Poultry manure kept in the pit days before seedling	-	-	-
T3	1.31 kg/plant vermicompost placed in the pit days before seedling	-	-	-
T4	2.42 g Urea, 3 g DAP, 1 g MOP + 0.98 kg farmyard manure/plant was applied in soil before transplanting	1.21 g Urea/plant was top-dressed.	1.21 g urea/plant was top-dressed.	-
T5	1.96 kg/plant FYM was applied per pit a day before transplanting.	-	-	-
T6	-	At 30DAT Jeevamrut was applied at the dose of 1L/plant. Jeevamrut was applied following the ring-basin method.	At 30DATJeevamrut was applied at the dose of 1L /plant.Jeevamrut was applied following the ring-basin method.	At 30DAT Jeevamrut was applied at the dose of 1L /plant. Jeevamrut was applied following the ring basin method.
T7	4.84 g Urea, 6 g DAP, and 2 g MOP/plant was applied in the soil before transplanting	2.42 g Urea/plant was top-dressed.	2.42 g urea/plant was top-dressed.	-
T8	-	-	-	-

2.5. Observations and Data Collection

Data were collected from three randomly selected, healthy plants in each experimental plot to evaluate crop performance. Measurements were grouped into vegetative and reproductive attributes. Vegetative growth parameters, namely leaf number and lateral branch count, were recorded at 15, 30, and 45 days after transplanting (DAT). Reproductive observations included days to first flowering, days to 50% flowering, number of fruits per plant, average fruit weight, fruit yield per plant, fruit length, and fruit diameter.

2.6. Statistical Analysis

Data were organized in Microsoft Excel 2019 and analyzed using RStudio (version 4.1.1). Treatment effects were evaluated through one-way ANOVA under a Randomized Complete Block Design (RCBD), and mean separation was performed using the Least Significant Difference (LSD) test at 5% significance ($p \leq 0.05$). Model assumptions were checked prior to analysis. Pearson correlation and linear regression were used to examine relationships between yield and key vegetative and reproductive traits, with R^2 used to describe association strength. Multivariate analyses, including Principal Component Analysis (PCA), correlation heatmaps, hierarchical clustering, and radar charts, were conducted to assess trait interrelationships and treatment patterns. Although the experiment included three replications, which is standard for field-based RCBD studies, the low CV values and clear treatment separation indicate adequate precision and sufficient statistical reliability for both univariate and multivariate analyses. All analyses and visualizations were performed in RStudio, and results are presented in tables and figures.

3. Results

3.1. Effect of Organic Fertilizers on Vegetative Parameters

3.1.1. Number of Leaves per Plant

The number of leaves per plant was significantly affected by fertilizer treatments at 30 DAT ($p \leq 0.01$) and 45 DAT ($p \leq 0.05$), whereas differences at 15 DAT were statistically non-significant (Table 4). Although NPK recorded the highest leaf number at 15 DAT (8.36), the treatments did not differ significantly at this early growth stage (CV = 8.48%), suggesting uniform crop establishment. Clear treatment effects emerged at 30 DAT, where NPK (17.77 leaves plant^{-1}) produced the maximum leaf number and remained statistically comparable with poultry manure (15.99) and $\frac{1}{2}$ (NPK + FYM) (15.88), but significantly superior to the control (11.66). At 45 DAT, NPK (36.27) and vermicompost (35.03) maintained higher leaf production and were statistically at par with other organic and integrated treatments, while the control (21.81) recorded significantly fewer leaves. The progressive increase in leaf number under integrated and nutrient-enriched treatments indicates improved nutrient availability and sustained nutrient release, which enhanced vegetative growth compared to the unfertilized control.

Table 4. Effect of organic fertilizer on leaf number per plant.

Treatments	Leaf number per plant		
	15DAT	30DAT	45DAT
Bio-fertilizer	7.03b	15.22bc	32.80a
Poultry manure	7.27b	15.99ab	33.09a
Vermicompost	7.40ab	14.66bc	35.03a
$\frac{1}{2}$ (NPK + FYM)	7.33ab	15.88abc	32.49a
Farmyard Manure	6.84b	13.44bc	30.92a
Jeevamrit	6.86b	14.44cd	31.20a
NPK	8.36a	17.77a	36.27a
Control	6.37b	11.66d	21.81b
Grand mean	7.18	14.88	31.70
F-test	0.0520^{NS}	0.0052**	0.0232*
LSD $_{(0.05)}$	0.92	2.15	6.19
CV (%)	8.48	9.54	12.88
SEM (±)	0.30	0.71	2.04

