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Influence on yield and quality attributes of cape gooseberry (*Physalis peruviana* L.) with the application of nitrogen, zinc and boron

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ABSTRACT

An experiment was conducted on cape gooseberry (*Physalis peruviana* L.) in the Department of Fruit Science, CSAUAT, Kanpur during two concequitive years *i.e.,* 2023-24 and 2024-25, using nine treatments *viz.,* T_1-75 kg N/ha + 0.6% $ZnSO_4$ + 0.6% boron; T_2-75 kg N/ha + 0.6% $ZnSO_4$ + 0.9% boron; T_3-75 kg N/ha + 0.9% $ZnSO_4$ + 0.6% boron; T_4-75 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron; T_5-100 kg N/ha + 0.6% $ZnSO_4$ + 0.6% boron; T_6-100 kg N/ha + 0.6% $ZnSO_4$ + 0.9% boron; T_7-100 kg N/ha + 0.9% $ZnSO_4$ + 0.6% boron; T_8-100 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron; T_9-Control (without application of any nutrient), in Randomised Block Design with three replications. Results of the experiments revealed that plants in treatment T_8-100 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron produced consistently highest fruit yield (99.58 and 105.68 q/ha), TSS (13.18 and 13.49 °Brix), total sugars (10.04% and 10.14%), ascorbic acid (46.81 and 47.13 mg/100g), TSS: acid ratio (12.52 and 13.06), sugar : acid ratio (12.49 and 12.63) along with antioxidant traits including phenols (101.25 and 107.65) and carotenoids (848.62 and 907.23) with lower amount of titratable acidity (1.05 and 1.03). Pooled data of both years also confirmed the statistical superiority of T_8, which was comparable to T_6 and T_7 for most yield and quality parameters, while the lowest values were recorded in the control (T_9). Principal Component Analysis (PCA) revealed that the first two components explained 94.95% of the total variance, with the T_6 and T_8 treatments being strongly associated with yield and biochemical traits. At the same time, T_9 was negatively aligned with quality indices. Correlation analysis revealed strong positive associations between fruit yield and total sugars (r = 0.98), ascorbic acid (r = 0.95), phenols (r = 0.94) and carotenoids (r = 0.99), indicating a synergistic role of nutritional and antioxidant traits in enhancing productivity. The study concludes that integrated foliar application of nitrogen, zinc and boron significantly enhances both yield and fruit quality in cape gooseberry under plains of north India.

Key words : Input synergy, nitrogen, micro nutrient, fruit quality, PCA, sustainable yield.

INTRODUCTION

Cape gooseberry (*Physalis peruviana* L.), a commercially underutilised but nutritionally potent fruit crop belonging to the family Solanaceae, widely known as "golden berry" or "Rasbhari," Inca berry or Peruvian groundcherry, produces edible berries, covered by a protective husk (calyx) is valued for its rich bioactive compounds (Petkova *et al.,* 17). The growing popularity of cape gooseberry is attributed to a combination of favourable factors, including its attractive appearance, pleasant taste and aroma, rich chemical composition, and associated nutritional, biological, and physiological benefits. In addition, the crop offers high yields and good profitability for farmers. The fruit contains a wide range of phytonutrients and bioactive compounds, making it an excellent functional food. These constituents contribute to its reported antidiabetic, antihypercholesterolemic, hepatoprotective, anti-inflammatory, immunomodulatory, and antioxidant properties (Ramadan, 20). The fruit has gained significance in both fresh consumption and processed forms, such as jam, jelly, juice, and dried snacks (Akhand *et al.,* 4). Despite its wide adaptability and medicinal potential, the cultivation of cape gooseberry in India remains limited due to suboptimal nutrient management. The crop's shallow root system and high berry load demand efficient and balanced nutrition, especially involving nitrogen (N), zinc (Zn) and boron (B).

Although several studies have explored the individual effects of nitrogen, zinc, and boron on various horticultural crops, but limited research has been conducted on their combined and interactive influence on yield and quality parameters of Cape gooseberry. Most existing literature focuses on major fruit crops, leaving minor or underutilized fruits like Cape gooseberry under-researched in terms of micronutrient management (Ramadan, 20). Moreover, there is a lack of standardized nutrient recommendations specific to different agro-climatic zones for this crop. This creates a critical gap in understanding the synergistic or antagonistic effects of these nutrients on growth, fruit development,

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biochemical composition, and overall productivity of Cape gooseberry. Addressing this gap could support improved nutrient management practices and enhance the commercial viability of this high-value crop.

