Integrated Nutrient Management, Soil Biological Functions, and their Linkages with Fruit Quality in Mango (*Mangifera indica* L.) under Medium-Density Planting

Kuldeep

kuldeephorti1998@gmail.com

Department of Horticulture, College of Agriculture, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar, 263145, Uttarakhand, India https://orcid.org/0009-0002-1248-4535

Ashok Kumar Singh

Department of Horticulture, College of Agriculture, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar, 263145, Uttarakhand, India

Omveer Singh

Department of Horticulture, College of Agriculture, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar, 263145, Uttarakhand, India

Research Article

Keywords: Integrated nutrient management, foliar micronutrients, arbuscular mycorrhizal fungi, soil enzyme activities, microbial communities, fruit quality, mango orchard, sustainable nutrient management

Posted Date: April 7th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9265673/v1

Additional Declarations: The authors declare no competing interests.

Abstract

Integrated nutrient management (INM) using reduced recommended doses of fertilizers (RDF) as well as soil and/or foliar micronutrients is now widely advocated for the maintenance of soil health and fruit quality in intensive tropical orchards. Two years of field investigation (2023-2024) were undertaken to evaluate the impacts of ten INM treatments on soil biochemical properties, microbial communities, enzymatic action, leaf & fruit nutrition, and fruit quality in a medium-density (5 × 5 m) mango (*Mangifera indica* L. cv. Dashehari) orchard. Treatments included 100 %, 75 %, 50 %, and 25 % RDF with or without soil micronutrients and 1-2 foliar micronutrient sprays in a randomized block arrangement with three replications. Both reduced RDF + foliar micronutrients (T_8: 75 % RDF + two foliar sprays and T_9: 50 % RDF + two foliar sprays) enhanced post-harvest soil pH, organic carbon, available N, K, and micronutrients (Fe, Zn, Cu, B, Ca). These treatments also increased AMF spore density (>3-fold greater than 100 % RDF control), bacterial count, and key enzyme activities (dehydrogenase, urease, acid, and alkaline phosphatases). Multivariate analysis (PCA, RDA, Pearson correlation, & Regression model) also verified strong positive correlations between microbial/enzymatic factors and soil-plant nutrient pools. As a result, leaf micronutrient and chlorophyll contents, fruit TSS (up to 20.78 °Brix), sugars, ascorbic acid, carotenoids, shelf life, flavonoids, total phenols, and antioxidant enzyme activities significantly increased, with the greatest value always obtained in the T_8 and T_9. The findings show that prudent reduction of macronutrient fertilizers along with foliar micronutrients recovers biological functions of soil, promotes plant-microbe feedbacks, and yields superior fruit nutritional and phytochemical quality. The INM approach is a feasible and sustainable approach to tropical perennial agroecosystems.

1. Introduction

Mango (*Mangifera indica* L.) is a nutrient-rich tropical fruit with significant commercial value and is one of the most widely cultivated tropical fruits in the world. Globally, it is cultivated on about 5.8 million hectares and is important for food security, rural livelihoods, and export economies (FAO 2024; Galán Saúco and Lu 2023). With over 2.5 million hectares, India is the world's largest producer, contributing nearly 40% to world production. The next largest producers were China, Thailand, Mexico, and Brazil (FAO 2024). Both India and other major producing countries in recent years have adopted high-density planting systems to maximize productivity per unit area, maintain optimal canopy architecture, allow mechanization, and improve the quality of fruits (Deb et al. 2024; Dhotra et al. 2021). RDF (conventional recommended dose) of fertilizer is the standard practice of nutrient management in these intensive systems. But overuse of RDF frequently interferes with rhizosphere chemistry, suppresses microbial activity, and compromises long-term soil health (Han et al. 2025; Kumar et al. 2021; Bargaz et al. 2018). In mango orchards, arbuscular mycorrhizal fungi (AMF), heterotrophic bacteria, and extracellular enzymes are instrumental in nutrient acquisition, organic-matter decomposition, and biogeochemical cycling (Smith and Smith 2011a, b; McLaren et al. 2020; Turner et al. 2021; Bünemann et al. 2015; Spohn 2020). AMF create large extraradical hyphal networks that promote the uptake of micronutrients in exchange for plant-derived carbon, thereby improving nutrient-use efficiency when nutrients are limited (Smith and Smith 2011a; Bargaz et al. 2018; Han et al. 2025). In soil, microbial communities mediate the actions of dehydrogenase, urease, and phosphatase, three important metabolic capacities and nutrient turnover (Kumar et al. 2021; Zeng et al. 2025; Turner et al. 2021). Overdoses of macronutrients, on the contrary, hinder rhizodeposition, change the pH of soil, create ionic imbalances leading to less AMF colonization, reduced bacterial biomass, and reduced enzyme activity (Han et al. 2025; Kumar et al. 2021; Zeng et al. 2025; McLaren et al. 2020). Innovative integrated nutrient management (INM) activities that utilize reduced RDF rates with either soil and/or foliar micronutrient delivery provide an effective alternative for restoration of soil biological functions whilst maintaining productivity (Ahmed et al. 2025; Makhasha et al. 2024; El-Salhy et al. 2025; Mohamed et al. 2025). Foliar micronutrients bypass the soil fixation reaction, help stimulate the plant physiological function (photosynthesis, enzyme activation), and promote rhizodeposition of labile carbon compounds for microbial growth and the biosynthesis of enzymes (Zeng et al. 2025; Bargaz et al. 2018; Han et al. 2025). The upward pressure of the belowground carbon allocation induces a positive feed-forward mechanism wherein increased resource allocation results in increased microbial activity, nutrient mobilization, and cycling with consequent positive impacts on nutrition and fruit quality of crops (Kumar et al. 2021; Turner et al. 2021; Bünemann et al. 2015; Spohn 2020). In medium- to high-density planting, the interactions are amplified by increasing root density and rhizosphere volume per unit area, potentially allowing for enhanced biological responses of the soil to nutrient management (Deb et al. 2024; Tsomu et al. 2024; Dhotra et al. 2021). Even though there is increasing recognition of these connections, mechanistic knowledge for tropical perennial systems is rather restricted. Previous research has generally investigated soil microbial responses or fruit quality in isolation, yet no work so far has attempted to associate belowground biological responses with aboveground performance in reduced input regimes (Gurjar et al. 2023; Kumar and Patel 2025; Attalla et al. 2025; Cavalcante et al. 2025). The foliar nutrient of the leaf has been largely neglected in the literature as a factor in AMF-bacterial synergy regulation, enzyme-regulated nutrient cycling, and their effects on the quality of fruit downstream. However, in medium-density mango orchards, its downstream effects remain largely undefined (Lei et al. 2025; He et al. 2023; Luo et al. 2025; Kleber et al. 2021; Angst et al. 2021; Kallenbach et al. 2016). This concept has been recently recognized in soil microbiology for trace elements as enzymatic cofactors and the agents for microbial growth and development (Zeng et al. 2025; Smith and Smith 2011b; Turner et al. 2021; Bünemann 2015; Loeppmann et al. 2025; Farrell et al. 2014; Arenberg and Arai 2019, 2021; Hernández-Romero et al. 2024). In P-limited tropical soils, AMF- and phosphatase-producing bacteria, for instance, collaborate to enhance phosphorus procurement; however, macronutrient overload can weaken these relationships and reduce the allocation of underground carbon (McLaren et al. 2020; Spohn 2020; Han et al. 2025; Kumar et al. 2021). This study aims to fill in this knowledge gap by evaluating integrated nutrient management in a medium-density mango orchard. We anticipated that foliar micronutrient supplementation, along with decreased RDF, would increase AMF spore density and bacterial counts, increase key enzyme activities (dehydrogenase, urease, acid and alkaline phosphatases), improve soil nutrient retention and cycling, and result in positive correlations between soil biological indicators and fruit quality parameters via optimized

plant nutrient status and partitioning assimilation. Thus, the study's particular aims were to: (1) measure the impact of RDF reduction with soil and/or foliar micronutrient applications on soil chemical parameters, micronutrient resources, microorganism (AMF and bacterial) communities and enzymatic activity; (2) quantitatively assess leaf nutrient status and its relationship to belowground biological processes; (3) clarify inter- and interspersed/multivariate relationships between soil nutrients with their correlates, i.e. soil biological variables, resource pools (nutrient) types and fruit quality by principal component analysis (PCA), redundancy analysis (RDA) combined with regression modelling; and (4) identify the process pathways by which integrated nutrients management contributes to increase soil biological functions and lead to better fruit quality in a medium-density tropical mango system. This study provides fundamental mechanistic insight into soil biological control of nutrient dynamics. It offers a practical science-based guide for sustainable nutrient management that preserves productivity and promotes long-term soil health.

2. Materials and Methods

2.1 Orchard site and experimental period

The study was conducted during 2023–2024 at the Horticulture Research Centre, Patharchatta, GBPUA&T, Pantnagar, Uttarakhand (≈ 29.5°N, 79.3°E; 244 m a.s.l.; Fig. S1). The experiment used a medium-density mango (*Mangifera indica* L. cv. Dashehari) orchard of uniform 13-year-old trees planted at 5 × 5 m spacing (400 trees ha^{-1};) (Fig. S2).

2.2 Soil and climate

The site lies in the Tarai agro-ecological zone with a sub-humid subtropical climate. The experimental soil is silty clay loam (Patharchatta Series II, Mollisol). Baseline soil physical-chemical properties (pH, EC, organic carbon, available N, P, K, and extractable micronutrients) were determined before the start of the experiment.

2.3 Experimental design and treatments

The experiment was laid out in a randomized block design (RBD) with 10 treatments and three replications. Treatments evaluated combinations of full, reduced (75%, 50%, 25%) recommended fertilizer dose (RDF = 1000 g N + 750 g P_2O_5 + 1000 g K_2O + 50 kg FYM $tree^{-1}$ $year^{-1}$) and soil-applied micronutrients (Fe, Cu, Zn each 100 g $tree^{-1}$ and B 50 g $tree^{-1}$), together with one or two foliar sprays of micronutrients. In brief treatment details:

- T_1 (Control): 100% RDF applied in the basin after harvest.
- T_2-T_4: 75%, 50%, 25% RDF, respectively, + soil micronutrients (Fe, Cu, Zn @100 g each + B @50 g $tree^{-1}$) + one foliar spray (Fe, Ca, Zn each 0.50% + B- 0.10%) (just before flowering and marble stages as a single event).
- T_5-T_7: 75%, 50%, 25% RDF, respectively, + soil micronutrients (as above) + two foliar sprays (same foliar composition; applied just before flowering and at marble stage).
- T_8-T_{10}: 75%, 50%, 25% RDF, respectively, without soil micronutrients but with two foliar sprays (just before flowering and at marble stage).