3.1.2. Number of Lateral Branches per Plant

The number of lateral branches per plant was significantly influenced by fertilizer treatments at all observation stages (15 DAT: $p \leq 0.01$; 30 and 45 DAT: $p \leq 0.05$) (Table 5). At 15 DAT, NPK produced significantly higher lateral branches (2.92) compared to all other treatments, while the control recorded the lowest value (1.77), indicating early responsiveness to readily available nutrients. At 30 DAT, NPK (3.50) maintained superiority and was statistically at par with vermicompost (2.87), poultry manure (2.86), and $\frac{1}{2}$ (NPK + FYM) (2.87), but significantly higher than the control (2.10). A similar trend was observed at 45 DAT, where NPK (4.81) recorded the maximum number of branches and differed significantly from the control (2.99), while vermicompost (4.40) and $\frac{1}{2}$ (NPK + FYM) (4.06) showed comparable and improved performance over sole organic treatments. The overall means (2.05, 2.68, and 3.81 at 15, 30, and 45 DAT, respectively) indicate progressive branching with crop growth, and acceptable CV values (10.47–16.32%) confirm experimental precision. The enhanced branching under integrated and inorganic nutrient sources suggests improved nitrogen availability and balanced nutrient supply, which promoted vegetative proliferation compared to the unfertilized control.

3.1.3. Days to First Flowering

Days to first flowering were highly significantly influenced by fertilizer treatments ($p \leq 0.001$) (Table 6). The earliest flowering was recorded under NPK (18.66 days), which was statistically at par with bio-fertilizer, vermicompost, and farmyard manure (19.00 days), but significantly earlier than the control (21.66 days). Poultry manure, Jeevamrit, and $\frac{1}{2}$ (NPK + FYM) required 20.00 days to initiate flowering and showed intermediate performance. The overall mean was 19.66 days with a low CV (2.35%), indicating high experimental precision. The earlier flowering under nutrient-enriched treatments suggests that balanced nutrient availability accelerated vegetative growth and promoted timely transition to the reproductive stage compared to the unfertilized control.

Table 5. Effect of organic fertilizers on lateral branches formation.

Treatments	Lateral branches		
	15DAT	30DAT	45DAT
Bio-fertilizer	1.87b	2.53b	3.73bcd
Poultry manure	1.84b	2.86ab	3.74bcd
Vermicompost	1.91b	2.87ab	4.40ab
$\frac{1}{2}$ (NPK + FYM)	2.08b	2.87ab	4.06abc
Farmyard manure	1.96b	2.31b	3.40cd
Jeevamrit	2.05b	2.46b	3.41cd
NPK	2.92a	3.50a	4.81a
Control	1.77b	2.10b	2.99d
Grand mean	2.05	2.68	3.81
F-test	0.0003**	0.0416*	0.0224*
LSD $_{(0.05)}$	0.32	0.66	0.82
CV (%)	10.47	16.32	14.30
SEM (±)	0.10	0.21	0.27

3.1.4. Days to 50% Flowering

Days to 50% flowering also differed highly significantly among treatments ($p \leq 0.001$). NPK recorded the earliest 50% flowering (22.00 days), followed closely by bio-fertilizer (22.33 days), farmyard manure (22.33 days), and vermicompost (22.66 days), whereas the control took significantly longer (25.33 days). Integrated treatment $\frac{1}{2}$ (NPK + FYM) (23.66 days) and poultry manure (23.33 days) showed moderate response. The grand mean was 23.08 days with a CV of 2.93%, reflecting reliable experimental consistency. These findings indicate that improved nutrient supply hastened crop maturity and synchronized flowering compared to nutrient-deficient conditions.

Table 6. Effect of different organic fertilizers on Flowering of summer squash.

Treatments	Days to first flowering	Days to 50% flowering
Bio-fertilizer	19.00c	22.33cd
Poultry manure	20.00b	23.33bc
Vermicompost	19.00c	22.66bcd
$\frac{1}{2}$ (NPK + FYM)	20.00b	23.66b
Farmyard manure	19.00c	22.33cd
Jeevamrit	20.00b	23.00bcd
NPK	18.66c	22.00d
Control	21.66a	25.33a
Grand mean	19.66	23.08
F-test	0.000032***	0.00078***
LSD $_{(0.05)}$	0.70	1.02
CV (%)	2.35	2.93
SEM (±)	0.23	0.33

3.2 Effect of Organic Fertilizers on Reproductive Traits

The reproductive performance of summer squash was markedly affected by different nutrient management practices (Table 7). All yield-related parameters showed significant variation among treatments, clearly indicating the decisive role of nutrient sources and integration on fruit development and productivity. The individual effects on each reproductive trait are elaborated below:

3.2.1. Fruit Diameter (mm)

Fruit diameter was highly significantly influenced by nutrient treatments ($p \leq 0.001$) (Table 6). NPK recorded the maximum fruit diameter (80.26 mm), which was statistically superior to most treatments and markedly higher than the control (53.46 mm). Integrated treatment $\frac{1}{2}$ (NPK + FYM) (78.28 mm) and vermicompost (77.90 mm) performed comparably and remained at par with NPK. The lowest diameter under the control indicates nutrient deficiency effects on fruit development. The low CV (2.81%) reflects high experimental precision.