Recent findings suggest that the integrated use of macro- and micronutrients significantly improves plant vigour, reproductive efficiency and fruit quality traits, such as total soluble solids (TSS), sugar content, ascorbic acid and carotenoid levels. In view of the above context, the present investigation was undertaken to evaluate the impact of different levels of macro- (N) and micronutrients (Zn and B) on yield and quality attributes of cape gooseberry under field conditions of north Indian plains.

MATERIALS AND METHODS

The present experiments were conducted over two consecutive years, *i.e.*, during the 2023-24 and 2024-25 growing seasons, Department of Fruit Science, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India. The site is situated in a subtropical zone at an elevation of 135 meters above mean sea level, positioned between 25.26° and 26.58° North latitude and 79.31° and 80.34° East longitude. The experiment involved varying levels of nitrogen combined with foliar applications of zinc sulphate ($ZnSO_4$) and boron at different concentrations in nine treatments *viz.,* T_1-75 kg N/ha + 0.6% $ZnSO_4$ + 0.6% boron; T_2-75 kg N/ha + 0.6% $ZnSO_4$ + 0.9% boron; T_3-75 kg N/ha + 0.9% $ZnSO_4$ + 0.6% boron; T_4-75 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron; T_5-100 kg N/ha + 0.6% $ZnSO_4$ + 0.6% boron; T_6-100 kg N/ha + 0.6% $ZnSO_4$ + 0.9% boron; T_7-100 kg N/ha + 0.9% $ZnSO_4$ + 0.6% boron; T_8-100 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron; T_9-Control (without application of any nutrient), in a Randomized Block Design (RBD) with three replications.

Seeds of cape gooseberry were procured from Sharma Farming Solutions, Aligarh, Uttar Pradesh and were sown in the month of September during both year on raised nursery beds and 30-35 days after sowing, healthy seedlings containing 4-5 functional leaves, which are uniform and vigorous in growth were transplanted at a plant spacings of 60 x 60 cm into the main field. A basal dose of N (75:100 kg/ha) was uniformly applied using urea as the nitrogen source at the time of transplanting. Zinc sulphate and boron were applied through foliar spray using a knapsack sprayer at two growth stages: 45 and 75 days after transplanting. All other agronomic practices and plant protection measures were uniformly followed throughout the experimental period.

A comprehensive set of observations on yield (q/ha) and quality attributes *viz.,* total soluble solids (°Brix), titratable acidity (%), total sugar (%), ascorbic acid content (mg/100g), TSS: acid ratio, sugar: acid ratio, total phenol content (mg GAE/100g) and total flavonoids (mg/100g) were recorded during the experimental period using the methods as described (Ahamad *et al.,* 2; Arya *et al.,* 5). Analysis of variance (ANOVA) was performed to test the significance of treatment effects, and the validity of the results was tested through the F-test.

Statistical analyses of data recorded during the experimentation period were estimated as per treatments using the Statistical Methods as suggested by Panse and Sukhatame (16). For multivariate interpretation of trait interrelationships and treatment effects, Principal Component Analysis (PCA) was conducted using SPSS statistical software (version 25.0). The PCA helped to identify the significant contributing variables influencing growth and quality traits under different nutrient treatments.

RESULTS AND DISCUSSION

During both years of experimentation (2023-24 and 2024-25), plants in the treatment T_8 consistently produced the highest fruit yield of 99.58 and 105.68q/ha, respectively, followed by T_7, which produced fruit yield of 99.18q/ha in 2023-24 and 104.30q/ha in 2024-25. The control treatment (T_9) produced the lowest fruit yield during both years of experimentation (68.59q/ha and 72.27q/ha, respectively). Pooled data also confirmed the superiority of T_8 (102.63q/ha), which is statistically at par with T_7 (101.74q/ha) and T_6 (101.56q/ha). In contrast, T_9 (70.43q/ha) remained significantly inferior, as indicated in Table 1. Overall, the data clearly showed a substantial positive impact of foliar nutrient treatments on fruit yield enhancement. Nitrogen plays a crucial role in promoting vegetative growth and leaf area development, thereby enhancing photosynthetic rate and assimilating production. Zinc contributes to chlorophyll formation, hormone activation, and reproductive development, while boron is known to facilitate pollination, fruit set, and the translocation of sugars to developing fruits. These findings are supported by the reports of Arya *et al.* (5), who reported that yield under zinc and boron treatments was due to improved vegetative vigour and reproductive efficiency in Aonla. Similar finding was also reported by Babu and Tripathi (6) in guava, Yadav and Tripathi (24) in phalsa and Bhadauria *et al.* (7) in aonla, and Tripathi and Shukla (23) in strawberry.

