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RESEARCH ARTICLE

Influence of bio-enhancers and bio-fertilisers on the physical, physicochemical and yield attributes of winter-season guava (*Psidium guajava* L.) cv. L-49

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Abstract

The study explores the impact of bio-enhancers and bio-fertilizers on the physical and physicochemical characteristics of guava (*Psidium guajava* L.) cv. L-49. An experiment was conducted over 2022-23 and 2023-24 at Nursery Kalyanpur, Department of Fruit Science, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur. The study evaluated different treatments, including combinations of Farm Yard Manure (FYM), organic mulch (paddy), Amritpani, Panchagavya, Jivamrit, *Azotobacter* and PSB culture. The study evaluated various physical (fruit diameter, weight, volume, specific gravity, pulp weight, seed weight, pulp to seed ratio and seed count per fruit) and physicochemical attributes (ascorbic acid content, total soluble solids (TSS), titratable acidity, reducing sugar and non-reducing sugar). Yield per ha was also assessed. The results demonstrated significant improvements in the physical attributes of guava with the T_9 treatment (FYM, organic mulch, Panchagavya, PSB culture and *Azotobacter*), yielding the largest fruit diameter (8.26 cm), highest fruit weight (146.61 g) and highest pulp weight (121.83 g). Physicochemical properties such as increased ascorbic acid (294.91 mg/100 g), TSS (13.54 %), total sugars (12.3 %) and reduced titratable acidity (0.61 %) were also improved. This study underscores the potential of integrating bio-enhancers and bio-fertilisers to enhance guava fruit quality and yield.

Keywords: bio-enhancers; bio-fertilisers; fruit quality; guava; physicochemical characters

Introduction

Guava (*Psidium guajava* L.), a plant belonging to the family Myrtaceae, includes approximately 133 genera and 3800 species of trees and shrubs (1, 2). Guava, native to the American tropics, holds substantial economic significance due to its extensive cultivation and diverse applications in the fruit industry, pharmaceuticals and nutraceuticals. India leads global guava production, with a cultivation area of 3.14 lakh ha and an annual yield of 4.92 million tons (3). The fruit is consumed fresh or processed, generating by-products such as seeds, rinds and pulp, which constitute nearly 30 % of its total volume. These residues are valuable resources in the food, chemical and pharmaceutical industries due to their richness in dietary fiber, essential vitamins (A, B, C and β-carotene) and proteins (such as transferrin, ceruloplasmin and albumin). They also contain significant amounts of pectins, antioxidants (including flavonoids, flavonols and condensed tannins) and volatile organic compounds, making them suitable for applications like seed oil extraction and antioxidant-based formulations. These bioactive compounds contribute to health benefits, including chronic disease prevention, reinforcing status of guava as a nutraceutical (4).

Soil degradation due to excessive chemical inputs has prompted a shift towards sustainable alternatives like biofertilizers, which improve soil fertility and plant nutrition. Microbial inoculants, such as Rhizobacteria and Mycorrhiza, enhance nitrogen fixation, facilitate nutrient bioavailability and support plant resilience under abiotic stress. In guava cultivation, nutrient imbalances often lead to poor tree health, reduced yields and inferior fruit quality (5, 6). Given the pivotal role of soil health in horticulture, evaluating the influence of biofertilizers on the physicochemical properties of guava is vital for enhancing fruit yield and quality.

Although the benefits of bio-enhancers such as Panchagavya and Jeevamrit are well-documented in improving soil fertility and enhancing crop yield, their specific influence on the physical, physicochemical and yield attributes of winter-season guava (*Psidium guajava* L.) cv. L-49 remains inadequately studied. Traditional organic formulations have been widely used in sustainable agriculture, yet their potential in guava production, particularly during the winter season when growth conditions vary, is still not fully understood. While chemical fertilizers provide immediate nutrient availability, their long-term use has resulted in declining soil health, environmental pollution such as nitrate leaching and increased production costs, necessitating the search for eco-friendly alternatives (7). Biofertilizers, composed of beneficial microorganisms such as *Pseudomonas*, *Azotobacter* and phosphate-solubilizing bacteria, enhance nutrient availability, nitrogen fixation and phosphorus solubilization, thereby improving plant growth and fruit development (8). However, the extent to which these microbial inoculants interact with bio-enhancers to influence guava's fruit size, weight, biochemical composition and yield remains an area requiring further investigation. Panchagavya, a fermented organic formulation derived from cow dung, urine, milk, ghee and curd, contains essential macro- and micronutrients, amino acids, vitamins and plant growth regulators such as auxins and gibberellins, which improve soil microbial activity and stimulate plant metabolism (9). It has been reported to enhance fruit yield and quality in several crops, including turmeric, ginger and sugarcane (10). Similarly, Jeevamrit, a liquid organic manure made from cow dung, cow urine, gram flour, jiggery and soil, has been found to improve soil fertility and enhance the yield of capsicum and other vegetable crops (11). While these bio-enhancers have shown promising results in various crops, their potential impact on the growth of guava and productivity remains largely unexplored. Understanding how these formulations interact with soil microbiota and nutrient dynamics in guava cultivation is crucial for optimizing organic farming strategies.

Despite these findings, limited research exists on the impact of these bio-enhancers on guava productivity, particularly regarding fruit quality parameters and yield variability during winter-season cultivation. Given the economic importance of guava and the increasing demand for sustainable cultivation practices, it is imperative to explore organic solutions that not only maintain soil fertility but also optimize fruit quality and overall productivity. Therefore, this study aims to evaluate the impact of bio-enhancers and biofertilizers on the growth and yield attributes of guava cv. L-49, with the objective of identifying cost-effective, sustainable alternatives to chemical inputs. The findings will contribute to the development of organic management strategies that support long-term soil health, enhance nutrient efficiency and improve fruit yield and quality, ultimately benefiting both farmers and the environment. These insights will also aid in reducing the dependency on chemical inputs, promoting sustainable agriculture. Furthermore, they can serve as a foundation for future research aimed at optimizing organic cultivation practices for diverse agro-climatic conditions.