3.2.2. Fruit length (cm)

Fruit length differed highly significantly among treatments ($p \leq 0.001$). The longest fruits were observed under $\frac{1}{2}$ (NPK + FYM) (25.24 cm), which was statistically at par with NPK (24.78 cm), while the control recorded the shortest fruits (20.24 cm). Organic treatments such as vermicompost (23.96 cm) and farmyard manure (23.81 cm) showed intermediate performance. The results suggest that integrated nutrient supply promoted enhanced cell expansion and fruit elongation.

3.2.3. Number of Fruits per Plant

The number of fruits per plant was significantly affected ($p \leq 0.01$). NPK produced the highest fruit number (7.16), followed by poultry manure (6.83) and $\frac{1}{2}$ (NPK + FYM) (6.73), whereas the control recorded the lowest (5.62). The moderate CV (5.56%) indicates reliable variability. Enhanced fruit number under nutrient-enriched treatments may be attributed to improved flowering and fruit set.

3.2.4. Individual Fruit Weight (g)

Individual fruit weight showed significant variation ($p \leq 0.05$). NPK recorded the highest fruit weight (920.94 g), significantly higher than the control (733.83 g). Integrated and organic treatments such as $\frac{1}{2}$ (NPK + FYM) (866.78 g) and farmyard manure (867.04 g) were statistically comparable and produced heavier fruits than sole bio-fertilizer treatment. Adequate nutrient availability likely enhanced assimilation, accumulation and fruit filling.

3.2.5. Fruit Yield per Plant (g)

Fruit yield per plant varied significantly among treatments ($p \leq 0.01$). NPK produced the highest yield per plant (6033.64 g), followed by $\frac{1}{2}$ (NPK + FYM) (5357.00 g) and vermicompost (5282.16 g), all significantly superior to the control (3698.45 g). The observed trend corresponds closely with fruit number and individual fruit weight, indicating that yield per plant was directly derived from these components.

3.2.6. Fruit Yield (t/ha)

Total fruit yield was significantly influenced by nutrient management ($p \leq 0.01$). NPK achieved the highest yield (46.07 t ha^{-1}), whereas the control recorded the lowest (28.55 t ha^{-1}). Integrated treatments, particularly $\frac{1}{2}$ (NPK + FYM) (40.99 t ha^{-1}) and vermicompost (40.43 t ha^{-1}), produced yields statistically comparable to NPK, demonstrating that partial substitution of inorganic fertilizer with organic sources can sustain high productivity. The close correspondence between yield per plant and yield per hectare reflects mathematical conversion rather than independent biological variation.

Table 7. Value of yield parameters as influenced by different nutrient management practices.

Treatments	Fruit diameter (mm)	Fruit length (cm)	No. of fruits per plant	Individual fruit weight (g)	Fruit yield per plant (g)	Fruit yield (t/ha)
Bio-fertilizer	77.89ab	22.27d	6.38bc	786.53bc	4327.36cd	33.27cd
Poultry manure	76.41bc	22.96cd	6.83ab	821.13bc	5078.73bc	38.91bc
Vermicompost	77.90ab	23.96bc	6.63abc	830.06b	5282.16ab	40.43ab
$\frac{1}{2}$ (NPK + FYM)	78.28ab	25.24a	6.73abc	866.78ab	5357.00ab	40.99ab
Farmyard manure	69.00d	23.81bc	6.66abc	867.04ab	5248.40ab	40.18ab
Jeevamrit	73.34c	23.49cd	6.16cd	838.78ab	4701.71bc	36.08bc
NPK	80.26a	24.78ab	7.16a	920.94a	6033.64a	46.07a
Control	53.46e	20.24e	5.62d	733.83c	3698.45d	28.55d
Grand mean	73.32	23.34	6.52	833.14	4965.93	38.06
F-test	***	***	**	*	**	**
P-value	4.703e-09	2.254e-05	0.005017	0.01990	0.001723	0.001725
$LSD_{(0.05)}$	3.13	1.09	0.55	78.05	745.29	5.59
CV (%)	2.81	3.08	5.56	6.17	9.89	9.68
SEM (±)	1.03	0.36	0.18	25.73	245.71	1.84

3.3. Regression and Correlation

The regression analysis demonstrated significant associations between fruit yield (t ha^{-1}) and major vegetative, phenological, and reproductive traits of summer squash (Figure 2). Yield showed strong positive linear relationships with number of leaves