The quality attributes of fruits treated with treatment T_8 consistently having the highest ascorbic acid content with the values of 46.81mg/100g and 47.13mg/100g, respectively, followed by T_7 (45.30 and

Table 1: Response on ascorbic acid, TSS, total sugar and titratable acidity and field yield of cape gooseberry with the application of nitrogen, zinc and boron.

Treatment	Ascorbic acid (mg/100 g)			TSS (°Brix)			Titratable acidity (%)			Total sugar (%)			Fruit yield (q/ha)		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T_1	34.41	35.60	35.00	12.62	12.72	12.67	1.100	1.100	1.100	9.16	9.20	9.18	70.34	72.72	71.53
T_2	35.56	36.21	35.88	12.66	12.77	12.72	1.097	1.093	1.095	9.25	9.27	9.26	76.40	79.92	78.16
T_3	38.75	39.26	39.01	12.83	12.95	12.89	1.087	1.080	1.083	9.32	9.41	9.37	81.93	85.44	83.69
T_4	39.88	41.18	40.53	13.01	13.03	13.02	1.073	1.070	1.072	9.35	9.59	9.47	93.06	98.08	95.57
T_5	42.45	44.42	43.43	13.03	13.12	13.07	1.067	1.063	1.065	9.42	9.58	9.50	96.94	102.45	99.70
T_6	44.79	45.60	45.20	13.11	13.14	13.13	1.063	1.060	1.062	9.56	9.62	9.59	98.73	104.39	101.56
T_7	45.30	46.21	45.75	13.16	13.21	13.18	1.060	1.043	1.052	9.92	9.95	9.94	99.18	104.30	101.74
T_8	46.81	47.13	46.97	13.18	13.49	13.33	1.053	1.033	1.043	10.04	10.14	10.09	99.58	105.68	102.63
T_9	34.14	35.42	34.78	11.36	11.38	11.37	1.097	1.107	1.102	9.08	9.12	9.10	68.59	72.27	70.43
S.E. ±	0.42	0.54	0.38	0.11	0.10	0.09	0.01	0.01	0.01	0.09	0.06	0.07	0.58	0.36	0.34
C.D. at 5% level	0.90	1.17	0.80	0.24	0.22	0.20	0.02	0.02	0.02	0.21	0.14	0.14	1.25	0.77	0.73

46.21 mg/100g, respectively), while the lowest was found in T_9 (34.14 and 35.42mg/100g, respectively). Pooled data also confirmed the superiority of T_8 (46.97mg/100g), which was statistically at par with T_7 (45.75mg/100g) and T_6 (45.20mg/100g), while T_9 (34.78mg/100g) remained significantly inferior (Table 1). The increase in ascorbic acid content resulting from the integrated application of nitrogen, zinc and boron may be attributed to the enhanced physiological activity in the plants, including improved photosynthesis, protein synthesis, and enzyme activation, which collectively promote the biosynthesis and stabilisation of ascorbic acid during fruit development. Nitrogen supports the formation of glucose precursors required for vitamin C synthesis. Zinc activates ascorbate-related dehydrogenases and boron regulates membrane permeability, which stabilises antioxidant retention in fruit tissues. The lower vitamin C content in control plants was likely due to poor nutrient uptake, limited metabolic efficiency and rapid oxidative breakdown during ripening (Ahamad *et al.,* 1). Deficiencies in nitrogen, zinc and boron are known to restrict vitamin C synthesis and impair its storage stability due to reduced enzyme cofactor availability and higher cellular leakage. These findings are supported by Chaturvedi *et al.* (8) in strawberry cv. Chandler, Yadav and Tripathi (24) in phalsa, Katiyar *et al.* (11) in ber and Mohit *et al.* (15) in aonla.