Materials and Methods

Experimental site

The study took place in 2022 - 2023 and 2023 - 2024 at the Nursery Kalyanpur, Department of Fruit Science, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur (U.P.). The site is located in a subtropical zone at a latitudes 25.26°-26.58° North and longitudes 79.31°-80.34° East, with an elevation of 135 m above sea level. Various treatments viz., T_1-Control (no treatment), T_2- FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + *Azotobacter* (50 g/tree), T_3-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + *Azotobacter* (50 g/tree), T_4-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + *Azotobacter* (50 g/tree), T_5-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree), T_6-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree), T_7-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree), T_8-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), T_9-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), T_{10}-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree).

Physical attributes such as fruit diameter (cm), fruit weight (g), fruit volume (cc), pulp weight (g), seed weight per fruit (g), pulp to seed ratio, number of seeds per fruit and specific gravity (g/cm^3) were recorded at 120 days. Similarly, physicochemical attributes, including Ascorbic acid content (mg/100 g fruit pulp), total soluble solids (°Brix), titratable acidity (%), TSS : acid ratio and total sugars (%), were measured. Yield (t/ha) was also assessed. The methodologies followed were based on recommendations by previous study (12).

Methodology and crop management

The guava cultivar L-49 was treated with bio-enhancers according to the specific treatment protocols outlined in the study. Panchagavya was applied as a foliar spray on the plant canopy, while Jeevamrit and Amritpani were administered through basal drenching. These applications were performed before and during the flowering and fruit-setting phases to maximize nutrient uptake.

To ensure through foliar coverage, a 10 L solution was administered using a pneumatic foot sprayer with a nozzle, targeting the entire foliage between 8:00 am and 10:00 am. A high-legged stool was employed to facilitate the complete drenching of the plant, including the upper portions. Paddy straw was used as mulch around the root zone to reduce soil moisture loss, suppress weed growth and prevent excess spray runoff. Crop management followed regional agronomic recommendations specific to guava cultivation. Paddy straw was used as mulch around the root zone to minimize soil moisture loss, suppress weed growth and reduce excess spray runoff. Bio-fertilizers were applied as per specific treatment requirements, mixed thoroughly with FYM and incorporated into the soil.

Results and Discussion

Physical attribute

Fruit diameter (cm)

The fruit diameter significantly increased under treatment T9 (FYM, organic mulch, Panchagavya, PSB culture and Azotobacter), reaching an average of 8.26 cm (Table 1). Treatment T_{10}, however, had smaller diameters averaging 8.12 cm. The control exhibited the smallest diameter. These results align with previous study, in which increased size, weight and volume of strawberry fruits with *Azotobacter*, PSB and vermicompost were observed (13). According to another studies, similar findings were reported in strawberry (14, 15).

Fruit weight (g)

Fruit weight was significantly affected by treatment T_9-FYM 10 kg/tree/year + Organic mulch (Paddy) + Panchagavya 3 % + PSB culture 50 g/tree + *Azotobacter* 50 g/tree). Maximum fruit weight (146.61 g) was recorded in both years, compared to lower weights with reduced treatment doses, yet still significant compared to the control 112.54 g fruit weight (Table 1). This correlates with previous findings that taller plants with more branches enhance the photosynthetic area, leading to higher fruit yield (16). Panchagavya use, as noted in an earlier report, may enhance fruit set and reduce flower shedding, improving crop output through better chlorophyll synthesis, nutrient availability and growth-promoting compounds (16–19).

Fruit volume (cc)

Fruit volume was significantly influenced by the application of biofertilizers combined with FYM, particularly in treatment T9, which recorded the highest fruit volume (134.98 cc), followed by T10 (134.32 cc), while the lowest volume was observed in the control (122.12 cc) (Table 1). The improved fruit volume under T9 may be attributed to the synergistic effects of biofertilizers and FYM, which enhance microbial activity, improve soil structure and increase the availability of macro- and micronutrients. This, in turn, promotes better nutrient uptake and assimilation during the critical stages of fruit development. Similar findings earlier reported, demonstrated that Panchagavya application significantly enhances fruit yield and quality in guava, offering an effective alternative to synthetic NPK fertilization (16). The integration of biofertilizers and FYM likely facilitated more efficient nutrient cycling and hormonal stimulation, resulting in improved fruit growth and development (20).

Fruit specific gravity (cc)

T_9 (1.08 cc) recorded the highest specific gravity, the difference with T_{10} (1.06 cc) was not statistically significant, indicating that both treatments had a comparable effect on fruit density. This suggests that the combined application of biofertilizers and FYM in both treatments improved nutrient translocation and dry matter accumulation to a similar extent, leading to denser, higher-quality fruits. Specific gravity is an indicator of fruit density and biochemical composition. Higher specific gravity often correlates with improved sugar content and nutrient density, leading to better fruit quality and consumer preference. Fruits with the lowest specific gravity (0.92 cc pooled) were observed in untreated control plants (Table 1).

Fruit pulp weight

The pulp weight of fruits significantly increased with bio-enhancers and bio-fertilisers. Fruits from (Table 1). T_9 had the highest pulp weight (121.83 g), followed closely by T_{10} (118.44 g). Control fruits had the lowest pulp weight (87.66 g). All treatments, including panchagavya, jivamrit and amritpani with bio-fertilisers, enhanced pulp content compared to the control. These formulations boost soil microbial activity, aiding in nutrient availability and promoting fruit growth throughout the crop cycle, which directly coincided with the findings of earlier reports in strawberry and maize (21–23).