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per plant (R^2 = 0.93) and number of lateral branches per plant (R^2 = 0.90), indicating that improved vegetative growth enhanced assimilate production and sink development. In contrast, days to first flowering and days to 50% flowering exhibited negative relationships with yield (R^2 = 0.74), suggesting that delayed flowering reduced yield potential, whereas early flowering favored better reproductive performance. Among fruit traits, yield was positively associated with fruit diameter (R^2 = 0.84), fruit length (R^2 = 0.93), and number of fruits per plant (R^2 = 0.97), confirming that both fruit size and fruit number substantially contributed to total productivity. The apparent perfect linear relationship between individual fruit weight and yield (R^2 = 1.00) reflects mathematical dependency rather than biological causation. Fruit yield per plant was calculated directly as the product of number of fruits per plant and individual fruit weight; therefore, a deterministic relationship is expected. Similarly, the perfect association between yield per plant and yield per hectare (R^2 = 1.00) resulted from direct unit conversion based on planting density and does not represent an independent biological correlation. These relationships were therefore interpreted as computational derivations rather than causal physiological interactions Therefore, these relationships should be interpreted as computational rather than causal. Overall, the analysis indicates that yield variation was primarily driven by vegetative vigor, timely flowering, and enhanced fruit attributes under improved nutrient management.

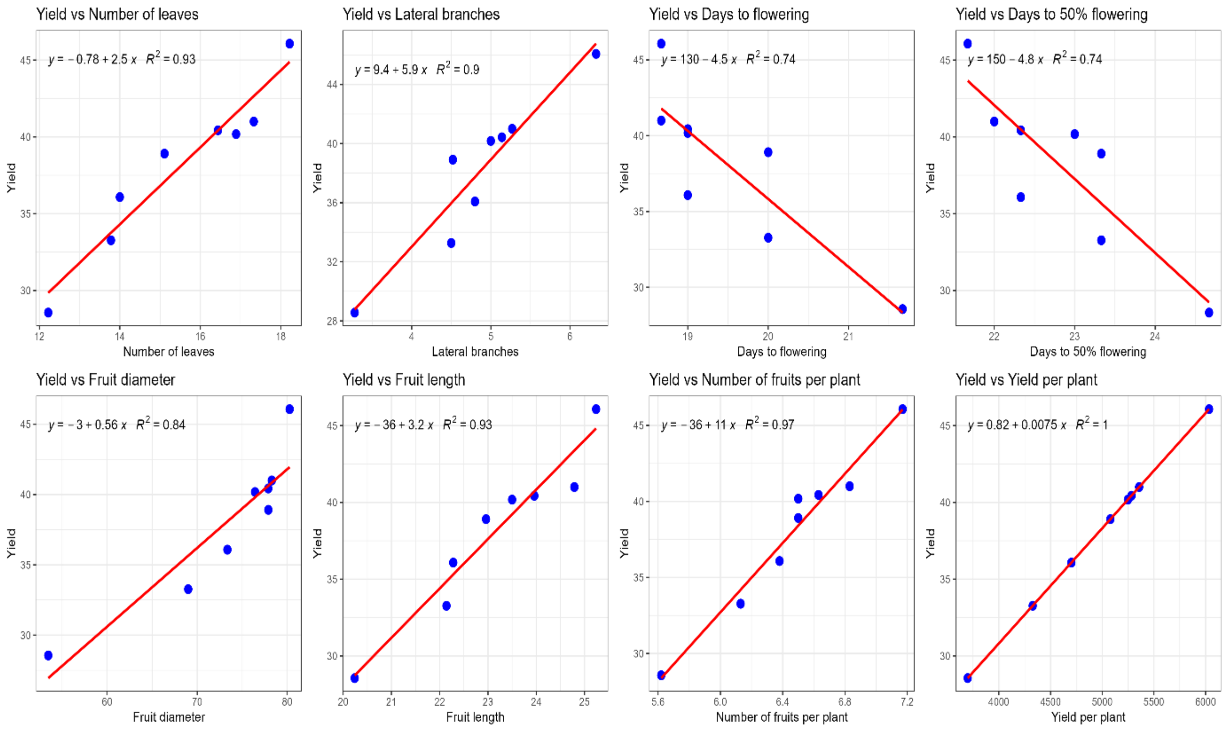

Figure 2. Linear regression equations, coefficients of determination (R^2), and scatter plots illustrating the relationships between yield and major vegetative, phenological, and reproductive traits of summer squash, including leaf number, lateral branches, flowering time, fruit size, fruit number, individual fruit weight, and yield per plant.

3.4. Multivariate Analysis

3.4.1. Principal Component Analysis (PCA)

Principal Component Analysis was performed to identify the major traits contributing to yield variation and to reduce multicollinearity among measured variables (Figure 3). The first two principal components explained 96.2% of the total variability, with PC1 accounting for 92.7% and PC2 for 3.5%, indicating that most trait variation was captured along a single dominant gradient. PC1 showed strong positive loadings for fruit yield, fruit yield per plant, number of fruits per plant, individual fruit weight, fruit diameter, fruit length, number of leaves, and lateral branches, demonstrating that these traits collectively contributed to higher productivity. In contrast, days to first flowering and days to 50% flowering exhibited negative loadings on PC1, confirming that delayed flowering was associated with reduced yield performance. The PCA biplot clearly separated high-performing treatments from low-performing ones along PC1. NPK and $\frac{1}{2}$ (NPK + FYM) were positioned in the positive quadrant closely aligned with yield and yield-attributing traits, indicating their strong contribution to productivity. Conversely, the control treatment was located in the negative direction of PC1, associated with lower values of growth and yield parameters. Sole organic treatments occupied intermediate positions, suggesting moderate performance. Rather than merely describing graphical distribution, the PCA results biologically confirm that yield improvement was primarily governed by enhanced fruit number, fruit weight, and vegetative vigor under balanced nutrient supply.