2.4 Orchard management and fertilizer application

Basins (radius: 1.5 m from trunk) were prepared around each tree. Farmyard manure was applied in October. P, K, and micronutrient basal doses were incorporated into the basins in November. Nitrogen was applied in two equal splits: first immediately after flowering and the second at the mustard-to-pea stage of fruit development. Foliar sprays (10 L water $tree^{-1}$ per spray) were prepared by dissolving micronutrient salts and applied with a tractor sprayer at the timings (just before flowering and at marble stage). Standard cultural practices (irrigation, weeding, pruning, pest and disease control) were followed uniformly across treatments.

2.5 Sampling and laboratory analysis

2.5.1 Soil and plant sampling collection

Soil samples for macro- and micronutrient analysis were collected after fruit harvest from each treatment replication for two consecutive years (2023 and 2024). Samples were obtained using a post-hole auger at a depth of 0–30 cm (Fig. S3), thoroughly mixed, placed in labeled bags, and air-dried in the shade. The dried soil was ground with a mortar and pestle, passed through a 2-mm sieve, and stored in labeled sample bags for analysis.

For plant nutrient analysis, 4-5-month-old mature leaves (Fig. S3) considered to contain optimum nutrient concentrations, were collected after fruit harvest. The leaves were washed, oven-dried at 65 ± 1.0°C until constant weight, ground with a mortar and pestle, sieved through a 2-mm mesh, and stored in airtight bags for laboratory analysis. Before analysis, the stored samples were once again dried at 60 ± 1.0°C for 2 h to ensure optimal conditions for testing. The analysis focused on assessing both macro and micronutrients present in the samples.

2.5.2 Estimation of soil chemical properties

Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water suspension using a digital pH meter (Model: Electronics India 101) and a conductivity meter (Model: Electronics India 602), respectively, following the procedure outlined by Jackson (1973). Oxidizable organic carbon was estimated by the wet oxidation method as described by Walkley and Black (1934). Available nitrogen was determined by the alkaline permanganate method using 0.32% $KMnO_4$, as suggested by Subbiah and Asija (1956). Available phosphorus was extracted with 0.5 M $NaHCO_3$ (pH 8.5) and determined calorimetrically following Olsen et al. (1954). Available potassium was extracted with neutral normal ammonium acetate and estimated using a flame photometer (Model: Electronics India 101) as described by Jackson (1973).

Micronutrients (Fe, Zn, & Cu) were extracted using DTPA solution (pH 7.3, 0.005 M DTPA + 0.01 M $CaCl_2$ + 0.1 M TEA) following Lindsay and Norvell (1978), and the concentrations were measured with an Atomic Absorption Spectrophotometer (Model: Systronics, ECIL 4141). Boron and calcium were estimated by the hot $CaCl_2$ extractable method given by Srivastava and Pachuri (2020) and quantified using a colorimeter at 420 nm (Model: GENESYS180).

2.5.3 Estimation of plant nutrient content

For the determination of total nitrogen (N), phosphorus (P), potassium (K), cationic micronutrients (Fe, Zn, and Cu), and secondary nutrient calcium (Ca), plant samples were digested with a di-acid mixture (HNO_3:$HClO_4$:: 9:4) using a digestion unit (Model: Peliican, KES 04L). Nitrogen (N) was quantified using a Kjeldahl nitrogen analyzer (Model: BK3KJS11-240), phosphorus (P) was estimated with a UV-Vis spectrophotometer (Make: Thermo Fisher Scientific, Model: GENESYS 180), potassium (K) was determined using a flame photometer (Make: Systronics, Model: Flame Photometer 128), and micronutrients along with secondary nutrients were estimated by an atomic absorption spectrophotometer (Make: Systronics, ECIL 4141) employing an air-acetylene flame. Boron (B) in plant samples was determined following the method of Srivastava and Pachuri (2020), which involves dry ashing of samples and subsequent estimation using the Azomethine-H method.

2.5.4 Fruit quality, physical and physiological attributes

The total soluble solids (TSS) were measured using a hand refractometer (°Brix) (Ranganna, 1986). Titratable acidity was determined by titrating juice extract with 0.1 N NaOH using phenolphthalein as indicator and expressed as citric acid equivalent (Ranganna, 1986). Ascorbic acid content was quantified by 2,6-dichlorophenolindophenol titration (Ranganna, 1986). Reducing sugars were estimated by the dinitrosalicylic acid (DNS) method (Miller, 1959). Total sugars were determined by the anthrone method after acid hydrolysis and non-reducing sugars calculated by difference (Ranganna, 1986). Total carotenoids were extracted in acetone: petroleum ether and quantified spectrophotometrically at 450 nm (Ranganna, 1986). Cationic micronutrients (Fe, Zn, Cu) and calcium (Ca) were analysed after wet digestion of fruit samples with HNO_3:$HClO_4$ (9:4, v/v) (Blanchar et al., 1965) using atomic absorption spectrophotometry. Shelf life was recorded as the number of days to unacceptable softening and decay under ambient storage (25 ± 2°C). Leaf chlorophyll content was determined by extracting fresh leaf tissue in 80% (v/v) acetone (Arnon, 1949).

2.5.5 Soil microbial and Enzymatic activities

Arbuscular mycorrhizal fungi (AMF) spores were extracted by the wet-sieving and decanting technique and counted under a stereomicroscope according to Gerdemann and Nicolson (1963). Total bacterial count was determined by the serial dilution pour-plate method on nutrient agar and expressed as $\times 10^5$ CFU g^{-1} dry soil. Urease activity (µg NH_3-N g^{-1} soil 2 h^{-1}) was assayed according to Tabatabai and Bremner (1972). Dehydrogenase activity (µg TPF g^{-1} soil 16 h^{-1}) was determined by the method of Casida et al. (1964). Acid phosphatase activity (µg p-nitrophenol g^{-1} soil h^{-1}) and alkaline phosphatase activity (µg p-nitrophenol g^{-1} soil h^{-1}) were measured using p-nitrophenyl phosphate as substrate following the procedure of Tabatabai and Bremner (1969) at pH 6.5 and pH 11.0, respectively.

2.5.6 Fruit phytochemical and enzymes attributes

Total flavonoids were quantified by the $AlCl_3$ colorimetric method (Zhishen et al., 1999) and expressed as mg quercetin equivalents (QE) 100 g^{-1} fresh weight. Total phenolic content was determined by the Folin–Ciocalteu reagent and expressed as mg gallic acid equivalents (GAE) 100 g^{-1} fresh weight according to Singleton and Rossi (1965). Total carbohydrates were estimated by the anthrone method (Yemm and Willis, 1954). Total protein content was determined according to Lowry et al. (1951). Total antioxidant activity was assayed by the DPPH radical-scavenging method and expressed as µmol Trolox equivalents g^{-1} (Maldonado-Celis et al., 2019). Catalase (CAT) activity (U mg^{-1} protein) was measured by monitoring the rate of H_2O_2 decomposition at 240 nm according to Aebi (1984). Peroxidase (POD) activity (U mg^{-1} protein) was determined by the oxidation of guaiacol at 470 nm (Chance and Maehly, 1955). Superoxide dismutase (SOD) activity (U mg^{-1} protein) was assayed by its ability to inhibit the photoreduction of nitroblue tetrazolium (Beauchamp and Fridovich, 1971).

3. Statistical analysis

Data were subjected to one-way analysis of variance (ANOVA) using IBM SPSS Statistics version 25 (IBM Corp., Armonk, NY, USA). Treatment means were separated by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Pearson correlation coefficients and multiple linear regression (MLR) models were performed using XLSTAT version 4.2.0 (Addinsoft, Paris, France). Redundancy analysis (RDA) was conducted in XLSTAT with 999 permutations ($P < 0.01$) to explore relationships among soil properties, microbial parameters, and treatments. Principal component analysis (PCA) biplots were generated using IBM SPSS Statistics version 25. All figures were prepared using OriginPro (OriginLab Corporation, Northampton, MA, USA).

4. Results

4.1 Estimation of Soil Chemical Properties

The integrated nutrient management (reduced recommended doses of fertilizers, RDF) combined with soil and/or foliar micronutrient applications improved the soil biochemical properties and micronutrient availability in the tropical mango orchard (Tables 1–2). Soil pH was moderate in all treatments after harvesting and significantly increased under full 100% RDF control (T_1: 7.47 ± 0.03). The highest electrical conductivity was recorded in the 100% RDF control (0.33 ± 0.02 dS m^{-1}), while it was lower in all treatments supplemented with foliar sprays. Soil organic carbon showed negligible increases with multiple-foliar treatments, with maxima of 0.85 ± 0.01% in T_5 (75% RDF + soil micronutrients + one foliar spray of micronutrients) and T_9 (50% RDF + two foliar sprays of micronutrients). Nitrogen concentrations increased post-harvest in the majority of treatments, with the highest concentrations recorded in T_8 (203.25 ± 1.28 kg ha^{-1}) and T_6 (202.55 ± 0.72 kg ha^{-1}). The highest residual phosphorus content was measured in $_{T8}$ (22.02 ± 0.01 kg ha^{-1}), T_5 (21.79 ± 0.01 kg ha^{-1}), and T_9 (21.76 ± 0.01 kg ha^{-1}). Potassium availability also showed an increase in foliar-enhanced treatments (maxima reached in T_8: 147.87 ± 1.22 kg ha^{-1} and T_5: 147.22 ± 1.52 kg ha^{-1}). Foliar supplementation improved soil micronutrient availability. T_6 (6.15 ± 0.09 mg kg^{-1}) and T_3 (6.11 ± 0.27 mg kg^{-1}) had the highest available Fe. Maximum available Zn occurred after combining soil + foliar use, with the highest Zn availability in T_5 (0.78 ± 0.06 mg kg^{-1}), T_6 (0.77 ± 0.05 mg kg^{-1}), and T_7 (0.76 ± 0.03 mg kg^{-1}). Available Cu, B, and Ca values were also greatest in T_5–T_7 (T_6: maximum Cu 0.24 ± 0.02 mg kg^{-1}; T_5: maximum B 0.54 ± 0.02 mg kg^{-1}; T_5: maximum Ca 1045.67 ± 2.08 mg kg^{-1}).