Fruit seed weight per fruit (g)

The application of bio-enhancers and bio-fertilizers led to a slight reduction in seed weight per fruit compared to the control (Table 1). The lowest seed weight (24.77 g) was recorded under treatment T9, while the highest (24.88 g) was observed in the control. This reduction may be attributed to improved nutrient availability enhancing sink strength towards pulp development, thereby allocating more assimilates to fruit flesh rather than seed formation.

Fruit pulp: seed ratio

Fruit pulp: seed ratio was significantly influenced by the application of bio-enhancers and bio-fertilizers compared to control (Table 1). The plants treated with T_9 produced fruits with the highest pulp: seed ratio (4.91 %) followed (4.78 %) by T_{10}. The minimum pulp: seed ratio (3.52 %) was recorded in fruits produced from the plants kept under control. The

Table 1. Influence of various treatments on physical characteristics of Winter Season Guava (*Psidium guajava* L.) cv. L-49

Treatments	Fruit diameter (cm)	Fruit weight (g)	Fruit volume (cc)	Specific gravity (cc)	Pulp weight (g)	Seed weight per fruit (g)	Pulp seed ratio	Number of seed per fruit
T_1	6.06 ± 0.02i	112.54 ± 1.86g	122.12 ± 2.31c	0.92 ± 0.00f	87.66 ± 1.03h	24.88 ± 0.07a	3.52 ± 0.05i	250.56 ± 1.89b
T_2	6.44 ± 0.05h	121.47 ± 0.79f	128.05 ± 1.22b	0.95 ± 0.01ef	96.60 ± 0.89g	24.86 ± 0.29a	3.88 ± 0.02h	248.89 ± 3.86ab
T_3	7.12 ± 0.06f	126.62 ± 2.20de	131.01 ± 1.05ab	0.97 ± 0.01de	101.79 ± 1.60ef	24.83 ± 0.42a	4.10 ± 0.01fg	246.68 ± 0.98ab
T_4	6.80 ± 0.00g	124.29 ± 2.19ef	130.32 ± 0.72ab	0.95 ± 0.01ef	99.44 ± 1.56fg	24.85 ± 0.42a	4.00 ± 0.01gh	247.79 ± 0.86ab
T_5	7.36 ± 0.09e	129.55 ± 2.13cd	131.56 ± 1.50ab	0.98 ± 0.01cd	104.73 ± 0.26de	24.82 ± 0.23a	4.22 ± 0.01ef	245.60 ± 2.99ab
T_6	7.78 ± 0.08cd	134.42 ± 0.54bc	133.00 ± 2.58ab	1.01 ± 0.00c	109.62 ± 0.55bc	24.80 ± 0.14a	4.42 ± 0.03d	243.96 ± 2.18ab
T_7	7.59 ± 0.06d	131.36 ± 0.38cd	132.75 ± 0.86ab	0.99 ± 0.01c	106.55 ± 0.16cd	24.81 ± 0.40a	4.29 ± 0.06e	244.91 ± 2.21ab
T_8	7.92 ± 0.04bc	137.77 ± 2.43b	133.76 ± 2.03a	1.02 ± 0.00b	112.98 ± 1.99b	24.79 ± 0.19a	4.56 ± 0.01c	242.99 ± 4.51ab
T_9	8.26 ± 0.14a	146.61 ± 1.40a	134.98 ± 0.71a	1.08 ± 0.00a	121.83 ± 1.37a	24.77 ± 0.19a	4.91 ± 0.00a	240.79 ± 3.70a
T_{10}	8.12 ± 0.09ab	143.22 ± 0.27a	134.32 ± 2.08a	1.06 ± 0.00a	118.44 ± 1.14a	24.78 ± 0.32a	4.78 ± 0.07b	241.76 ± 2.35ab

[**T_1**-Control (no treatment), **T_2**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + *Azotobacter* (50 g/tree), **T_3**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + *Azotobacter* (50 g/tree), **T_4**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + *Azotobacter* (50 g/tree), **T_5**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree), **T_6**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree), **T_7**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree), **T_8**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), **T_9**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), **T_{10}**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree)].

findings of previous studies agree with the present findings (22, 23).

Number of seeds per fruit

The application of bio-enhancers and bio-fertilizers resulted in a reduction in the number of seeds per fruit compared to the control (Table 1). The lowest number of seed (240.79) was recorded in fruits from plants treated with T_9, while the highest (250.56) was observed in the control. The variation in seed count can be attributed to multiple factors, including improved plant development due to organic manure and enhanced nitrogen fixation facilitated by *Azotobacter*. Additionally, phosphate-solubilizing bacteria (PSB) play a crucial role in making phosphorus more bioavailable, thereby supporting improved fruit set and growth. Azotobacter fixes atmospheric nitrogen, enhancing vegetative growth, which supports fruit expansion while reducing excessive seed formation. PSB enhances phosphorus solubilization, which improves flowering and fruit set, affecting seed number. The synergistic effect of balanced nutrition, coupled with increased nitrogen and phosphorus availability through bio-fertilizer and organic manure application, contributes to these findings. These results align with previous studies on Isabgol and similar trends reported for papaya (24–26).