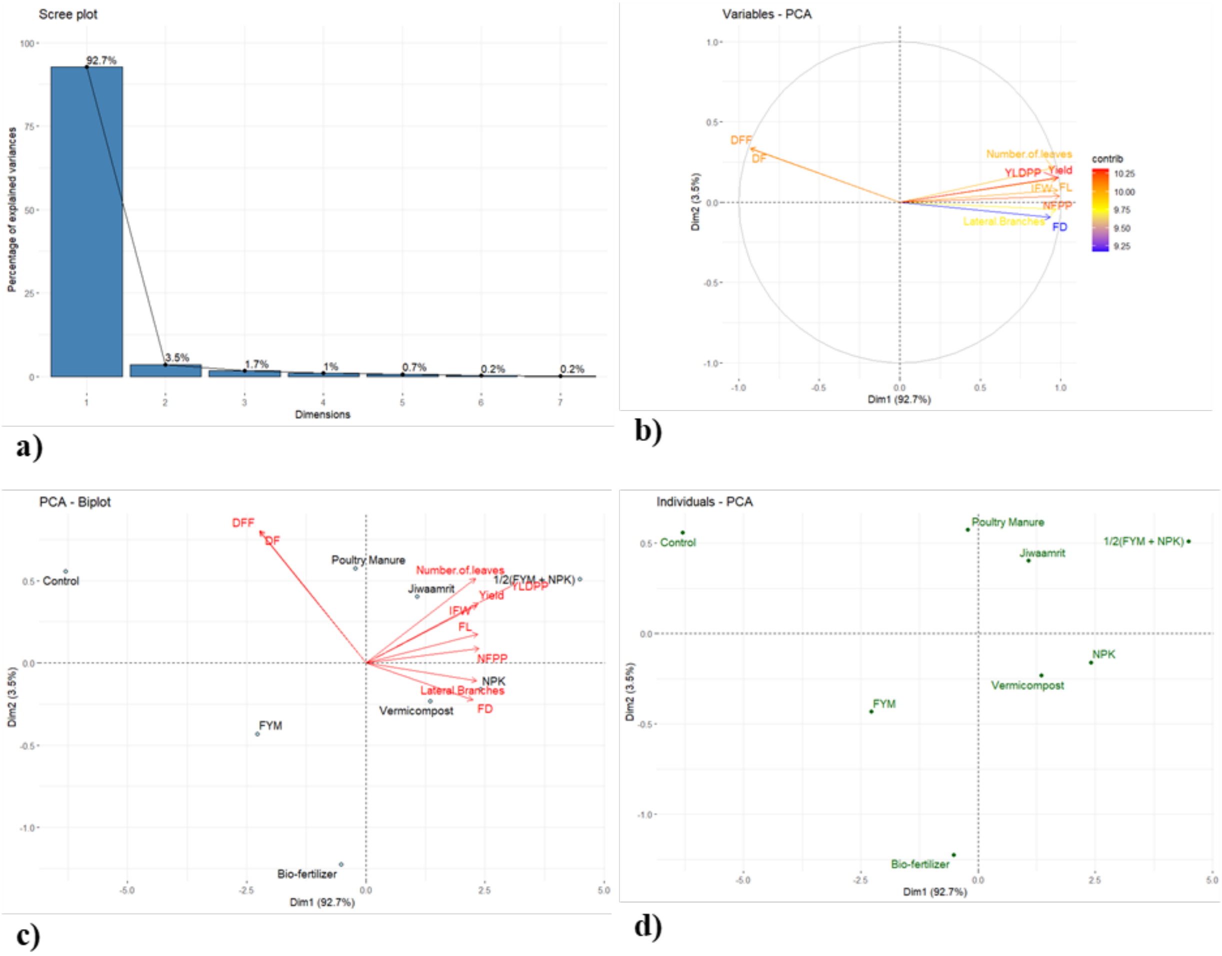

Figure 3. Principal component analysis (PCA): a) Scree plot showing the key components proportion of variance explained, b) PCA-variable plot, loading plot showing each measured variables contribution for PC1 vs. PC22, c) PCA biplot, d) Individual treatment principal component analysis between PC1 and PC2.