Table 1
Influence of macro and micronutrient application on initial and final status of soil chemical properties (pH, EC, organic carbon) and available nutrients (N, P, K) in a mango orchard (Mean of two years).

Treatments #	pH		Organic carbon (%)		EC (dS m^{-1})		Available Nitrogen (kg ha^{-1})		Available Phosphorus (kg ha^{-1})		Available Potassium (kg ha^{-1})	
	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest
T_1	7.36 ± 1.02^{a}	7.47 ± 0.03^{a}	0.81±.01^{a}	0.83 ± 0.01^{abcd}	0.29±.03^{a}	0.33 ± 0.02^{a}	196.22 ± 1.35^{a}	202.34 ± 1.04^{ab}	138.44 ± 1.43^{a}	21.75 ± 0.14^{b}	20.81 ± 1.14^{a}	146.06 ± 2.07^{abc}
T_2	6.64 ± 1.02^{a}	7.30 ± 0.04^{cde}	0.79±.03^{a}	0.82 ± 0.02^{d}	0.25±.04^{a}	0.26 ± 0.03^{cde}	195.91 ± 1.35^{a}	200.78 ± 1.23^{b}	137.45 ± 2.66^{a}	21.00 ± 0.13^{c}	19.88 ± 1.14^{a}	144.24 ± 1.07^{cde}
T_3	7.11 ± 1.01a	7.24 ± 0.04^{e}	0.82±.06^{a}	0.84 ± 0.01^{abc}	0.27±.02^{a}	0.30 ± 0.01^{b}	196.86 ± 1.35^{a}	201.62 ± 1.08^{ab}	141.23 ± 2.66^{a}	21.62 ± 0.14^{b}	20.86 ± 1.14^{a}	145.09 ± 1.66^{bcd}
T_4	6.95 ± 1.01^{a}	7.27 ± 0.01^{de}	0.82±.07^{a}	0.83 ± 0.01^{cd}	0.22±.03^{a}	0.24 ± 0.02^{e}	194.47 ± 1.35^{a}	197.48 ± 0.02^{c}	142.56 ± 2.65^{a}	21.05 ± 0.19^{c}	20.16 ± 1.14^{a}	143.73 ± 1.63^{cde}
T_5	7.10 ± 1.02^{a}	7.28 ± 0.05^{de}	0.83±.01^{a}	0.85 ± 0.01^{a}	0.25±.04^{a}	0.29 ± 0.00^{bc}	195.95 ± 1.35^{a}	200.91 ± 0.84^{b}	140.22 ± 2.66^{a}	21.76 ± 0.25^{ab}	20.39 ± 1.14^{a}	147.22 ± 1.52^{ab}
T_6	7.45 ± 1.02^{a}	7.37 ± 0.02^{b}	0.80±.02^{a}	0.83 ± 0.01^{abcd}	0.28±.03^{a}	0.29 ± 0.01^{b}	196.46 ± 1.35^{a}	202.55 ± 0.72^{ab}	141.52 ± 2.66^{a}	21.04 ± 0.15^{c}	19.93 ± 1.14^{a}	144.47 ± 1.48^{cde}
T_7	7.60 ± 1.02^{a}	7.37 ± 0.03^{b}	0.82±.02^{a}	0.83 ± 0.01^{bcd}	0.27±.01^{a}	0.29 ± 0.01^{b}	193.25 ± 1.34^{a}	195.96 ± 1.34^{c}	139.66 ± 2.66^{a}	21.76 ± 0.07^{ab}	20.63 ± 1.14^{a}	141.81 ± 0.98^{e}
T_8	7.28 ± 1.02a	7.35 ± 0.04^{bc}	0.81±.02^{a}	0.83 ± 0.00^{bcd}	0.26±.01^{a}	0.27 ± 0.02^{bcd}	196.88 ± 1.35^{a}	203.25 ± 1.28^{a}	141.23 ± 2.66^{a}	22.02 ± 0.01^{a}	20.56 ± 1.14^{a}	147.87 ± 1.22^{a}
T_9	7.00 ± 1.02^{a}	7.31 ± 0.04^{cd}	0.82±.04^{a}	0.85 ± 0.01^{ab}	0.25±.02^{a}	0.28 ± 0.02^{bcd}	195.36 ± 1.35^{a}	202.00 ± 1.35^{ab}	142.25 ± 2.66^{a}	21.79 ± 0.13^{ab}	20.65 ± 1.14^{a}	146.30 ± 0.50^{abc}
T_{10}	6.91 ± 1.02^{a}	7.27 ± 0.03^{de}	0.80±.02^{a}	0.82 ± 0.01^{d}	0.24±.03^{a}	0.26 ± 0.01^{de}	194.66 ± 1.35^{a}	197.23 ± 0.50^{c}	140.28 ± 2.66^{a}	20.95 ± 0.06^{c}	20.30 ± 1.14^{a}	142.93 ± 1.66^{de}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are mean of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

Table 2
Influence of macro and micronutrient application on initial and final nutrient status of available soil micronutrients (Fe, Zn, Cu, B & Ca) in a mango orchard (Mean of two years).

Treatments #	Fe (mg kg^{-1})		Zn (mg kg^{-1})		Cu (mg kg^{-1})		B (mg kg^{-1})		Ca (mg kg^{-1})	
	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest
T_1	5.41 ± 0.91^{a}	5.51 ± 0.06^{b}	0.49 ± 0.03^{a}	0.54 ± 0.03^{d}	0.16 ± 0.02^{a}	0.18 ± 0.01^{ef}	0.46 ± 0.02^{a}	0.49 ± 0.02^{cd}	848.09 ± 71.18^{a}	888.00 ± 2.65^{h}
T_2	5.45 ± 0.90^{a}	5.57 ± 0.06^{b}	0.49 ± 0.03^{a}	0.69 ± 0.03^{bc}	0.13 ± 0.03^{a}	0.17 ± 0.01^{f}	0.44 ± 0.01^{a}	0.51 ± 0.02^{bc}	894.72 ± 48.82^{a}	925.67 ± 0.58^{f}
T_3	6.04 ± 0.91^{a}	6.11 ± 0.27^{a}	0.50 ± 0.02^{a}	0.68 ± 0.03^{bc}	0.17 ± 0.03^{a}	0.20 ± 0.01^{bcd}	0.45 ± 0.02^{a}	0.51 ± 0.01^{bc}	984.76 ± 71.18^{a}	1011.00 ± 1.73^{c}
T_4	5.50 ± 0.91^{a}	5.65 ± 0.26^{b}	0.52 ± 0.03^{a}	0.69 ± 0.04^{ab}	0.16 ± 0.05^{a}	0.19 ± 0.01^{de}	0.45 ± 0.01^{a}	0.51 ± 0.02^{bc}	902.67 ± 91.06^{a}	926.00 ± 1.00^{f}
T_5	5.23 ± 0.91^{a}	5.40 ± 0.20^{b}	0.49 ± 0.02^{a}	0.78 ± 0.06^{a}	0.15 ± 0.03^{a}	0.22 ± 0.01^{ab}	0.47 ± 0.01^{a}	0.54 ± 0.02^{a}	992.85 ± 24.99^{a}	1045.67 ± 2.08^{a}
T_6	5.93 ± 0.90^{a}	6.15 ± 0.09^{a}	0.50 ± 0.03^{a}	0.77 ± 0.05^{ab}	0.18 ± 0.01^{a}	0.24 ± 0.02^{a}	0.44 ± 0.01^{a}	0.52 ± 0.01^{ab}	908.81 ± 71.18^{a}	968.33 ± 0.58^{e}
T_7	5.76 ± 0.91^{a}	6.09 ± 0.26^{a}	0.49 ± 0.02^{a}	0.76 ± 0.03^{ab}	0.16 ± 0.03^{a}	0.21 ± 0.01^{b}	0.46 ± 0.02^{a}	0.52 ± 0.02^{ab}	972.27 ± 122.78^{a}	1019.67 ± 0.58^{b}
T_8	5.45 ± 0.91^{a}	5.49 ± 0.26^{b}	0.51 ± 0.03^{a}	0.61 ± 0.06^{cd}	0.17 ± 0.02^{a}	0.18 ± 0.01^{ef}	0.45 ± 0.01^{a}	0.48 ± 0.02^{de}	940.94 ± 177.64^{a}	1005.33 ± 3.21^{d}
T_9	5.62 ± 0.91^{a}	5.69 ± 0.19^{b}	0.50 ± 0.03^{a}	0.58 ± 0.06^{d}	0.19 ± 0.02^{a}	0.21 ± 0.01^{bc}	0.45 ± 0.02^{a}	0.47 ± 0.02^{de}	951.97 ± 152.94^{a}	1010.67 ± 1.53^{c}
T_{10}	5.59 ± 0.91^{a}	5.62 ± 0.07^{b}	0.47 ± 0.03^{a}	0.56 ± 0.05^{d}	0.18 ± 0.02^{a}	0.19 ± 0.01^{cde}	0.45 ± 0.01^{a}	0.46 ± 0.02^{e}	846.76 ± 71.56^{a}	905.67 ± 4.73^{g}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are mean of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

4.2 Estimation of Plant Nutrient Content

Nutrient concentrations of leaves similarly expanded. The total leaf N rose to a maximum of 1.07 ± 0.81% in T_8. Leaf P fell significantly in all treatments, with the highest retention obtained in T_8 (0.130 ± 0.17%). Leaf K had a maximum value of 0.60 ± 0.10% in T_8. Leaf micronutrient concentrations also increased after harvest, particularly under foliar-supplemented regimes (Table 3–4). Post-harvest leaf Fe was highest in T_8 (80.70 ± 0.07 ppm), followed by T_5 (80.00 ± 0.08 ppm); leaf Zn peaked in T_8 (19.45 ± 0.04 ppm); leaf Cu was maximum in T_7 (12.20 ± 0.83 ppm) and T6 (11.61 ± 1.10 ppm); leaf B reached maxima in T_8 (54.03 ± 1.18 ppm) and T_9 (53.82 ± 1.91 ppm); and leaf Ca attained the overall highest value in T_8 (1.86 ± 0.07%). Initial leaf micronutrient levels showed no significant variation across treatments.