Yield per hectare (ton)

Fig. 1 shows that the highest yields were recorded in T_9 (8.81), followed by T_{10} (7.84), while the lowest yield (3.46) was observed in T_1 (control). Application of Farm Yard Manure (10 kg/tree/year), paddy mulch and bio-fertilisers like Amritpani (20 %), Panchagavya (3 %), Jivamrit (20 %), *Azotobacter* (50 g/tree) and PSB culture (50 g/tree) significantly enhances soil fertility and nutrient availability, leading to robust growth and higher fruit yield. Farm Yard Manure improves soil structure, paddy mulch conserves moisture effectively and bio-fertilisers stimulate beneficial soil microbial activity. Increased nitrogen and phosphorus availability and enhanced phytohormone production promote nutrient uptake and support greater fruit development and weight due to higher carbohydrate content. Panchagavya enhances guava yield by improving soil fertility through beneficial microbes that aid in nitrogen fixation and phosphorus solubilization. It stimulates key enzymes like nitrate reductase and peroxidase, enhancing nutrient assimilation and plant growth. The presence of auxins, gibberellins and cytokinins boosts cell division, chlorophyll synthesis and photosynthesis, leading to higher fruit production. As well, it improves root proliferation, enhances water and nutrient uptake and strengthens plant resilience against environmental stress. The combined use of farmyard manure, paddy mulchand bio-fertilizers further supports soil structure, moisture retention and microbial activity, ensuring better fruit development, weight and overall yield. These findings are consistent with similar studies carried out in banana, strawberry, aonla and in guava (14, 15, 21, 27–31).

Physicochemical characteristics

TSS (Brix)

The combined data (Table 2) indicated that the highest total soluble solids (TSS) content (13.54 %) was recorded in T_9 (FYM 10 kg/tree/year + Organic mulch + Panchagavya 3 % + PSB culture 50 g/tree + Azotobacter 50 g/tree), which was statistically at par with T_{10}. The results align with findings from earlier report in bananas, which observed increased parameters under organic farming (14). It was reported that using Panchagavya boosted fruit TSS levels by enhancing nitrogen availability for secondary metabolite formation, including phenols that act as natural plant defences (7). The study suggests Panchagavya improves yield metrics and enhances phytochemicals like carotenoids, phenolic compounds, ascorbic acid and antioxidant capacity, potentially inducing plant structural changes. The study suggests Panchagavya improves yield metrics and enhances

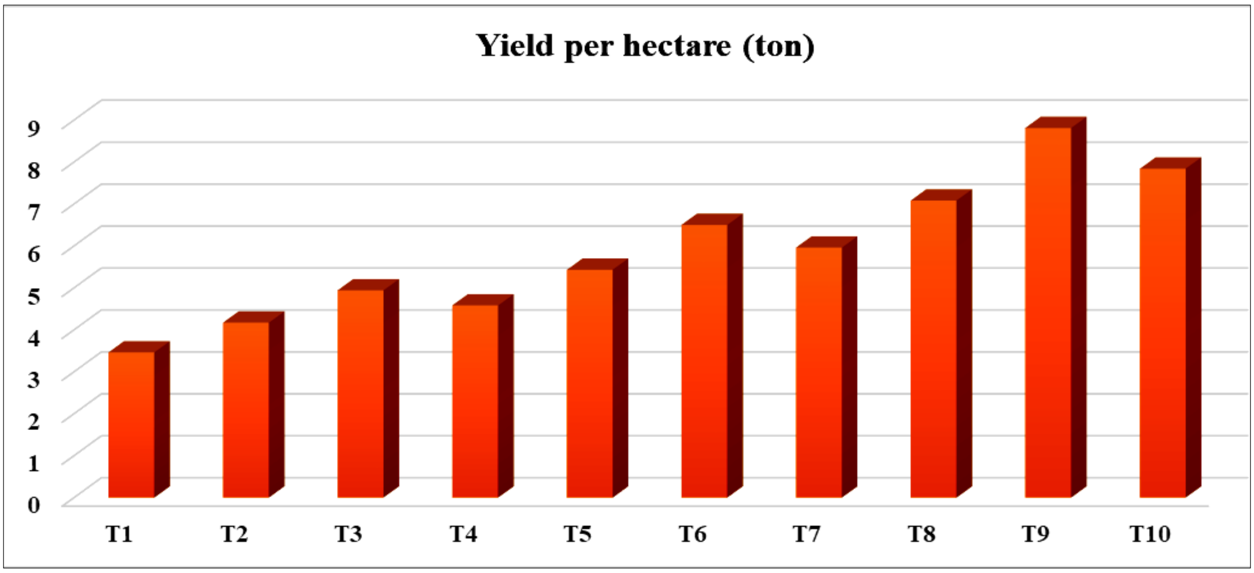

Fig. 1. Effect of various treatments on yield per ha (ton) of Winter season guava (*Psidium guajava* L.) cv. L-49. [Various treatments *viz.*, $\mathbf{T_1}$-Control (no treatment), $\mathbf{T_2}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + *Azotobacter* (50 g/tree), $\mathbf{T_3}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + *Azotobacter* (50 g/tree), $\mathbf{T_4}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + *Azotobacter* (50 g/tree), $\mathbf{T_5}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree), $\mathbf{T_6}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree), $\mathbf{T_7}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree), $\mathbf{T_8}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), $\mathbf{T_9}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), $\mathbf{T_{10}}$-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree)].

phytochemicals like carotenoids, phenolic compounds, ascorbic acid and antioxidant capacity, potentially inducing plant structural changes.

Titratable acidity (%)

According to Table 2, the lowest titratable acidity was observed in T_9 (0.61 %), followed by T_{10} (0.64 %). The reduction in fruit titratable acidity resulting from the application of plant bio-enhancers and bio-fertilisers can be explained by enhanced carbohydrate translocation and increased metabolic conversion of acids into sugars, possibly through processes such as the reversal of the glycolytic pathway or enhanced respiratory activity (32). Furthermore, using micronutrients and bio-enhancers on treated fruits likely contributed to this titratable acidity decrease by promoting earlier fruit ripening, which may accelerate acid breakdown. The reduction in fruit titratable acidity resulting from the application of plant bio-enhancers and bio-fertilisers can be explained by enhanced carbohydrate translocation and increased metabolic conversion of acids into sugars, possibly through processes such as the reversal of the glycolytic pathway or enhanced respiratory activity (32). These findings are consistent with previous research (33).