The highest total soluble solids (13.18°Brix and 13.49°Brix, respectively) and total sugar (10.04% and 10.14%, respectively) was recorded in fruits produced from the plants treated with T_1-100 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron, followed by T_7, with TSS of 13.16° and 13.21°Brix, respectively and total sugars of 9.92% and 9.95%, respectively, during both years of experimentation *i.e.,* 2023-24 and 2024-25, as shown in Table 1. The lowest TSS (11.36° and 11.38°Brix, respectively) and total sugar content (9.08% and 9.12%, respectively) were recorded in fruits produced from plants kept under control (T_9). Pooled data also confirms the superiority of T_8 with 13.33°Brix of TSS and 10.09% total sugar content, which was statistically at par with T_7 (13.18°Brix and 9.94%, respectively) and T_6 (13.13°Brix and 9.59%, respectively), while treatment T_9 remained significantly inferior (11.37°Brix and 9.10%, respectively). Overall, the data indicate a significant positive effect of optimum nutrient applications on the accumulation of total soluble solids and total sugar in fruits. The increase in TSS and total sugar under T_8 during the present experimentation period may be attributed to improved carbohydrate synthesis and translocation, which is promoted by a balanced nutrition of nitrogen, zinc and boron. Nitrogen, as a core component of chlorophyll, amino acids and enzymes, enhances photosynthetic efficiency and sugar accumulation. Zinc acts as a cofactor in sugar metabolism enzymes, such as dehydrogenases, and plays a role in auxin production, which supports sugar partitioning in sink tissues like fruits. Boron contributes to the movement of sugars across membranes and enhances their deposition in the vacuoles of developing fruits.

These findings align with Prakash *et al.* (18), who reported that the application of 100 kg N/ha, along with 0.9% Zn and 0.9% B, significantly increased total soluble solids (TSS) and total sugar content in cape gooseberry fruits, attributing the response to enhanced vegetative metabolism and assimilate flow to the fruits. These findings are supported by Rawat and Tripathi (22) and substantial rise in TSS with the integrated use of FYM and mineral fertilisers in mango and litchi, Babu and Tripathi (6) in guava, Kumar *et al*. (12) in aonla, Yadav and Tripathi (24) in phalsa and Kumar *et al.* (13) in mango.

The lowest titratable acidity content was consistently recorded in fruit produced under T_8 (1.053% and 1.033%, respectively), followed by T_7 (1.060% and 1.043%, respectively), while the highest titratable acidity was found in T_9 (1.097% and 1.107%, respectively) during both years (Table 1). Pooled data also revealed that the lowest titratable acidity was in T_8 (1.043%), which was statistically at par with T_7 (1.052%) and T_6 (1.062%), whereas T_9 (1.102%) recorded the highest value. These findings indicated a significant acid-lowering effect in treatment applied with optimum nutrient contents. The increase in titratable acidity resulting from the optimum application of nitrogen and micronutrients may be attributed to enhanced organic acid biosynthesis during early fruit development and a delay in acid conversion to sugars during ripening. Nitrogen supports respiratory metabolism and amino acid turnover; zinc facilitates the activity of dehydrogenases in the TCA cycle and boron regulates membrane function and electrolyte balance, all of which influence organic acid accumulation. These findings are supported by Chaturvedi *et al.* (8) in strawberries, the application of zinc and iron with nitrogen improved fruit quality parameters, including acid content, by modulating enzymatic activities associated with organic acid metabolism. These findings are supported by Babu and Tripathi (6) in guava, Kashyap *et al*. (10) in phalsa and Mohit *et al*. (15) in aonla.