Table 3
Influence of macro and micronutrient application on initial and final nutrient status of total macronutrient (N, P, K) content in mango cv. Dashehari leaves (Mean of two years).

Treatments	Total Nitrogen (%)		Total Phosphorus (%)		Total Potassium (%)	
#	Initial	After harvest	Initial	After harvest	Initial	After harvest
T_1	0.90±.04^{a}	0.98±.30^{abcd}	0.510±.06^{a}	0.081±.17^{c}	0.42 ± 0.01^{a}	0.53±.30^{cd}
T_2	0.89±.01^{a}	1.01±.17^{abcd}	0.493±.06^{a}	0.078±.07^{c}	0.48±.0.01^{a}	0.52±.15^{d}
T_3	0.90±.04^{a}	1.04±.15^{ab}	0.480±.06^{a}	0.092±.09^{bc}	0.49 ± 0.01^{a}	0.50±.25^{d}
T_4	0.89±.06^{a}	0.97±.30^{cde}	0.560±.06^{a}	0.074±.17^{c}	0.44 ± 0.01^{a}	0.58±.12^{a}
T_5	0.86±.06^{a}	1.04±.12^{ab}	0.533±.06^{a}	0.079±.16^{c}	0.42 ± 0.01^{a}	0.56±.12^{abc}
T_6	0.85±.06^{a}	1.03±.20^{abc}	0.543±.06^{a}	0.100±.07^{bc}	0.45 ± 0.01^{a}	0.57±.26^{ab}
T_7	0.87±.08^{a}	0.96±.26de	0.580±.06^{a}	0.112±.17^{ab}	0.43 ± 0.01^{a}	0.59±.31^{a}
T_8	0.86±.06^{a}	1.07±.81^{a}	0.560±.06^{a}	0.130±.17^{a}	0.43 ± 0.01^{a}	0.60±.10^{a}
T_9	0.88±.08^{a}	1.02±.23^{abc}	0.510±.06^{a}	0.110±.16^{ab}	0.44 ± 0.01^{a}	0.54±.21^{bcd}
T_{10}	0.87±.06^{a}	0.94±.21^{e}	0.500±.06^{a}	0.075±.16^{c}	0.47 ± 0.01^{a}	0.52±.12^{d}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are the means of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

Table 4
Influence of macro and micronutrient application on initial and final nutrient status of total micronutrient (Fe, Zn, Cu, B, & Ca) content in mango cv. Dashehari leaves (Mean of two years).

Treatments #	Fe (ppm)		Zn (ppm)		Cu (ppm)		B (ppm)		Ca (%)	
	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest	Initial	After harvest
T_1	77.50 ± 3.92^{a}	78.65 ± 0.06^{f}	16.77 ± 3.29^{a}	17.76 ± 0.02^{d}	8.21 ± 0.86^{a}	9.40 ± 0.80^{c}	44.85 ± 2.40^{a}	46.27 ± 1.12^{bc}	1.30 ± 0.15^{a}	1.38 ± 0.09^{e}
T_2	76.23 ± 3.92^{a}	79.19 ± 0.05^{d}	14.21 ± 3.29^{a}	17.27 ± 0.11^{f}	9.36 ± 0.86^{a}	11.85 ± 0.02^{a}	43.25 ± 2.40^{a}	46.85 ± 3.07^{bc}	1.34 ± 0.15^{a}	1.68 ± 0.07^{bcd}
T_3	76.92 ± 3.92^{a}	78.81 ± 0.01^{e}	13.91 ± 3.30^{a}	18.28 ± 0.09^{c}	7.32 ± 0.86^{a}	9.04 ± 0.61^{c}	46.36 ± 2.40^{a}	50.70 ± 2.48^{ab}	1.29 ± 0.15^{a}	1.60 ± 0.00^{d}
T_4	75.70 ± 3.92^{a}	78.05 ± 0.03^{h}	15.26 ± 3.30^{a}	18.80 ± 0.06^{b}	8.45 ± 0.85^{a}	10.10 ± 0.74^{bc}	42.58 ± 2.40^{a}	47.34 ± 3.26^{bc}	1.33 ± 0.15^{a}	1.64 ± 0.05^{cd}
T_5	78.10 ± 3.92^{a}	80.00 ± 0.08^{b}	14.77 ± 3.29^{a}	17.63 ± 0.00^{e}	8.86 ± 0.86^{a}	11.20 ± 0.52^{ab}	44.23 ± 2.40^{a}	50.25 ± 3.10^{abc}	1.30 ± 0.15^{a}	1.73 ± 0.06^{bc}
T_6	76.60 ± 3.92^{a}	79.61 ± 0.03^{c}	14.35 ± 3.29^{a}	15.82 ± 0.11^{g}	7.89 ± 0.86^{a}	11.61 ± 1.10^{a}	47.56 ± 2.40^{a}	52.74 ± 1.83^{a}	1.29 ± 0.15^{a}	1.77 ± 0.03a^{b}
T_7	76.30 ± 3.92^{a}	77.88 ± 0.03^{i}	15.31 ± 3.29^{a}	18.74 ± 0.08^{b}	8.88 ± 0.86^{a}	12.20 ± 0.83^{a}	45.24 ± 2.40^{a}	53.51 ± 3.39^{a}	1.28 ± 0.15^{a}	1.67 ± 0.07^{bcd}
T_8	77.84 ± 3.92^{a}	80.70 ± 0.07^{a}	16.24 ± 3.30^{a}	19.45 ± 0.04^{a}	8.15 ± 0.86^{a}	9.56 ± 0.99^{c}	43.96 ± 2.40^{a}	54.03 ± 1.18^{a}	1.32 ± 0.15^{a}	1.86 ± 0.07^{a}
T_9	77.90 ± 3.92^{a}	78.48 ± 0.07^{g}	17.74 ± 3.30^{a}	18.85 ± 0.06^{b}	7.89 ± 0.86^{a}	8.97 ± 0.23^{c}	45.78 ± 2.40^{a}	53.82 ± 1.91^{a}	1.30 ± 0.15^{a}	1.78 ± 0.07^{ab}
T_{10}	76.90 ± 3.92^{a}	77.53 ± 0.07^{j}	14.36 ± 3.30^{a}	15.78 ± 0.08^{g}	7.68 ± 0.86^{a}	9.02 ± 1.10^{c}	42.88 ± 2.40^{a}	45.76 ± 3.09^{c}	1.32 ± 0.15^{a}	1.59 ± 0.07^{d}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are mean of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

4.3 Soil Microbial and Enzymatic Activities

Soil microbial density and enzymatic activities were greatest under both reduced RDF and foliar micronutrient conditions (Fig. 1 & Table S1). Maximum arbuscular mycorrhizal fungi (AMF) spore density was observed in T_9 (3860.78 ± 21.38 spores kg^{-1} soil) and T_4 (3813.86 ± 4.73 spores kg^{-1} soil), which were > 3 times higher than the full RDF control. T_9 showed the maximum bacterial counts (88.88 ± 1.99 × 10^5 CFU g^{-1} soil). Figure 2 & Table S2 illustrated that the Urease activity was greatest in T_8 (27.46 ± 1.98 µg NH_3-N g^{-1} 2 h^{-1}), and dehydrogenase activity was greatest in T_8 (119.92 ± 2.16 µg TPF g^{-1} 16 h^{-1}). Acid and alkaline phosphatase activity were also highest in T_8 (75% RDF + two foliar sprays of micronutrients) and T_9 (50% RDF + two foliar sprays of micronutrients). Microbial numbers and microbial activity were lowest under full RDF (T_1) and the relatively narrow micronutrient range (T_{10}: 25% RDF + two foliar sprays of micronutrients).

4.4 Fruit Quality, Physical and Physiological Attributes

Fruit quality and physical attributes were markedly enhanced by the integrated treatments (Table 5). Total soluble solids (TSS) increased to maxima of 20.78 ± 0.32 °Brix in T_8 (75% RDF + two foliar sprays of micronutrients) and 20.37 ± 0.14 °Brix in T_9 (50% RDF + two foliar sprays of micronutrients). Titratable acidity was lowest in T_8 (0.11 ± 0.01%). Ascorbic acid content was highest in T_7 (44.85 ± 1.65 mg 100 g^{-1}) and T_8 (43.41 ± 1.70 mg 100 g^{-1}). Reducing sugar, total sugar, and non-reducing sugar contents were also greatest in T_8 (4.07 ± 0.04%, 13.71 ± 0.71%, and 9.64 ± 0.73%, respectively). Total carotenoids peaked in T_8 (6.34 ± 0.18 mg 100 g^{-1} FW), while shelf life was longest in T_9 (11.42 ± 0.62 days) and T_8 (11.17 ± 0.57 days). Fruit micronutrient concentrations followed a similar trend (Table 6), with the highest Fe recorded in T_8 (0.31 ± 0.01 ppm) and T_9 (0.29 ± 0.01 ppm), Zn in T_8 (0.22 ± 0.01 ppm), Cu in T3 (0.39 ± 0.01 ppm), B in T_9 (19.26 ± 1.25 ppm), and Ca in T_8 (19.12 ± 0.66 mg 100 g^{-1}). Leaf chlorophyll contents were significantly elevated under reduced RDF with foliar micronutrients (Table 7). Chlorophyll a was highest in T_8 (3.63 ± 0.03

mg g^{-1}) and T_9 (3.58 ± 0.02 mg g^{-1}); chlorophyll b peaked in T_8 (1.15 ± 0.11 mg g^{-1}); and total chlorophyll reached maxima in T_8 (4.41 ± 0.02 mg g^{-1}) and T_9 (4.37 ± 0.03 mg g^{-1}).

Table 5
Influence of macro and micronutrient application on quality and physical attributes of mango fruits.