Total sugar (%)

According to Table 2, the highest total sugar content (12.03 %) was recorded in T_9-treated guava fruits, while the lowest was observed in the control (T_1). The enhanced total sugar content can be attributed to increased photosynthetic activity, stimulated by higher chlorophyll and carotenoid levels in leaves following Panchagavya application. This leads to greater production and translocation of photosynthates, particularly glucose and fructose, into the developing fruits. Additionally, enzymes such as invertase and sucrose synthase play key roles in sugar metabolism by catalyzing the hydrolysis of sucrose into glucose and fructose, thereby increasing the sugar pool available in fruits. These findings are consistent with the earlier reports, which highlight the beneficial impact of Panchagavya and organic inputs on sugar accumulation in guava (7, 13, 14, 34–36).

TSS acid ratio

In Table 2, the application of bio-enhancers and bio-fertilizers significantly influenced the TSS: acid ratio in guava. Among the treatments, T_9 (22.71) exhibited the highest ratio, which was statistically comparable to T10. The progressive increase in the TSS: acid ratio during fruit maturation and ripening can be attributed to the accumulation of total soluble solids and the simultaneous decline in titratable acidity. This trend aligns with previous findings, indicating a natural increase in the TSS: acid ratio during the later growth stages of guava (37). The improved balance between sugars and acids due to bio-enhancer applications suggests their role in enhancing fruit quality, making them a promising alternative for optimizing guava's postharvest attributes.

Ascorbic acid (mg/100 g)

As shown in Fig. 2, the integrated application of bio-fertilizers and bio-enhancers significantly increased ascorbic acid content, with T9 recording the highest level (294.91 mg/100 g). The improvement in physicochemical parameters of fruits can be attributed to the role of bio-fertilizers in enhancing nitrogen fixation and nutrient uptake, which in turn stimulate enzymatic activity involved in key physiological processes. This leads to increased synthesis of sugars and amino acids, thereby elevating overall metabolic activity, including ascorbic acid accumulation (38). The enzyme L-galactono-1,4-lactone dehydrogenase (GalLDH), involved in the terminal step of vitamin C biosynthesis, is likely activated under improved nutrient conditions. These results are consistent with earlier findings reported by (39, 40). The enhancement in fruit quality is also attributed to improved vegetative growth in treated plants, facilitating better photosynthate production and translocation, particularly of starches and carbohydrates, to the developing fruits.

Organoleptic test

In Table 2, the maximum organoleptic test ratings for guava were observed under treatment T_9, with the scores of 95.26 respectively. In contrast, the lowest rating of 75.38 was recorded for treatment T_1 (control). This disparity in ratings can likely be attributed to the application of beneficial microbial agents such as *Azotobacter* and jeevamrit. According to one

Table 2. Influence of various treatments on physicochemical characteristics of Winter season guava (*Psidium guajava* L.) cv. L-49.

Treatments	TSS (°Brix)	Titratable acidity (%)	TSS: acid ratio	Total sugar	Organoleptic Test
T_1	9.81 ± 0.05g	0.93 ± 0.00a	10.56 ± 0.11j	8.24 ± 0.06i	75.38 ± 0.09i
T_2	10.87 ± 0.00f	0.89 ± 0.00b	12.23 ± 0.11i	9.31 ± 0.07h	79.39 ± 0.21h
T_3	12.16 ± 0.04de	0.82 ± 0.01d	14.86 ± 0.01g	10.61 ± 0.04f	82.66 ± 0.59fg
T_4	11.69 ± 0.01e	0.86 ± 0.00c	13.53 ± 0.20h	10.12 ± 0.13g	81.63 ± 0.65g
T_5	12.56 ± 0.01cd	0.77 ± 0.00e	16.31 ± 0.09f	11.04 ± 0.09e	84.41 ± 0.70ef
T_6	12.94 ± 0.09abc	0.69 ± 0.00g	18.98 ± 0.17d	11.45 ± 0.11cd	87.41 ± 0.44cd
T_7	12.82 ± 0.02bc	0.74 ± 0.00f	17.40 ± 0.04e	11.31 ± 0.08de	85.69 ± 0.17de
T_8	13.17 ± 0.09abc	0.67 ± 0.00h	20.12 ± 0.22c	11.68 ± 0.15bc	89.43 ± 0.87c
T_9	13.54 ± 0.12a	0.61 ± 0.00j	22.71 ± 0.17a	12.03 ± 0.16a	95.26 ± 0.84a
T_{10}	13.33 ± 0.09ab	0.64 ± 0.00i	21.13 ± 0.14b	11.84 ± 0.07ab	92.53 ± 1.33b

[Various treatments *viz.*, **T_1**-Control (no treatment), **T_2**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + *Azotobacter* (50 g/tree), **T_3**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + *Azotobacter* (50 g/tree), **T_4**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + *Azotobacter* (50 g/tree), **T_5**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree), **T_6**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree), **T_7**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree), **T_8**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), **T_9**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), **T_{10}**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree)].

report, these treatments contributed to significant improvements in vegetative parameters, leading to enhanced photosynthesis rates and improved translocation of metabolites to the fruits (41). Reports are on the support of efficacy of organic formulations like Panchagavya, Amritpani, Jivamrit, PSB and *Azotobacter* in guava (42, 43). These formulations aim to enhance soil fertility, increase nutrient availability and promote overall plant health. By boosting plant vigor and nutrient uptake, they indirectly contribute to enhancing organoleptic qualities such as taste, aroma, texture and appearance of crops.

Analysis of traits associations for physical, physicochemical and yield attributes of winter-season guava (*Psidium guajava* L.) cv. L-49

Pearson correlation analysis was conducted to evaluate the relationships among physical, physicochemical and yield attributes of winter-season guava under the influence of bio-enhancers and bio-fertilizers (Fig. 3). Most traits exhibited significantly positive correlations with one another, except for ascorbic acid (AC), number of seeds per fruit (NSPF) and seed weight per fruit (SWPF), which showed negative associations with key fruit quality traits.