3.4.2. Correlation Heatmap and Hierarchical Clustering of Summer Squash Traits

The heatmap and hierarchical clustering (Figures 4 and 5) collectively illustrate trait associations and treatment similarity based on standardized values. The color gradient (blue = lower performance; red = higher performance) clearly shows that $\frac{1}{2}$ (FYM + NPK) and NPK exhibit strong positive responses (intense red) for yield and yield-attributing traits, including fruit diameter, fruit length, number of leaves, lateral branches, fruit weight, number of fruits per plant, yield per plant, and total yield, while flowering traits (DF and DFF) display negative associations (blue shades), confirming that earlier flowering favored higher productivity. In contrast, the control treatment shows the opposite pattern, with red coloration for delayed flowering and deep blue for yield traits, indicating poor overall performance. The dendrogram further groups $\frac{1}{2}$ (FYM + NPK) and NPK together as a high-performing cluster, closely associated with yield-enhancing traits, followed by Jeevamrit and vermicompost as moderately performing treatments. FYM, poultry manure, and bio-fertilizer form another cluster with intermediate responses, while the control appears as a distinct and isolated cluster. Together, these analyses biologically confirm that integrated and balanced nutrient management strengthens positive trait interactions and maximizes yield performance in summer squash.

3.4.3. Radar Chart Showing Comparative Analysis of Growth and Yield Traits

The radar chart (Figure 6) presents a comparative overview of standardized growth, flowering, and yield traits under different nutrient management treatments, where each axis represents one trait and the distance from the center indicates relative performance. Treatments with larger and more expanded polygon shapes demonstrate superior and balanced expression across multiple traits. The integrated treatment $\frac{1}{2}$ (FYM + NPK) and NPK show broad and outward-expanded profiles for key yield-related parameters such as fruit diameter (FD), fruit length (FL), number of fruits per plant (NFPP), individual fruit weight (IFW), yield per plant (YLDPP), and total yield, along with strong vegetative traits (number of leaves and lateral branches). In contrast, the control treatment forms a smaller and inward-contracted polygon for yield traits but extends outward for flowering duration (DF and DFF), indicating delayed flowering and reduced productivity. Organic treatments such as vermicompost, Jeevamrit, poultry manure, and

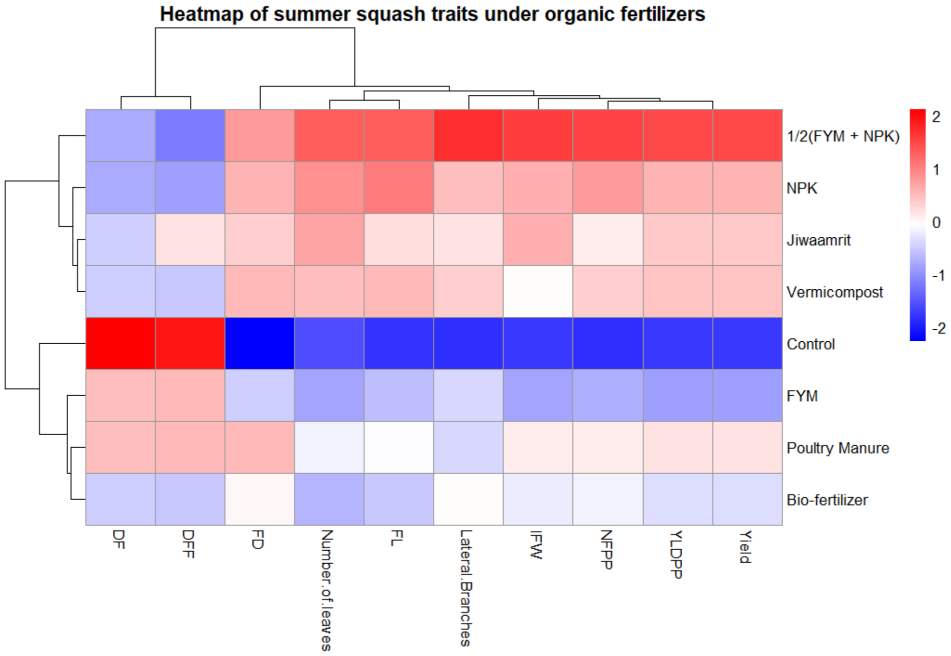

Figure 4. Heatmap illustrating the correlation patterns among vegetative, flowering, and yield traits of summer squash.