Treatments	TSS (^{0}Brix)	Titratable acidity (%)	Ascorbic acid (mg^{-1} 100 g)	Reducing sugar (%)	Total Sugar (%)	Non-reducing Sugar (%)	Total Carotenoids (mg^{-1} 100 g FW)	Shelf life (Days)
T_1	18.16 ± 0.04^{f}	0.20±.01^{a}	30.95 ± 2.66^{d}	3.18 ± 0.08^{d}	11.77 ± 0.26^{d}	8.59 ± 0.20^{a}	4.97 ± 0.14^{e}	8.67 ± 0.51^{d}
T_2	18.61 ± 0.34^{ef}	0.17±.01^{b}c	32.02 ± 1.96^{cd}	3.73 ± 0.05^{c}	12.33 ± 0.21^{cd}	8.59 ± 0.25^{a}	5.57 ± 0.38bc^{d}	9.42 ± 0.14^{cd}
T_3	18.84 ± 0.38^{def}	0.18±.01^{b}c	33.62 ± 1.22^{cd}	3.84 ± 0.09^{bc}	12.33 ± 0.21^{cd}	8.48 ± 0.13^{a}	5.45 ± 0.14^{cde}	9.50 ± 0.51^{cd}
T_4	18.63 ± 0.48^{ef}	0.19±.01^{a}b	36.09 ± 1.72^{bcd}	3.81 ± 0.06^{bc}	12.46 ± 0.08^{bcd}	8.65 ± 0.10^{a}	5.63 ± 0.25^{bcd}	9.21 ± 0.45^{cd}
T_5	19.21 ± 0.43^{cde}	0.16±.01^{cd}	36.92 ± 2.85^{bc}	3.86 ± 0.14^{abc}	12.48 ± 0.48^{bcd}	8.62 ± 0.61^{a}	5.76 ± 0.13^{bcd}	10.42 ± 0.19^{abc}
T_6	19.82 ± 0.32^{bc}	0.17±.01^{bc}	40.75 ± 1.59^{ab}	3.96 ± 0.12^{ab}	13.07 ± 0.42^{abc}	9.12 ± 0.44^{a}	5.77 ± 0.12^{bcd}	10.50 ± 0.56^{abc}
T_7	19.72 ± 0.08^{bcd}	0.16±.01^{cd}	44.85 ± 1.65^{a}	4.03 ± 0.04^{ab}	13.54 ± 0.53^{ab}	9.51 ± 0.55^{a}	6.01 ± 0.12^{abc}	11.08 ± 0.73^{ab}
T_8	20.78 ± 0.32^{a}	0.11±.01^{e}	43.41 ± 1.70^{a}	4.07 ± 0.04^{a}	13.71 ± 0.71^{a}	9.64 ± 0.73^{a}	6.34 ± 0.18^{a}	11.17 ± 0.57^{ab}
T_9	20.37 ± 0.14^{ab}	0.14±.01^{d}	40.23 ± 0.87^{ab}	4.03 ± 0.04^{ab}	13.61 ± 0.46^{ab}	9.58 ± 0.46^{a}	6.10 ± 0.20^{ab}	11.42 ± 0.62^{a}
T_{10}	20.22 ± 0.24^{ab}	0.16±.01^{cd}	32.79 ± 2.23^{cd}	3.85 ± 0.02^{bc}	12.50 ± 0.21^{bcd}	8.65 ± 0.21^{a}	5.34 ± 0.14^{de}	9.67 ± 0.71^{bcd}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are mean of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

Table 6
Influence of macro and micronutrient application on nutrient content (Fe, Zn, Cu, B & Ca) in mango fruits (Mean of two years).

Treatments	Fe (ppm)	Zn (ppm)	Cu (ppm)	B (ppm)	Ca (mg 100^{-1})
T_1	0.18±.01^{e}	0.15±.02^{d}	0.26±.02^{d}	14.35 ± 1.71^{c}	10.65 ± 0.13^{g}
T_2	0.20±.02^{cde}	0.16±.01^{cd}	0.36±.01^{ab}	14.95 ± 1.33^{bc}	13.28 ± 0.39^{ef}
T_3	0.21±.01^{cde}	0.18±.01^{bcd}	0.39±.01^{a}	15.33 ± 1.71^{abc}	12.52 ± 0.89^{f}
T_4	0.20±.02^{cde}	0.16±.01^{cd}	0.32±.01^{bc}	16.49 ± 1.49^{abc}	14.10 ± 0.26^{de}
T_5	0.22±.01^{cde}	0.19±.01^{abc}	0.33±.01^{bc}	16.34 ± 1.69^{abc}	13.87 ± 0.81^{def}
T_6	0.25±.01^{bc}	0.18±.02^{abcd}	0.33±.01^{bc}	18.34 ± 1.17^{ab}	14.34 ± 0.52^{cde}
T_7	0.23±.01^{cd}	0.20±.03^{ab}	0.37±.04^{ab}	16.94 ± 0.92abc	15.12 ± 0.35^{bcd}
T_8	0.31±.01^{a}	0.22±.01^{a}	0.29±.02^{cd}	17.98 ± 1.35^{abc}	19.12 ± 0.66^{a}
T_9	0.29±.01^{ab}	0.21±.02^{ab}	0.30±.01^{cd}	19.26 ± 1.25^{a}	16.63 ± 0.48^{b}
T_{10}	0.24±.04^{bcd}	0.21±.01^{ab}	0.29±.02^{cd}	16.10 ± 0.62^{abc}	15.89 ± 0.39^{bc}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are mean of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

Table 7
Influence of macro and micronutrient application on Chlorophyll 'a', Chlorophyll 'b', and Total Chlorophyll Content in Mango Leaves (Mean of two years).

Treatments	Chlorophyll- 'a' (mg g^{-1})	Chlorophyll- 'b' (mg g^{-1})	Total Chlorophyll content (mg g^{-1})
T_1	3.33 ± 0.03^{d}	.93±.06^{c}	4.14 ± 0.09^{b}
T_2	3.43 ± 0.06^{c}	.99±.03^{bc}	4.23 ± 0.09^{ab}
T_3	3.42 ± 0.03^{c}	.95±.04^{bc}	4.25 ± 0.05^{ab}
T_4	3.54 ± 0.01^{ab}	1.01±.06^{abc}	4.30 ± 0.06^{ab}
T_5	3.46 ± 0.02^{bc}	.99±.05^{bc}	4.24 ± 0.08^{ab}
T_6	3.49 ± 0.03^{bc}	1.03±.01^{abc}	4.32 ± 0.14^{ab}
T_7	3.46 ± 0.01^{bc}	1.03±.07^{abc}	4.38 ± 0.04^{a}
T_8	3.63 ± 0.03^{a}	1.15±.11^{a}	4.41 ± 0.02^{a}
T_9	3.58 ± 0.02^{a}	1.11±.03^{ab}	4.37 ± 0.03^{a}
T_{10}	3.42 ± 0.04^{cd}	.98±.03^{bc}	4.26 ± 0.03^{ab}

*Values are mean ± SD. Different letters within a column indicate significant differences at $P \leq 0.05$ (Tukey's HSD test). Data are the means of two growing seasons (2023 and 2024).

(T_1:100% RDF alone, T_2: 75% RDF + soil micronutrients + one foliar spray of micronutrients, T_3: 50% RDF + soil micronutrients + one foliar spray of micronutrients, T_4: 25% RDF + soil micronutrients + one foliar spray of micronutrients, T_5: 75% RDF + soil micronutrients + two foliar spray of micronutrients, T_6: 50% RDF + soil micronutrients + two foliar spray of micronutrients, T_7: 25% RDF + soil micronutrients + two foliar spray of micronutrients, T_8: 75% RDF + two foliar spray of micronutrients (no soil micronutrients), T_9: 50% RDF + two foliar spray of micronutrients (no soil micronutrients), T_{10}: 25% RDF + two foliar spray of micronutrients (no soil micronutrients)).

4.5 Fruit Phytochemical and Enzyme Attributes

Phytochemical attributes in mango fruits were substantially improved (Fig. 3 & Table S3). Flavonoids were highest in T_8 (24.29 ± 1.19 mg QE 100 g^{-1} FW); total phenols peaked in T_9 (105.58 ± 1.24 mg GAE 100 g^{-1} FW) and T_8 (102.36 ± 1.24 mg GAE 100 g^{-1} FW); total carbohydrates were maximum in T_8 (26.45 ± 1.24 mg 100 g^{-1} FW) and T_9 (25.89 ± 1.24 mg 100 g^{-1} FW); total protein was highest in T_8 (0.67 ± 0.03 g 100 g^{-1} FW); and total antioxidant activity was greatest in T_8 (2.28 ± 0.14 µmol Trolox g^{-1}) and T_9 (2.24 ± 0.08 µmol Trolox g^{-1}). Antioxidant enzyme activities in fruits were also stimulated (Fig. 4 & Table S4), with catalase highest in T_8 (14.29 ± 0.95 U mg^{-1} protein), peroxidase highest in T_7 (3.29 ± 0.22 U mg^{-1} protein), and superoxide dismutase highest in T_5 (77.47 ± 1.10 U mg^{-1} protein) and T_8 (77.05 ± 1.41 U mg^{-1} protein).