Fruit weight was strongly and positively correlated with fruit diameter, pulp weight, pulp-to-seed ratio, specific gravity, TSS, titratable acidity, total sugar content, TSS: acid ratio, yield per ha and organoleptic score while, it showed negative correlations with AC, NSPF and SWPF. Ascorbic acid content was positively correlated with NSPF and SWPF but negatively associated with most other fruit quality traits, indicating a trade-off between vitamin C accumulation and bulk yield traits.

Pearson correlation analysis was conducted to examine the relationships among physical, physicochemical and yield attributes of winter-season guava under bio-enhancers and bio-fertilizers (Fig. 3). It is evident that except Ascorbic acid (AC), Number of seeds per fruit (NSPF) and Seed weight per fruit (SWPF), other traits exhibited significantly positive correlation among themselves. On the other hand, Ascorbic acid (AC), Number of seeds per fruit (NSPF), Seed weight per fruit (SWPF) were negatively correlated with fruit diameter, fruit weight, pulp weight, pulp: seed ratio, specific gravity, TSS, TSS: acid ratio, Total sugar, TSS: acid ratio, Yield per ha and Organoleptic Test. Fruit weight was positively correlated with fruit diameter, fruit weight, pulp weight, pulp: seed ratio, specific gravity, TSS, TSS: acid ratio, Titratable acidity, Total sugar, TSS: acid ratio, Yield per ha and Organoleptic Test, whereas negatively correlated with Ascorbic acid (AC), Number of seed per fruit (NSPF), Seed weight per fruit (SWPF). Ascorbic acid (AC) were positively correlated with the Number of seeds per fruit (NSPF) and seed weight per fruit (SWPF) and highly negatively correlated with traits like fruit diameter, fruit weight, pulp weight, pulp: seed ratio, specific gravity, TSS, TSS: acid ratio, Titratable acidity, Total sugar, TSS: acid ratio, Yield per ha and Organoleptic Test. Fruit weights were positively correlated. These correlations suggest that bio-enhancer treatments promoting fruit size and pulp development may simultaneously reduce seed load and modify nutritional content, which is beneficial for guava production.

Principal component analysis

The principal component analysis (PCA) loading plots illustrate the contribution of different variables to principal components and their interrelationships across treatments (Fig. 4). PCA was employed to assess the association between treatments and key fruit quality and yield attributes (Fig. 3). The biplot analysis revealed a structured grouping of traits based on their similarity and variation. Traits were primarily distributed across PC1 and PC2, forming distinct clusters. Group I comprised the majority of key parameters, including fruit

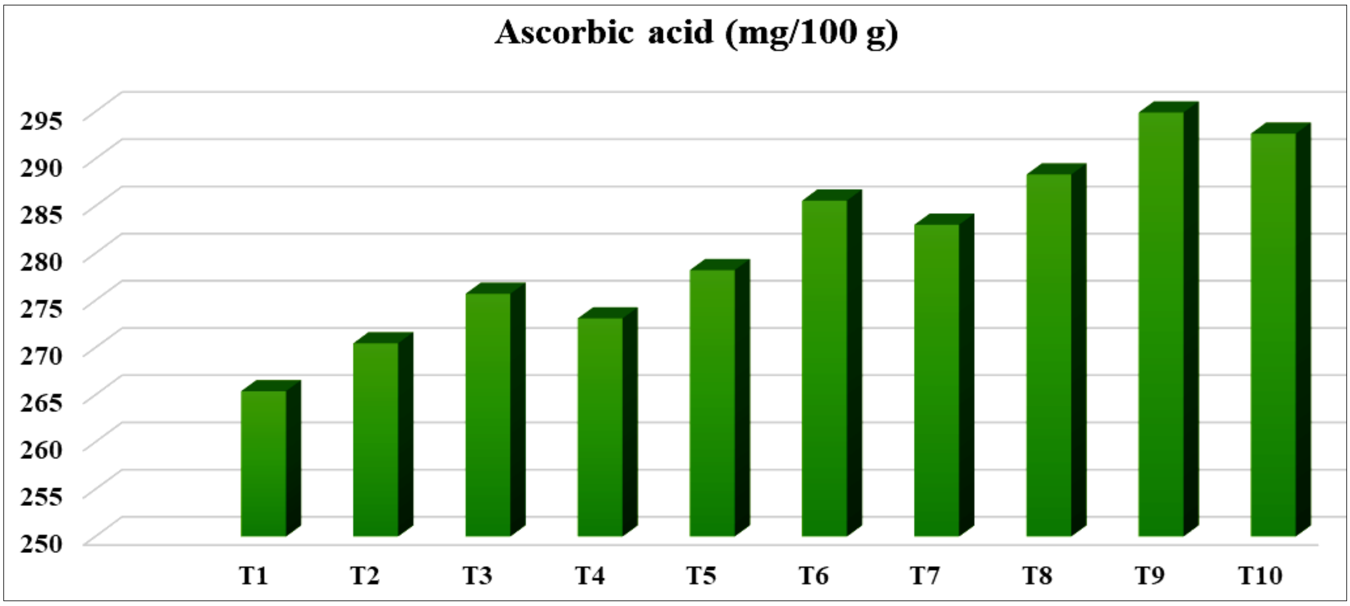

Fig. 2. Effect of various treatments on ascorbic acid (mg/100 g) of Winter season guava (*Psidium guajava* L.) cv. L-49. [Various treatments *viz.*, **T_1**-Control (no treatment), **T_2**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + *Azotobacter* (50 g/tree), **T_3**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + *Azotobacter* (50 g/tree), **T_4**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + *Azotobacter* (50 g/tree), **T_5**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree), **T_6**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) + PSB culture (50 g/tree), **T_7**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree), **T_8**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Amritpani (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), **T_9**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Panchagavya (3 %) +PSB culture (50 g/tree) + *Azotobacter* (50 g/tree), **T_{10}**-FYM (10 kg/tree/year) + Organic mulch (Paddy) + Jivamrit (20 %) + PSB culture (50 g/tree) + *Azotobacter* (50 g/tree)].