Data presented in Table 2, shows that fruit produced in treatment T_8 having the highest TSS: acid ratio (12.52 and 13.06, respectively) and sugar: acid ratio (99.58 and 105.68, respectively) during both years of experimentation, followed by in T_7 with the values of 12.42 and 12.67, respectively for TSS: acid ratio and 99.18 and 104.30 for sugar: acid ratio, whereas T_9 showed the lowest values of 10.36 and 10.28, respectively for TSS: acid ratio and 68.59 and 72.27 sugar: acid ratio. Pooled results also confirmed the same as the maximum TSS: acid ratio was recorded with the value of 12.78 and 102.63 value for sugar: acid in T_8, which was statistically comparable to T_7 (TSS: acid ratio of 12.53 and sugar: acid ratio of 101.56), while T_9 (TSS: acid ratio of 10.32 and sugar: acid ratio of 70.43) remained significantly inferior. These findings emphasise the enhancement in sweetness-to-acidity balance achieved through optimum nutrient application. The superior ratio under T_8 is attributed to enhanced sugar accumulation coupled with moderate acid retention. Nitrogen application enhances chlorophyll content and enzymatic activity associated with sugar biosynthesis. Zinc influences carbohydrate metabolism and acid regulation via its catalytic role

Table 2: Response on sugar: acid, TSS: acid ratio, total phenol and total carotenoid content of cape gooseberry with the application of nitrogen, zinc and boron.

Treatment	Sugar: acid ratio			TSS: acid ratio			Total phenol content (mg GAE/100g)			Total carotenoid content (µg/100g)		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
T_1	10.88	11.24	11.06	11.47	11.56	11.52	94.46	98.17	96.32	818.64	835.37	827.00
T_2	11.36	11.57	11.46	11.55	11.68	11.61	95.20	100.73	97.97	819.37	848.43	833.90
T_3	11.77	11.85	11.81	11.81	11.99	11.90	96.57	101.60	99.08	822.30	850.16	836.23
T_4	11.82	12.05	11.94	12.12	12.17	12.15	99.46	103.55	101.51	822.61	855.86	839.23
T_5	12.08	12.23	12.16	12.21	12.34	12.27	99.92	105.04	102.48	835.08	866.01	850.55
T_6	12.20	12.37	12.28	12.33	12.40	12.36	100.15	105.98	103.07	836.04	869.77	852.91
T_7	12.44	12.55	12.49	12.41	12.66	12.54	100.77	107.00	103.89	844.45	895.02	869.73
T_8	12.49	12.63	12.56	12.51	13.05	12.78	101.25	107.65	104.45	848.62	907.23	877.93
T_9	10.39	10.42	10.40	10.36	10.28	10.32	92.37	96.90	94.64	814.69	839.53	822.11
S.E. ±	0.22	0.10	0.14	0.17	0.10	0.10	1.43	1.61	1.17	10.51	18.79	14.11
C.D. at 5% level	0.46	0.22	0.30	0.36	0.21	0.22	3.06	3.45	2.51	22.47	40.19	30.17

in dehydrogenases, while boron assists in sugar mobilisation and stabilises cellular transport systems. These findings align with those of Chaturvedi *et al.* (8) in strawberries, who found that the application of zinc and iron in strawberries had a positive effect on the sugar-acid balance, supporting their essential role in enhancing quality and reports of Rani and Brahmachari (21) in litchi.

The highest total phenol content was recorded in fruits produced under T_8 (101.25 and 107.65 mg GAE/100g, respectively), followed by T_7 (100.77 and 107.00 mg GAE/100g, respectively). The lowest phenol content was observed in T_9 (92.37 and 96.90 mg GAE/100g, respectively). Pooled data further confirmed the superiority of T_8 (103.38 mg GAE/100g), which was statistically at par with T_7 (103.02 mg GAE/100g) and T_6 (99.43mg GAE/100g), while T_9 (96.4 mg GAE/100g) remained significantly inferior (Table 2). This demonstrates a significant improvement in antioxidant phenol levels resulting from the combined optimum dose of nutrient application. The increase in phenol content during the present experimental period under T_8 is likely due to enhanced metabolic activity triggered by nitrogen availability, zinc-activated enzymes and boron-facilitated membrane stability. Nitrogen supports the biosynthesis of phenylalanine, a precursor in the phenylpropanoid pathway responsible for phenol formation. Zinc acts as a cofactor for polyphenol oxidases and dehydrogenases, while boron is involved in maintaining cell wall integrity and vacuole storage of secondary metabolites. These findings align with those of Maity *et al.* (14) in pomegranate, citing enhanced activation of phenol biosynthesis enzymes as a key factor.