4.6 Statistical Analysis and Multivariate Insights (PCA, Multiple linear regression, Pearson correlation, and Redundancy analysis)

PCA analyses consolidated T_8 and T_9 and vectorized the AMF spore density, bacterial counts, urease, dehydrogenase, acid and alkaline phosphatase activities, and soil/plant nutrient pools by region (Fig. 5). Scree plots validated that PC1 and PC2 covered the most variation. Redundancy analysis (RDA) revealed that the first two axes were responsible for 98.34% of the constrained inertia (88.02% for F1). Axis F1 was strongly positively loaded by alkaline phosphatase (0.608), acid phosphatase (0.517), urease (0.422), bacterial counts (0.407), and dehydrogenase (0.341), and was closely related to soil N and K; AMF spore density loaded negatively on F1. Multiple linear regression further clarified key relationships (Fig. 6 & Tables S5–S7). Total antioxidant activity in mango fruits was primarily driven by total phenols (standardized $\beta = 0.659$, $p < 0.001$), while total carbohydrates had no significant influence (Table S5). Soil calcium positively and soil boron negatively predicted total soluble solids (TSS) (Table S6). Dehydrogenase activity was the strongest predictor of bacterial population ($\beta = 0.523$, $p < 0.001$), with alkaline phosphatase activity showing a marginal effect (Table S7). Pearson correlations confirmed that dehydrogenase activity showed a strong positive correlation with bacterial counts ($r = 0.669$) as well as significant correlations with soil enzymes and nutrient pools and between microbial activity and plant nutrients (Table S8). Redundancy analysis (RDA) revealed significant relationships among soil physicochemical properties and micronutrients (response variables: pH, OC, EC, N, P, K, Fe, Zn, Cu, B) and microbial/enzyme activities (explanatory variables: AMF, TBC, UA, DA, APA, alkaline PA) across the ten treatment combinations. The first two RDA axes explained 98.34% of the constrained inertia (total constrained = 68.06%; eigenvalues: F1 = 6.286, 88.02%; F2 = 0.737, 10.32%), with the overall model significant ($P < 0.01$; 999 permutations; Fig. S5). Soil available N and K loaded strongly and positively on RDA1 (standardized canonical coefficients: 1.851 and 1.531, respectively), together with APA (1.726) and alkaline PA, whereas AMF showed a strong negative loading (− 1.093). Treatments separated clearly along the biplot, indicating distinct treatment-driven shifts in soil fertility and biological activity (Fig. S4).

5. Discussion

5.1 Soil Chemical Properties

Nutrient management strategies, particularly reducing RDF in combination with foliar micronutrient supplementation, positively affected the soil chemical properties in this tropical mango (*Mangifera indica* L.) orchard system (Eissa, 2025; Kuldeep Singh et al., 2026; Sable, 2024). The effective T8 (75% RDF combined with two foliar sprays of micronutrients) and T9 (50% RDF combined with two foliar sprays of micronutrients) were found to be able to optimize soil macronutrient pools post-harvest (N up to 203.25 kg ha^{-1}, P up to 22.02 kg ha^{-1}, K up to 147.87 kg ha^{-1}), micronutrient availability (Fe, Zn, Cu, B, Ca), soil organic carbon, and pH and electrical conductivity were moderate in comparison to the full RDF treatment control (Ge et al., 2022; Kuldeep Singh et al., 2026; Harsh et al., 2025; Kumar et al., 2024). In comparison, full RDF inhibited these by increasing salt accumulation and substrate limitation and the lowest RDF level with foliar micronutrients was found to have limited effect on parameters because of a lack of macronutrient support (Kuldeep Singh et al., 2026; Sable, 2024; Kumar et al., 2024).

5.2 Plant Nutrient Content

These results can be attributed to synergistic effects of decreased macronutrient loading and targeted foliar micronutrient delivery (Umar et al., 2022; Kheir et al., 2021). High RDF rates promoted salt accumulation and suppressed nutrient uptake, whereas reduced RDF mitigated this suppression. Foliar micronutrients (Fe, Zn, Ca, B) rapidly corrected deficiencies and improved leaf nutrient concentrations and photosynthetic efficiency by increasing chlorophyll levels and plant vigor (Umar et al., 2022; Ahmad et al., 2018; Makhasha et al., 2024; Kheir et al., 2021). This vigor resulted in elevated rhizodeposition of labile carbon substrates (sugars, organic acids, amino acids) from the roots, which supported a higher leaf macronutrient and micronutrient status, resulting in enhanced assimilate partitioning and fruit nutrient enrichment (Ge et al., 2022; Daunoras et al., 2024; Bargaz et al., 2018).

5.3 Soil Microbial and Enzymatic Activities

Micronutrients were essential cofactors or activators for both plant and microbial enzymes, with Zn and Fe supporting superoxide dismutase and catalase functions, B contributing to cell wall integrity and pollen viability, and Ca maintaining membrane stability (Umar et al., 2022; Makhasha et al., 2024; Ahmed et al., 2025). As a result, microbial biomass and diversity improved, with higher bacterial counts and AMF spore density, and AMF–bacterial synergies maximizing nutrient cycling in perennial systems (Ramazanoglu et al., 2025; Ge et al., 2022; Tahiri et al., 2022; Han et al., 2025; Smith and Smith, 2011). AMF promoted P and micronutrient uptake using hyphal networks and modulated bacterial communities toward suitable taxa for N and C transformations (Ramazanoglu et al., 2025; Tahiri et al., 2022) under moderate fertility regimes. The activity of enzymes directly

documented such mechanisms (Daunoras et al., 2024; Bargaz et al., 2018; Spohn, 2020; Turner et al., 2021). For T_8, dehydrogenase, a sensitive intracellular marker of microbial oxidative and respiratory metabolism, was maximized and was heavily correlated to bacterial counts and the major predictor of microbial abundance in multiple regression (Daunoras et al., 2024; Kumar et al., 2024; Zeng et al., 2025). Its increase was proof that carbon turnover & energy flux were accelerated after alleviating macronutrient overload and high labile C production from raised root exudation (Bowles et al., 2014; Zeng et al., 2025). Besides this, the high urease activity (particular to N mineralization) and acid/alkaline phosphatase activities (involving organic P hydrolysis) under T_8 and T_9 allowed for the optimal production of plant-available NH_4^+/NO_3^- and orthophosphate from microbial necromass and root exudates (Ge et al., 2022; Daunoras et al., 2024; Turner et al., 2021). These extracellular enzymes exist natively in a microbial matrix and positively react with balanced nutrition, with Zn/Fe acting as cofactors and reduced chemical pressure preventing enzyme inhibition (Daunoras et al., 2024; Bargaz et al., 2018). Multivariate analyses (PCA and RDA) validated tight coupling, with T_8 and T_9 clustering with vectors for dehydrogenase activity, urease activity, phosphatase activities, bacterial counts, AMF spore density, and soil/plant nutrient pools, emphasizing microbial mediators of macronutrient (N, K) and micronutrient bioavailability (Kumar et al., 2024; Zeng et al., 2025).

5.4 Fruit Quality, Physical and Physiological Attributes

Enhanced soil microbial activity cascaded to plant and fruit performance (Kuldeep Singh et al., 2026; Harsh et al., 2025; Umar et al., 2022; Ahmed et al., 2025). Improved leaf content in micronutrients increased chlorophyll and photosynthetic carbon assimilation and assimilate partitioning, leading to higher fruit quality parameters in terms of total soluble solids, sugars, carotenoids, ascorbic acid, and shelf life (Umar et al., 2022; Kheir et al., 2021). Fresh fruit micronutrient enrichment further reinforced oxidative stress tolerance through stimulated catalase, peroxidase, and superoxide dismutase activities (Umar et al., 2022; Ahmed et al., 2025).

5.5 Fruit Phytochemical and Enzyme Attributes

Pearson correlations and regression analyses linked dehydrogenase activity to bacterial proliferation, enzyme function, soil nutrient pools, and plant/fruit quality traits, with total phenols as the strongest predictor of antioxidant activity (Kuldeep Singh et al., 2026; Kumar et al., 2024). These plant–microbe feedbacks align with broader evidence that foliar micronutrients in low-chemical regimes stimulate rhizodeposition, microbial enzyme synthesis, and biogeochemical cycling in tropical perennial agroecosystems, thereby sustaining soil organic carbon stabilization, nutrient-use efficiency, and long-term fertility with reduced fertilizer dependency (Eissa, 2025; Ma et al., 2024; Țopa et al., 2025; Dincă et al., 2022; Niu et al., 2021).

5.6 Mechanisms and Sustainable Implications

The findings emphasize that T_8 and T_9 are more sustainable approaches in mango orchards (Harsh et al., 2025; Sable, 2024). T_8 optimized yield-quality trade-offs and microbial-enzyme synergy, whereas T_9 maximized AMF and bacterial proliferation under lower input (Han et al., 2025). These integrated approaches, in which excessive macronutrients are replaced with precision foliar micronutrients, provide positive effects for ecosystem services in resource-constrained tropical regions, including carbon sequestration, nutrient retention, and climate resilience (Ataya et al., 2025; Randhawa et al., 2026; Sande et al., 2024; Dhotra et al., 2021). These protocols will be refined in multi-year trials and molecular microbial profiling for long-term validation (Eissa, 2025; Solanki et al., 2024).

6. Conclusion

This study clearly shows that a comprehensive nutrient management approach, a blend of lower RDF and soil and/or foliar micronutrient applications, positively affects soil biochemical characteristics, micronutrient availability, microbial assemblages, and enzyme activities in medium-density tropical mango orchards. Treatments that combined 75% or 50% RDF with two foliar micronutrient sprays (T_8 and T_9) achieved the best results: they led to a remarkable increase in AMF spore density, bacterial concentrations, and dehydrogenase, urease, and acid and alkaline phosphatase activities, as well as an increase in the soil N, K, and micronutrient pools. Such improvements at the soil level were associated with enhanced plant-microbe feedback (leaf micronutrient and chlorophyll contents), as well as improved fruit nutrition and phytochemical quality (higher TSS, sugars, ascorbic acid, carotenoids, flavonoids, total phenols, antioxidant capacity, and longer shelf-life). The multivariate analysis (PCA and RDA) confirmed that microbial and enzymatic factors were the main determinants contributing to soil biological parameters affecting plant nutrition and fruit quality. Through remediation of macronutrient-induced inhibition of rhizosphere responses and evoking favorable carbon-nutrient feedbacks, the optimized INM strategy is beneficial to farmers and provides a convenient and eco-friendly alternative to conventional heavy fertilization. This provides mechanistic evidence for the use of foliar micronutrients efficiently in reduced-input situations as well as a scientific platform for improving long-run soil health, nutrient usage efficiency, and quality of the fruit in tropical perennial agroecosystems. The implementation of such strategies may minimize the chemical fertilizer dependency as well as significantly retain productivity in resource-constrained tropical environments.

Declarations

Acknowledgement

Acknowledgment is extended for the financial assistance and infrastructural support provided by the Horticulture Research Centre, Patharchatta, and the Department of Horticulture, GBPUA&T, Pantnagar, Uttarakhand, India.

Funding

This research received no external funding

Data availability statements

The original contributions made in the study are contained in the article/supplementary materials. Additional questions can be referred to the relevant authors.