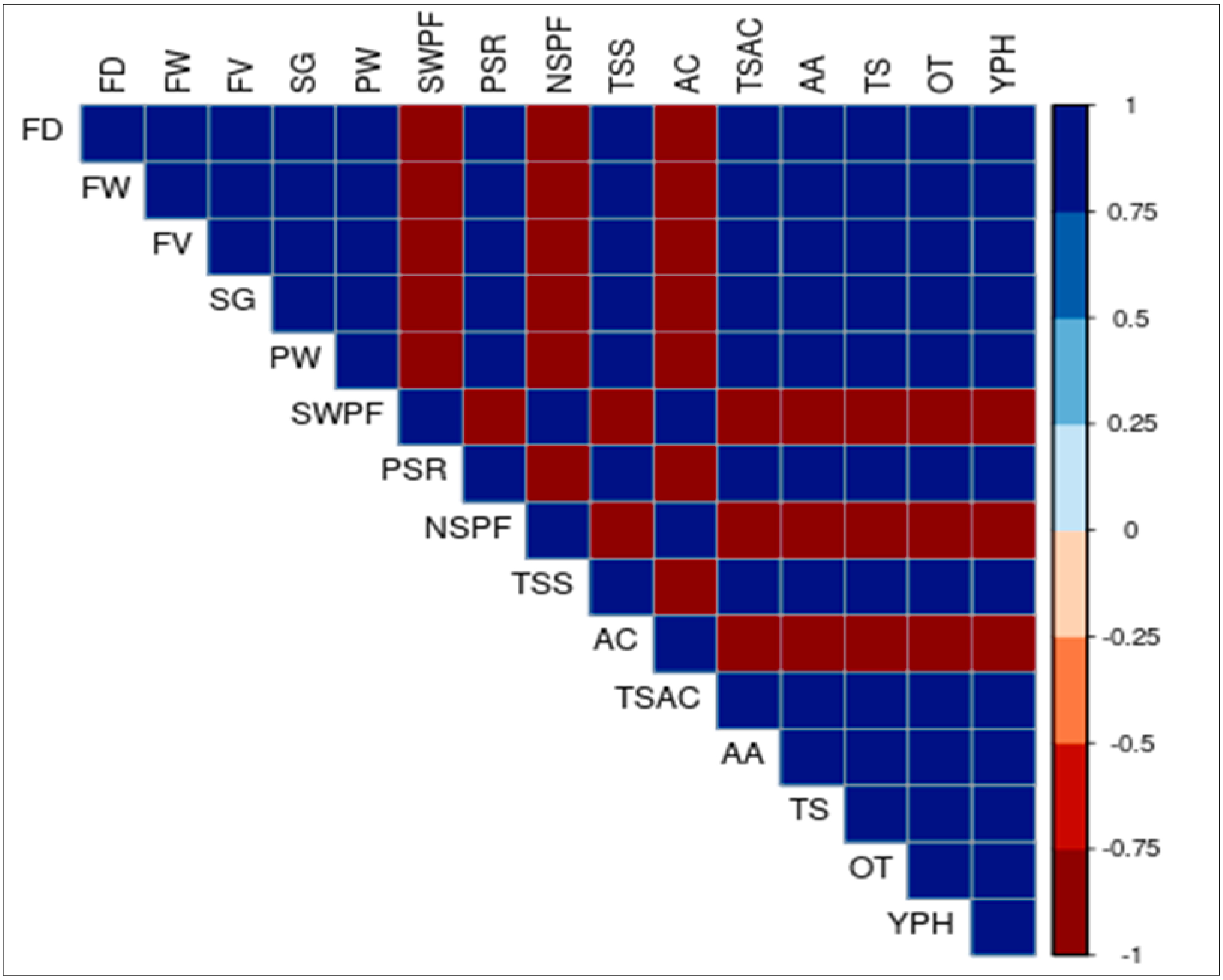

Fig. 3. Correlogram exhibiting relationship among various attributes of winter-season guava (*Psidium guajava* L.) cv. L-49. **FD** = Fruit diameter, **FW** = Fruit weight, **FV** = Fruit volume, **SG** = Specific gravity, **PW** = Pulp weight, **SWPF** = Seed weight per fruit, **PSR** = Pulp: seed ratio, **NSPF** = Number of seeds per fruit, **TSS** = Total soluble solids, **TA** = Titratable acidity, **AC** = Ascorbic acid, **TS** = Total sugar, **TSAC** = TSS: acid ratio, **OT** = Organoleptic Test, **YPH** = Yield per hectare.

weight, fruit diameter, pulp weight, pulp-to-seed ratio, ascorbic acid content, specific gravity, TSS: acid ratio and organoleptic score. In contrast, Group II included fruit value, total soluble solids (TSS) and total sugar content. Traits such as titratable acidity, seed count per fruit and seed weight per fruit were categorized into Groups III and IV respectively. The PCA biplot further indicated that Groups I and II had the highest contribution to PC1, reflecting a strong association among these parameters. The spatial distribution of treatments within the biplot underscores significant variation in treatment effects on the evaluated attributes. The PCA biplot showed that T8 and T10 were closely associated with key quality parameters such as fruit weight, TSS and organoleptic score. This suggests that these treatments are particularly effective for enhancing fruit quality and yield, offering practical guidance for guava growers aiming for premium fruit production.