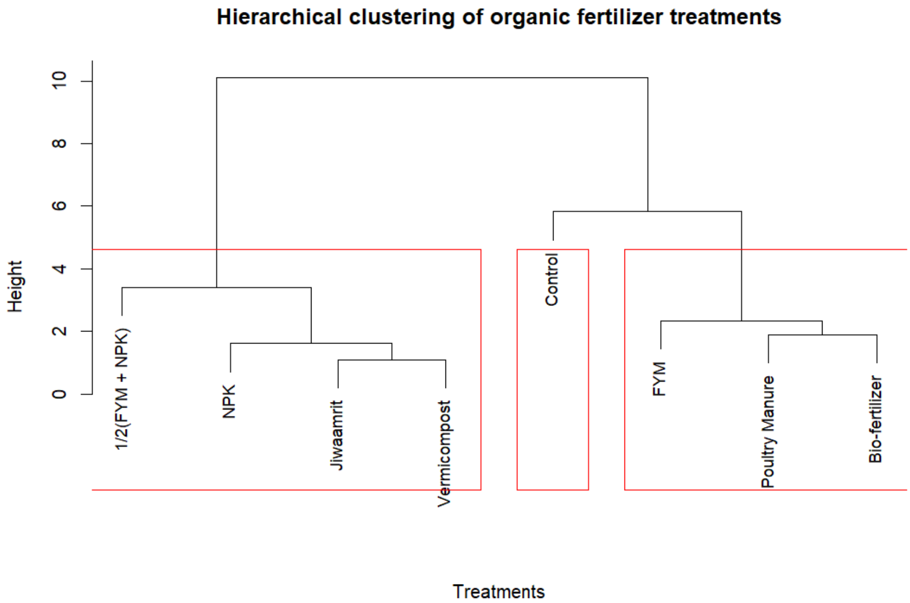

Figure 5. Hierarchical clustering dendrogram showing the similarity and grouping of nutrient management treatments based on overall growth, flowering, and yield traits of summer squash.

FYM display intermediate polygon sizes, reflecting moderate performance. Overall, the radar chart visually summarizes treatment performance, clearly distinguishing high-yielding integrated nutrient treatments from moderate and low-performing treatments, and demonstrating the advantage of balanced nutrient management in achieving improved growth and yield in summer squash.

4. Discussion

4.1. Effect of Organic Fertilizers on Vegetative Parameters

The significant variation observed in vegetative growth and flowering traits under different nutrient management practices highlights the critical role of balanced nutrient supply in summer squash production. The consistently higher number of leaves and lateral branches recorded under $\frac{1}{2}$ (NPK + FYM) across growth stages demonstrates the synergistic advantage of integrated nu-

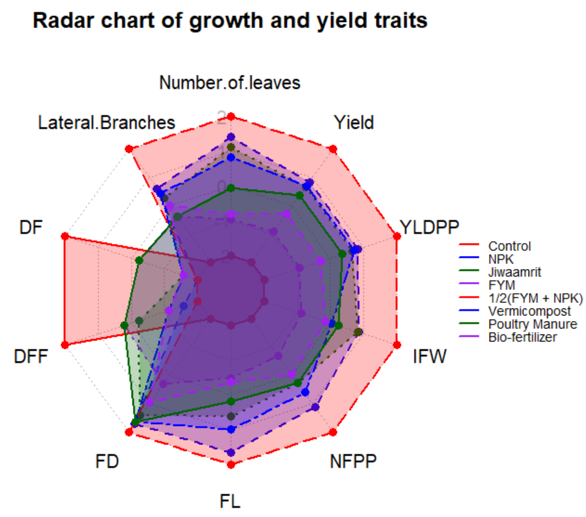

Figure 6. Radar chart depicting the comparative performance of different nutrient management treatments on key growth, flowering, and yield traits of summer squash.

trient management. The combined application ensured immediate nutrient availability from inorganic fertilizers while farmyard manure improved soil structure, enhanced microbial activity, and provided sustained nutrient release, collectively promoting vigorous vegetative development. These findings are consistent with earlier reports by Kaur and Rattan (2021) and Ibraheem et al. (2019), who documented enhanced vegetative growth in cucurbits under integrated fertilization systems. The strong performance of NPK alone further emphasizes the importance of readily available nitrogen in stimulating leaf expansion and branch proliferation, supporting greater photosynthetic capacity and sink development, as also reported by Ibraheim and Mohsen (2015). In contrast, Jeevamrit and vermicompost produced moderate improvements over the control, likely due to gradual nutrient mineralization and stimulation of beneficial soil microorganisms, which enhance nutrient uptake efficiency but may not meet peak crop demand during rapid growth phases (Kulkarni & Gargelwar, 2019; Kumar et al., 2014). Flowering behavior was similarly influenced by nutrient availability. The earlier onset of first flowering and 50% flowering observed under $\frac{1}{2}$ (NPK + FYM) and NPK indicates accelerated physiological maturity resulting from balanced nutrient supply. Adequate nitrogen and phosphorus likely supported optimal vegetative growth without prolonging the vegetative phase, thereby facilitating timely reproductive transition. Comparable findings were reported by Antonious et al. (2022), who observed earlier and more synchronized flowering in summer squash under balanced fertilization regimes. Conversely, delayed flowering under the control and sole organic treatments can be attributed to nutrient limitations and slower nutrient release patterns, which extended vegetative growth and postponed reproductive development, as also noted by Farhan et al. (2021). Overall, the present results confirm that integrated nutrient management not only enhances vegetative vigor but also promotes earlier and more synchronized flowering, thereby establishing favorable physiological conditions for improved fruit development and yield formation in summer squash.