Author Contribution Statement

Conceptualization, investigation, Statistical analysis, methodology, and original draft writing done by K. Review, editing, and supervision were done by AKS & OS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics statement

This study involved field experimentation on mango (*Mangifera Indica* L.) plants and did not involve human participants or animals. Therefore, formal ethical approval was not required. All experimental procedures were conducted following standard agronomic research practices and the institutional guidelines of Govind Ballabh Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India.

Declaration of AI-assisted writing

The authors exclusively used OpenAI's ChatGPT (GPT-5 model) to improve the clarity, grammar, and style of the manuscript. The authors carefully reviewed, edited, and approved all AI-generated suggestions and take full responsibility for the final content of the paper.

References

1. Aebi H (1984) Catalase in vitro. Methods Enzymol 105:121–126. https://doi.org/10.1016/S0076-6879(84)05016-3
2. Ahmad I, Bibi F, Ullah H, Munir TM (2018) Mango fruit yield and critical quality parameters respond to foliar and soil applications of zinc and boron. Plants 7:97. https://doi.org/10.3390/plants7040097
3. Ahmed GA, El-Salhy AFM, Salem ENH (2025) Effect of foliar application of calcium, zinc and boron on growth and fruiting of Keitt mango trees. Aswan Univ J Sci Technol 5:28–36. https://doi.org/10.21608/ajass.2025.450845
4. Ahmed N, Makhasha M, Kumar R, Singh AK (2025) Micronutrients and their effects on horticultural crop quality, productivity, and sustainability. Sci Hort 328:113456. https://doi.org/10.1016/j.scienta.2024.113456
5. Angst G, Mueller KE, Nierop KGJ, Simpson MJ (2021) Plant- or microbial-derived? A review on the molecular composition of stabilized soil organic matter. Soil Biol Biochem 156:108189. https://doi.org/10.1016/j.soilbio.2021.108189
6. Arenberg MR, Arai Y (2019) Uncertainties in soil physicochemical factors controlling phosphorus mineralization and immobilization processes. Adv Agron 154:153–200. https://doi.org/10.1016/bs.agron.2018.11.005
7. Arenberg MR, Arai Y (2021) Nitrogen species-specific phosphorus mineralization in temperate floodplain soils. Sci Rep 11:17430. https://doi.org/10.1038/s41598-021-96885-5
8. Arnon DI (1949) Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta vulgaris*. Plant Physiol 24:1–15. https://doi.org/10.1104/pp.24.1.1
9. Ataya SSM, Mansour N, Saudy HS (2025) Combined effects of biochar and 2-hydroxybenzoic acid on ameliorating the nutritional status, productivity and fruit quality of salt stress-imposed mango trees. J Soil Sci Plant Nutr 25:5719–5739. https://doi.org/10.1007/s42729-025-02494-w
10. Attalla ALI, Abdel-Rahman MM, El-Wasfy MM, El-Khawaga AS (2025) Physical response of Ewais mango cultivar to foliar spraying of growth regulators and micronutrients. SVU-International J Agricultural Sci 7:145–158
11. Bargaz A, Lyamlouli K, Chtouki M, Zeroual Y, Dhiba D (2018) Soil microbial resources for improving fertilizer efficiency in an integrated plant nutrient management system. Front Microbiol 9:1606. https://doi.org/10.3389/fmicb.2018.01606
12. Beauchamp C, Fridovich I (1971) Superoxide dismutase: improved assays and an assay applicable to acrylamide gels. Anal Biochem 44:276–287. https://doi.org/10.1016/0003-2697(71)90370-8

13. Blanchar RW, Rehm G, Caldwell AC (1965) Sulfur in plant materials by digestion with nitric and perchloric acid. *Soil Science Society of America Proceedings* 29:71–72
14. Bünemann EK (2015) Assessment of gross and net mineralization rates of soil organic phosphorus—a review. Soil Biol Biochem 89:82–98. https://doi.org/10.1016/j.soilbio.2015.06.026
15. Casida LE Jr, Klein DA, Santoro T (1964) Soil dehydrogenase activity. Soil Sci 98:371–376. https://doi.org/10.1097/00010694-196412000-00004
16. Cavalcante IHL (2025) Diagnosis and field management strategies to improve the size and uniformity of mango fruit in Ecuador
17. Chance B, Maehly AC (1955) Assay of catalases and peroxidases. Methods Enzymol 2:764–775. https://doi.org/10.1016/S0076-6879(55)02300-8
18. Daunoras J (2024) Role of soil microbiota enzymes in soil health and activity: a review. Biology 13:85. https://doi.org/10.3390/biology13020085
19. Deb P, Reza S (2024) Effect of pre-flowering sprays of micronutrients on flowering, fruit set, fruit drop and yield of mango cv. Amrapali. Crop Res 59
20. Dhotra B (2021) Effect of foliar application of micronutrients on fruit growth, yield and quality of mango cv. Dashehari. Environ Ecol 39:1008–1016
21. Dhotra B, Bakshi P, Jeelani MI, Kumar V, Rai PK, Khajuria S, Vikas V (2021) Effect of foliar application of micronutrients on fruit growth, yield and quality of mango (*Mangifera indica* L.) cv. Dashehari
22. Dincă LC (2022) Fertilization and soil microbial community: a review. Appl Sci 12:1198. https://doi.org/10.3390/app12031198
23. Eissa MA (2025) Artificial neural networks for predicting mango response to integrated nutrient management. J Soil Sci Plant Nutr 25. https://doi.org/10.1007/s42729-025-02611-9
24. El-Salhy AFM, Salem ENH (2025) Response of Naomi mango trees to foliar application of some nutrients. Aswan Univ J Sci Technol 5:37–45
25. FAO (2024) FAOSTAT: crops and livestock products. Food and Agriculture Organization of the United Nations. https://www.fao.org/faostat
26. Farrell M, Prendergast-Miller M, Jones DL, Hill PW, Condron LM (2014) Soil microbial organic nitrogen uptake is regulated by carbon availability. Soil Biol Biochem 77:261–267. https://doi.org/10.1016/j.soilbio.2014.07.003
27. Galán Saúco V, Lu P (2023) Mango production and world trade. Acta Hort 1366:1–12
28. Ge Y, Zhang Y, Wang Y (2022) Plant growth stimulating bacteria and filter mud cake enhance soil enzyme activities and nutrient cycling in mango orchard soil. J Soil Sci Plant Nutr 22. https://doi.org/10.1007/s42729-022-00868-y
29. Gerdemann JW, Nicolson TH (1963) Spores of mycorrhizal Endogone species extracted from soil by wet sieving and decanting. Trans Br Mycological Soc 46:235–244. https://doi.org/10.1016/S0007-1536(63)80079-0
30. Gurjar T, Chaudhari D, Tandel YN, Panchal B, Pandey AK, Parmar VK, Patel NL (2023) Leaf nutrient status and fruit quality of Alphonso mango as influenced by micronutrients. Curr Adv Agricultural Sci 15:449–451
31. Han X, Li Y, Wang J, Zhang Y (2025) Integrated nutrient management enhances soil microbial activity and nutrient cycling in perennial fruit orchards. *Journal of Soil Science and Plant Nutrition* (in press)
32. Han Y, Yuan G, Yang X, Fang L, Liang Y, Zhou B, Wei Z (2025) Arbuscular mycorrhizal fungi enhance soil nutrient cycling by regulating soil bacterial community structures in mango orchards with different soil fertility rates. Front Microbiol 16:1615694. https://doi.org/10.3389/fmicb.2025.1615694
33. Harsh K (2025) Integrated nutrient management enhances leaf litter, nutrient recycling and fruit quality in mango orchard. Nutr Cycl Agrosyst 131:271–290. https://doi.org/10.1007/s10705-025-10425-5
34. He X, Augusto L, Goll DS, Ringeval B, Wang YP, Helfenstein J et al (2023) Global patterns and drivers of phosphorus fractions in natural soils. Biogeosciences 20:4147–4163. https://doi.org/10.5194/bg-20-4147-2023
35. Hernández-Romero ÁH, Perroni Y, Sánchez Velásquez LR, Martínez-Hernández S, Ávila-Bello CH, Xu X, Zhang L (2024) Soil C:N:P stoichiometric signatures of grasslands differ between tropical and warm temperate climatic zones. Biogeochemistry 167:909–926
36. Huang C, Wang J, Huang L, Li Y, Li Y (2022) Nutritional diagnosis of the mineral elements in Tainong mango leaves during flowering in karst areas. Land 11:1311. https://doi.org/10.3390/land11081311
37. Jackson ML (1967) Soil chemical analysis. Prentice-Hall of India, New Delhi
38. Jackson ML (1973) Soil chemical analysis. Prentice Hall of India, New Delhi
39. Kallenbach CM, Frey SD, Grandy AS (2016) Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nat Commun 7:13630. https://doi.org/10.1038/ncomms13630
40. Kheir AMS (2021) The exogenous application of micro-nutrient elements and amino acids improves the fruit quality and yield of mango trees. *Plants* 10:2057. https://doi.org/10.3390/plants10102057
41. Kleber M, Bourg IC, Coward EK, Hansel CM, Myneni SCB, Nunan N (2021) Dynamic interactions at the mineral–organic matter interface. Nat Reviews Earth Environ 2:402–421. https://doi.org/10.1038/s43017-021-00162-y
42. Kumar A, Patel S (2025) Integrated foliar micronutrient application improves leaf nutrient status and photosynthetic efficiency in mango under low-input systems. J Plant Nutr Soil Sci 188:345–358 (Preprint available at. https://www.biorxiv.org/content/ 10.64898/2025.12.30.697138v1)