The highest carotenoid content in fruits, T_8 with 848.62 and 907.23 µg/100g, respectively closely followed by T_7 (844.45 and 895.02 µg/100g, respectively), whereas T_9 showed the lowest carotenoid levels (814.69 and 839.53 µg/100g, respectively). Pooled data also confirmed that the fruits produced in T_8 (852.09 µg/100g) were the most effective treatment, which is statistically at par with T_7 (845.59 µg/100g) and T_6 (840.54 µg/100g), while T_9 (807.69 µg/100g) remained significantly inferior (Table 2). The results indicated that the combined foliar treatments had a positive influence on carotenoid biosynthesis. These findings are consistent that nitrogen supplementation enhances carotenoid stability by increasing antioxidant enzyme activity and reducing photooxidative damage. The observed higher carotenoid content under nitrogen-rich treatments in the present study could, therefore, be a result of stimulated biosynthesis and reduced oxidative losses, particularly of β-carotene, the predominant pigment in cape googeberry. Nitrogen application can be reduced without affecting carotenoid content, maturation, shelf life, and yield in stabilising carotenoid pigments through its participation in the structure of superoxide dismutase and other antioxidative enzymes (Chormova *et al.*, 9; Ahamad *et al.,* 3). The sustained carotenoid levels in nitrogen-supplemented treatments in our study mirror the positive influence of nitrogen as enhanced retention of β-carotene and its derivatives was observed during the ripening phase, as reported by Puente *et al.* (19) in cape googeberry.

The PCA biplot (Fig. 1) illustrates the distribution of treatments and their relationships with biochemical and yield-related variables based on the first two principal components (F1 and F2), which together accounted for 94.95% of the total variance (F1: 83.30%, F2: 11.65%). The first component (F1) primarily differentiated treatments based on positive loadings of total soluble solids (TSS), total sugars (TS), total phenolic content (TPC), total carotenoid content (TCC), vitamin C, and yield traits (fruit yield per hectare). These variables formed a tight cluster with vectors pointing in a similar direction, indicating strong mutual correlations and a common influence on treatment performance. Treatments T_5 to T_8, clustered in the positive F1 quadrant, were associated with these traits, highlighting their superior biochemical richness and yield potential.

In contrast, titratable acidity (TA) was located in the negative quadrants of F1 and F2, indicating inverse relationships with quality and yield traits. Specifically, TA was negatively correlated with most productivity traits, while treatment T_9, plotted far left on the F1 axis, aligned closely with high acidity and low-quality indices. Similarly, T_1 to T_3 is positioned near TA, suggesting suboptimal quality performance. The clustering of variables such as S/A ratio, T/A ratio, and TSS suggests that sweetness and antioxidant

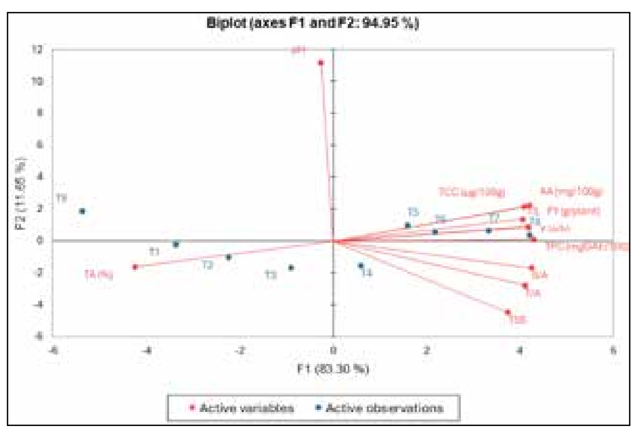

Fig. 1. Principal component analysis of biochemical and yield-related variables cape gooseberry.

richness were decisive contributors to variance, especially under treatments T_6-T_8.

The correlogram (Fig. 2) revealed significant interrelationships among the assessed biochemical parameters and yield attributes of cape gooseberry. A strong positive correlation was observed between total soluble solids (TSS) and total sugar (TS) (r = 0.72), indicating that sugar accumulation significantly contributed to the TSS content. Conversely, titratable acidity (TA) was negatively correlated with most traits, particularly with TSS (r = –0.76), TS (r = –0.96), and TSS/TA ratio (T/A) (r = –0.86), suggesting that an increase in acidity negatively impacts sweetness perception and fruit palatability. The TSS: TA ratio showed a strong positive correlation with vitamin C content (AA) (r = 0.85), total phenolic content (TPC) (r = 0.98), and total carotenoid content (TCC) (r = 0.93), all of which are key quality indicators in strawberries. TPC exhibited significant positive relationships with TSS (r = 0.93), TS (r = 0.88), and AA (r = 0.93), supporting the synergistic role of phenolics and sugars in enhancing antioxidant potential.