Conclusion

This study revealed that integrating bio-enhancers and bio-fertilisers, such as Farm Yard Manure (FYM), Panchagavya, Jivamrit, *Azotobacter* and Phosphate Solubilizing Bacteria (PSB) in guava (*Psidium guajava* L.) cultivation significantly enhances the physical and physicochemical qualities of the fruit. The most effective treatment (T9), which integrated FYM, organic mulch, Panchagavya, PSB and *Azotobacter*, led to significant improvements in fruit size (diameter, weight and volume) and pulp weight. Additionally, it enhanced key quality attributes such as specific gravity, pulp-to-seed ratio, total soluble solids (TSS), titratable acidity, sugars, TSS: acid ratio and ascorbic acid content. These findings underscore the value of organic formulations in improving soil health, nutrient availability and plant vigor, offering a sustainable alternative to chemical fertilisers. Bio-fertilisers enhance crop productivity and fruit quality, supporting long-term soil fertility and ecological balance. Future research should investigate the precise mechanisms by which bio-enhancers improve plant health. Specifically, studies should explore their impact on microbial communities, nutrient cycling and plant physiology across different soil types and climatic conditions. Such research could optimize bio-enhancer formulations for various agro-ecological zones, ensuring their effectiveness in diverse farming systems.

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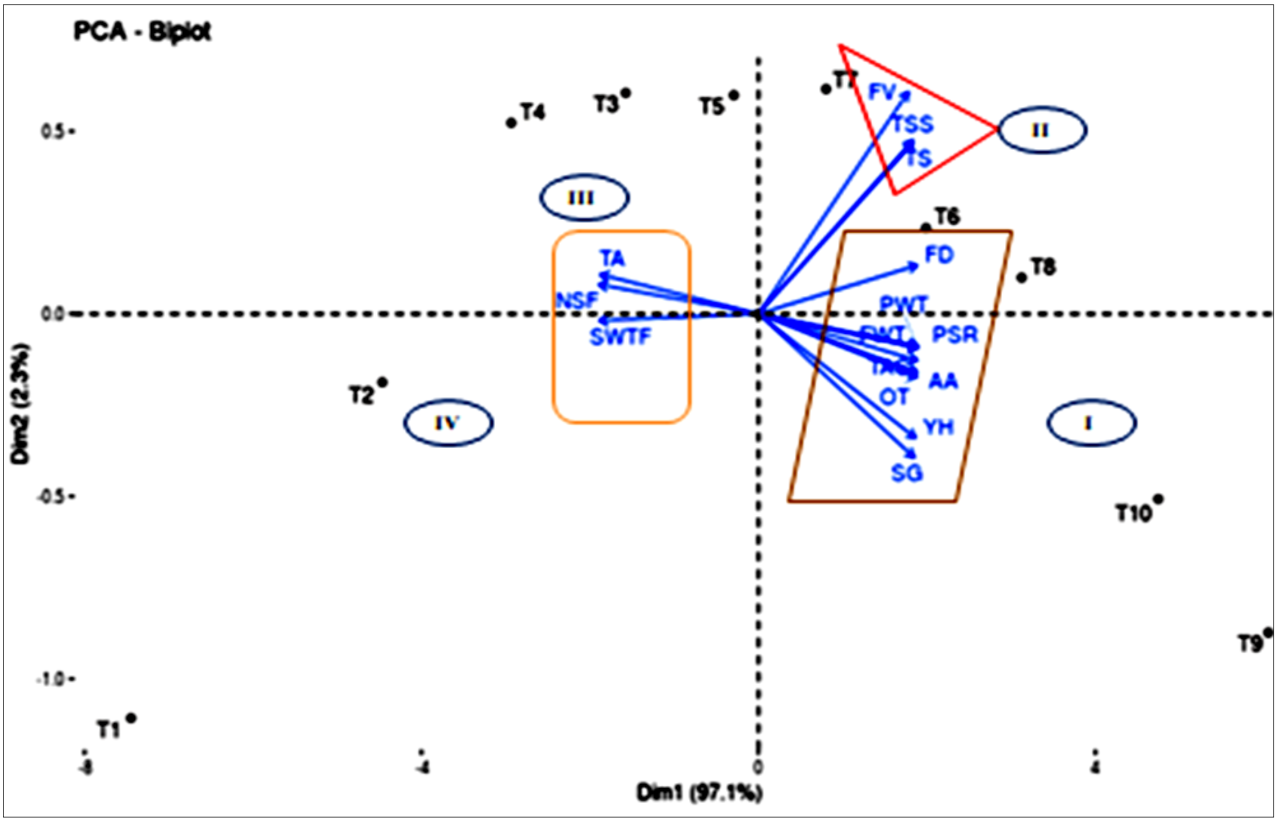

Fig. 4. Principal component analysis (PCA) map showing relationship among attributes and treatments. **FD** = Fruit diameter, **FW** = Fruit weight, **FV** = Fruit volume, **SG** = Specific gravity, **PW** = Pulp weight, **SWPF** = Seed weight per fruit, **PSR** = Pulp: seed ratio, **NSPF** = Number of seeds per fruit, **TSS** = Total soluble solids, **TA** = Titratable acidity, **AC** = Ascorbic acid, **TS** = Total sugar, **TSAC** = TSS: acid ratio, **OT** = Organoleptic Test, **YPH** = Yield per hectare.

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Authors' contributions

NKC conducted the experiment and wrote the main manuscript text. VKT provided substantial guidance and facilitated the research by offering necessary laboratory facilities. He also assisted in drafting the manuscript. VKT provided laboratory facilities for the experiment and assisted with data analysis. VKT provided experimental guidance and contributed to the manuscript draft preparation. All authors reviewed and approved the manuscript. This collaborative effort demonstrates the authors' commitment to producing a high-quality manuscript that accurately represents the research findings and contributes to the scientific community.

Compliance with ethical standards

Conflict of interest: The authors declare no competing interests.

Ethical issues: None

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