4.2 Effect of Organic Fertilizers on Reproductive Traits

The reproductive performance of summer squash was markedly influenced by the type and balance of nutrient supply, with integrated application of $\frac{1}{2}$ (NPK + FYM) producing the most consistent improvements across yield-attributing traits. The significantly greater fruit diameter and fruit length observed under integrated nutrient management indicate enhanced cell division and elongation, likely resulting from synchronized nutrient availability throughout the growth cycle. The immediate nutrient supply from inorganic fertilizers, combined with the gradual release and soil-conditioning effects of farmyard manure, created favorable conditions for sustained fruit development. Similar improvements in fruit size under integrated fertilization have been reported by Magray et al. (2025) and Pandit et al. (2025), who attributed the response to enhanced nutrient uptake and efficient assimilate partitioning. Kaur and Rattan (2021) also documented superior fruit dimensions in summer squash under combined nutrient sources compared to sole applications. The higher number of fruits per plant recorded under $\frac{1}{2}$ (NPK + FYM) and NPK treatments suggests improved flowering efficiency and fruit set under adequate nutrient availability, particularly nitrogen and potassium, which are critical for reproductive development. These findings align with those of Pandit et al. (2025) and Yadav et al. (2020), who emphasized the role of balanced fertilization in reducing flower drop and enhancing fruit retention in squash. Comparable responses have been observed in cucumber (Chapagain et al., 2022) and bitter gourd (Ghimire et al., 2023), indicating that integrated nutrient management promotes reproductive efficiency across cucurbit crops. In contrast, the reduced fruit number under the control treatment in the present study reflects nutrient stress conditions that likely limited carbohydrate production and allocation to developing fruits. The significant increase in individual fruit weight under integrated fertilization reflects improved assimilate accumulation and efficient nutrient transport to sink organs. This response may be attributed to enhanced photosynthetic activity resulting from improved vegetative vigor, as confirmed in the present study. Shareef et al. (2022) similarly reported heavier summer squash fruits under combined organic and inorganic fertilizer application. Mehta et al. (2024) also observed increased fruit weight in okra under integrated nutrient regimes, attributing the improvement to better synchronization between nutrient release and crop demand. Treatments involving vermicompost and Jeevamrit showed moderate fruit weights, likely due to gradual nutrient mineralization and stimulation of beneficial microbial activity (Pathma & Sakthivel, 2012; Mehata et al., 2023; 2024), which may not fully meet peak nutrient demand during rapid fruit development. The combined effects of increased fruit size, fruit number, and fruit weight were reflected in significantly higher fruit yield per plant and fruit yield per hectare under $\frac{1}{2}$ (NPK + FYM). It is important to note that the strong association between yield per plant and yield per hectare observed in this study reflects direct computational derivation rather than independent biological causation. Nevertheless, the superiority of integrated fertilization in maximizing total yield is consistent with findings by Pandit et al. (2025) and Kaur and Rattan (2021), who highlighted that integrated nutrient management ensures continuous and balanced nutrient supply throughout the crop cycle. Similar yield advantages of integrated fertilization have been reported in carrot and beetroot by Ishwar et al. (2024) and Majhi et al. (2024), suggesting broader applicability of this approach across vegetable crops. Conversely, the lowest yield recorded under the control treatment clearly demonstrates the adverse effects of nutrient omission on reproductive development and yield formation. Overall, the present findings confirm that integrating inorganic fertilizers with farmyard manure provides a balanced and efficient nutrient supply that enhances fruit development, improves reproductive efficiency, and maximizes yield under the studied agro-climatic conditions.

5. Conclusion and Recommendations

The present investigation clearly demonstrated that nutrient management practices significantly affected the growth, flowering behavior, and yield performance of summer squash. Among the tested treatments, the integrated application of $\frac{1}{2}$ (NPK + FYM) consistently achieved superior results across vegetative parameters, flowering traits, and yield attributes, ultimately producing the highest fruit yield per plant and per hectare. Multivariate analyses (PCA, clustering, heatmap, radar chart, and regression) further confirmed that yield improvement was primarily associated with enhanced vegetative vigor, increased fruit number, and greater individual fruit weight under balanced nutrient supply. Although NPK alone also produced high yields due to immediate nutrient availability, integrated fertilization provided a more balanced expression of growth and yield traits. Sole organic treatments showed moderate improvements, whereas the control consistently recorded the lowest performance, emphasizing the necessity of adequate nutrient supply. Considering productivity and sustainability together, the combined application of $\frac{1}{2}$ NPK + FYM can be recommended as an efficient nutrient management strategy for summer squash under similar agro-climatic conditions. This approach not only sustains high yield but also supports improved soil health through organic matter addition. Future research should focus on long-term soil fertility dynamics, nutrient use efficiency, economic feasibility through cost–benefit analysis, and validation of integrated nutrient strategies across different environments and cultivars to strengthen sustainable production recommendations.

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Author Contributions

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