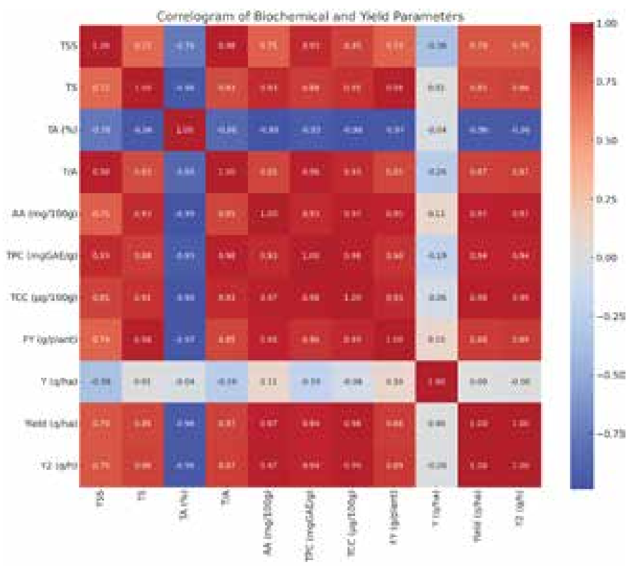

Fig. 2. Correlation among biochemical traits and yield attributes in cape gooseberry.

Among yield parameters, total yield per hectare (Y2) was highly correlated with AA (r = 0.97), TCC (r = 0.99) and TPC (r = 0.94), indicating that antioxidant-rich fruits are associated with higher productivity (Table 3). Interestingly, Y (q/ha), interpreted as marketable yield, showed weak or negligible correlations with biochemical traits (ranging from –0.36 to 0.11), suggesting that it may be influenced more by physical or environmental factors than by internal fruit chemistry. The consistently strong associations between antioxidant compounds (AA, TPC, TCC) and total yield underline the physiological role of bioactive constituents in modulating fruit growth and productivity.

The study concluded that the treatment T_8, consisting of 100 kg N/ha + 0.9% $ZnSO_4$ + 0.9% boron was the most effective treatment in yield and quality attributes in cape gooseberry. Specifically, T_8 improved the highest fruit yield (q/ha), TSS (°Brix), total sugars (%), ascorbic acid (mg/100g), TSS: acid ratio, sugar: acid ratio, along with antioxidant traits including phenols and carotenoids, with a lower amount of titratable acidity. Effective nutrient management, particularly through the application of nitrogen (N), zinc (Zn), and boron (B), which plays a vital role in enhancing yield and quality attributes and fruit development. The observed increase in plant height may be attributed to improved nitrogen

Table 3: Correlation among biochemical traits and yield attributes in cape gooseberry.

Variables	F1	F2	F3	F4	F5
TSS	0.867	-0.388	-0.086	0.299	-0.020
TS	0.938	0.118	0.322	-0.046	-0.031
TA (%)	-0.981	-0.140	-0.062	0.105	0.018
T/A	0.950	-0.240	0.021	0.194	-0.012
AA (mg/100g)	0.973	0.192	-0.029	-0.074	0.077
S/A	0.982	-0.146	-0.051	0.050	0.074
TPC (mgGAE/100)	0.995	0.010	-0.083	-0.040	-0.024
TCC (µg/100g)	0.945	0.185	0.261	0.031	0.007
FY (g/plant)	0.964	0.077	-0.217	-0.128	-0.029
Y (q/h)	0.968	0.074	-0.197	-0.132	-0.026
Eigenvalue	9.163	1.281	0.289	0.236	0.015
Variability (%)	83.302	11.650	2.626	2.148	0.140
Cumulative %	83.302	94.952	97.577	99.725	99.866

assimilation, enhanced uptake and utilization of organic forms of nitrogen, and the development of a well-established root system. Furthermore, the study demonstrated that the integrated application of these nutrients was significantly more effective than their individual application, indicating a synergistic interaction. This synergy can be strategically utilized to achieve sustainable, high-yield, and quality production of cape gooseberry.

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