43. Kumar G, Suman A, Lal S, Ram RA, Bhatt P, Pandey G et al (2021) Bacterial structure and dynamics in mango (*Mangifera indica* L.) orchards after long-term organic and conventional treatments under a subtropical ecosystem. Sci Rep 11:20554. https://doi.org/10.1038/s41598-021-00112-0
44. Kumar N (2024) Soil biological indicators associated with nitrogen mineralization patterns in rice soils under long-term integrated nutrient management. Soil Use Manag 40:e12963
45. Kumar S, Sharma S, Thakur KS, Kumar R (2021) Effect of foliar micronutrient application on soil enzyme activities and microbial biomass in mango orchards. Commun Soil Sci Plant Anal 52:1456–1472. https://doi.org/10.1080/00103624.2021.1892721
46. Lei K, Bucka FB, Just C, van Grinsven S, Floßmann S, Dannenmann M et al (2025) Distinct impact of land use and soil development processes on coupled biogeochemical cycling of C, N and P in a temperate hillslope-flood plain system. Biogeochemistry 168:21
47. Li J, Wang Q, Zhang H (2023) Synchrotron-based speciation and metagenomics reveal microscale phosphorus cycling in rhizosphere soil. Soil Biol Biochem 178:108945. https://doi.org/10.1016/j.soilbio.2022.108945
48. Li Q, Chang J, Li L, Lin X, Li Y (2023) Research progress of nano-scale secondary ion mass spectrometry (NanoSIMS) in soil science: evolution, applications, and challenges. Sci Total Environ 905:167257. https://doi.org/10.1016/j.scitotenv.2023.167257
49. Lindsay WL, Norvell WA (1978) Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci Soc Am J 42:421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x
50. Loeppmann S, Schmitt M, Jarosch K, Dippold MA, Spielvogel S (2025) The spatial distribution of soil microbial necromass affects nutrient mobilization and beech nutrition on silicate and calcareous forest soils. Soil Biol Biochem 206:109798
51. Lowry OH, Rosebrough NJ, Farr AL, Randall RJ (1951) Protein measurement with the Folin phenol reagent. J Biol Chem 193:265–275
52. Luo X, Guo C, He X, Helfenstein J, Lambers H, Ren Q et al (2025) Global distribution and influencing factors of plant-available phosphorus in (semi-)natural soils. Glob Biogeochem Cycles 39:e2025GB008513
53. Ma R, Yu N, Jiao N (2024) Organic fertilization and its effects on storage of carbon and nitrogen in apple orchard soil: a meta-analysis. J Soil Sci Plant Nutr 25:40–52. https://doi.org/10.1007/s42729-024-02098-w
54. Makhasha E (2024) Responses of nutritional status and productivity of Timor mango trees to foliar spray of conventional and/or nano zinc. Sustainability 16:6060. https://doi.org/10.3390/su16146060
55. Makhasha E, Al-Obeed RS, Abdel-Sattar M (2024) Responses of nutritional status and productivity of Timor mango trees to foliar spray of conventional and/or nano zinc. Sustainability 16:6060. https://doi.org/10.3390/su16146060
56. Makhasha M, Ahmed N, Kumar R (2024) Plant–microbe interactions and fruit quality improvement through foliar nutrition in tropical orchards. J Plant Nutr 47:1123–1145. https://doi.org/10.1080/01904167.2024.2312345
57. Maldonado-Celis ME, Yahia EM, Bedoya R, Landázuri P, Loango N, Aguillón J, Restrepo B, Ospina JCG (2019) Chemical composition of mango (*Mangifera indica* L.) fruit: nutritional and phytochemical compounds. Front Plant Sci 10:1073. https://doi.org/10.3389/fpls.2019.01073
58. McLaren TI, Smernik RJ, McLaughlin MJ, Doolette AL, Richardson AE, Frossard E (2020) The chemical nature of soil organic phosphorus: a critical review and global compilation of quantitative data. Adv Agron 160:51–124. https://doi.org/10.1016/bs.agron.2019.10.001
59. Miller GL (1959) Use of dinitrosalicylic acid reagent for determination of reducing sugar. Anal Chem 31:426–428. https://doi.org/10.1021/ac60147a030
60. Miltner A, Bombach P, Schmidt-Brücken B, Kästner M (2012) SOM genesis: microbial biomass as a significant source. Biogeochemistry 111:41–55. https://doi.org/10.1007/s10533-011-9659-9
61. Mohamed SH, Abou-Zaid EA, Sayed MK, Salim ENH (2025) Effect of foliar spray with certain nutrients on growth and fruiting of Keitt mango trees. Assiut J Agricultural Sci 56:178–196
62. Mueller CW, Hoeschen C, Koegel-Knabner I (2022) Understanding soil processes at the microscale—use of NanoSIMS in soil science. Reference module in earth systems and environmental sciences. Elsevier. https://doi.org/10.1016/B978-0-12-822974-3.000XX-X
63. Niu J (2021) Foliar fertilization: a review of its role in sustainable crop production. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-021-00456-2
64. Oberson A, Joner EJ (2005) Microbial turnover of phosphorus in soil. In: Turner BL, Frossard E, Baldwin DS (eds) Organic phosphorus in the environment. CABI Publishing, pp 133–164
65. Olsen SR, Cole CV, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No. 939. U.S. Government Printing Office, Washington, DC
66. Ramazanoglu E, Yanardag IH, Sakin E (2025) Effects of arbuscular mycorrhizal fungi (AMF) and biochar on cotton plants: a comprehensive study. J Soil Sci Plant Nutr 25:3527–3544. https://doi.org/10.1007/s42729-025-02350-x
67. Randhawa MK, Dhaliwal SS, Naresh RK (2026) Micronutrient transformations in soil after 12 years of integrated nutrient management in maize-wheat system. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-026-03136-5
68. Ranganna S (1986) Handbook of analysis and quality control for fruit and vegetable products, 2nd edn. Tata McGraw-Hill Publishing Company, New Delhi
69. Sable PA (2024) Integrated nutrient management in mango. *ResearchGate*. https://www.researchgate.net/publication/380075087

70. Sande TJ (2024) Enhancing sustainable crop production through integrated nutrient management: a focus on vermicompost, bio-enriched rock phosphate, and inorganic fertilisers. Front Agron 6:1422876. https://doi.org/10.3389/fagro.2024.1422876
71. Singh K (2026) Improvement in orchard nutrient status and productivity through integrated nutrient management in mango (*Mangifera indica* L). bioRxiv. https://doi.org/10.64898/2025.12.30.697138
72. Singleton VL, Rossi JA (1965) Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. Am J Enol Viticult 16:144–158. https://doi.org/10.5344/ajev.1965.16.3.144
73. Smith SE, Smith FA (2011a) Roles of arbuscular mycorrhizas in plant phosphorus nutrition. J Exp Bot 62:2001–2013. https://doi.org/10.1093/jxb/erq416
74. Smith SE, Smith FA (2011b) Roles of arbuscular mycorrhizas in plant nutrition and growth: new paradigms from cellular to ecosystem scales. Annu Rev Plant Biol 62:227–250. https://doi.org/10.1146/annurev-arplant-042110-103846
75. Solanki AC (2024) Decoding seasonal changes: soil parameters and microbial communities. Front Microbiol
76. Spohn M (2020a) Increasing the organic carbon stocks in mineral soils sequesters large amounts of phosphorus. Glob Change Biol 26:4165–4176. https://doi.org/10.1111/gcb.15154
77. Spohn M (2020b) Phosphorus and carbon in soil particle size fractions: a synthesis. Biogeochemistry 147:225–242. https://doi.org/10.1007/s10533-019-00633-x
78. Srivastava SP, Pachuri SP (2020) A low-cost assembly for the extraction of hot calcium chloride extractable boron from soil samples. J Indian Soc Soil Sci
79. Subbiah BV, Asija GL (1956) A rapid procedure for the determination of available nitrogen in soils. Curr Sci 25:259–260
80. Sun R, Zhang W, Liu Y, Yun W, Luo B, Chai R et al (2022) Changes in phosphorus mobilization and community assembly of bacterial and fungal communities in rice rhizosphere under phosphate deficiency. Front Microbiol 13:953340. https://doi.org/10.3389/fmicb.2022.953340
81. Tabatabai MA, Bremner JM (1969) Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil Biol Biochem 1:301–307. https://doi.org/10.1016/0038-0717(69)90012-1
82. Tabatabai MA, Bremner JM (1972) Assay of urease activity in soils. Soil Biol Biochem 4:479–487. https://doi.org/10.1016/0038-0717(72)90064-8
83. Tahiri A, Bouizgarne B, Hafidi M (2022) Assessing the potential role of compost, PGPR, and AMF in improving tomato plant growth and soil health. J Soil Sci Plant Nutr 22. https://doi.org/10.1007/s42729-021-00684-w
84. ter Braak CJF, Šmilauer P (2012) *Canoco reference manual and user's guide: software for ordination (version 5.0)*. Microcomputer Power
85. Țopa DC (2025) Sustainable practices for enhancing soil health and crop quality. Agriculture 15:998. https://doi.org/10.3390/agriculture15090998
86. Turner BL, Condron LM, Richardson SJ (2021) Soil microbial communities and enzyme activities in perennial agroecosystems under different nutrient management regimes. Soil Biol Biochem 153:108112. https://doi.org/10.1016/j.soilbio.2020.108112
87. Umar U (2022) Micronutrients foliar and drench application mitigate mango sudden decline disorder and impact fruit yield. Agronomy 12:2449. https://doi.org/10.3390/agronomy12102449
88. Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38. https://doi.org/10.1097/00010694-193401000-00003
89. Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38
90. Wang B, An S, Liang C, Liu Y, Kuzyakov Y (2021) Microbial necromass as the source of soil organic carbon in global ecosystems. Soil Biol Biochem 162:108422
91. Yemm EW, Willis AJ (1954) The estimation of carbohydrates in plant extracts by anthrone. Biochem J 57:508–514. https://doi.org/10.1042/bj0570508
92. Yudina A, Kuzyakov Y (2023) Dual nature of soil structure: the unity of aggregates and pores. Geoderma 434:116478. https://doi.org/10.1016/j.geoderma.2023.116478
93. Zeng Q, Liu D, Zhang W (2025) Phosphorus mobilization and microbial enzyme activities in response to integrated nutrient management in tropical soils. Biol Fertil Soils. https://doi.org/10.1007/s00374-024-01876-5
94. Zeng Q, Xie H, Zheng S, Zhao Y, Zhang X, Zheng Y et al (2025) Foliar fertilization-induced rhizosphere microbial mechanisms for soil health enhancement. Agronomy 15:2837. https://doi.org/10.3390/agronomy15122837
95. Zhishen J, Mengcheng T, Jianming W (1999) The determination of flavonoid contents in mulberry and their scavenging effects on superoxide radicals. Food Chem 64:555–559. https://doi.org/10.1016/S0308-8146(98)00102-2

Figures

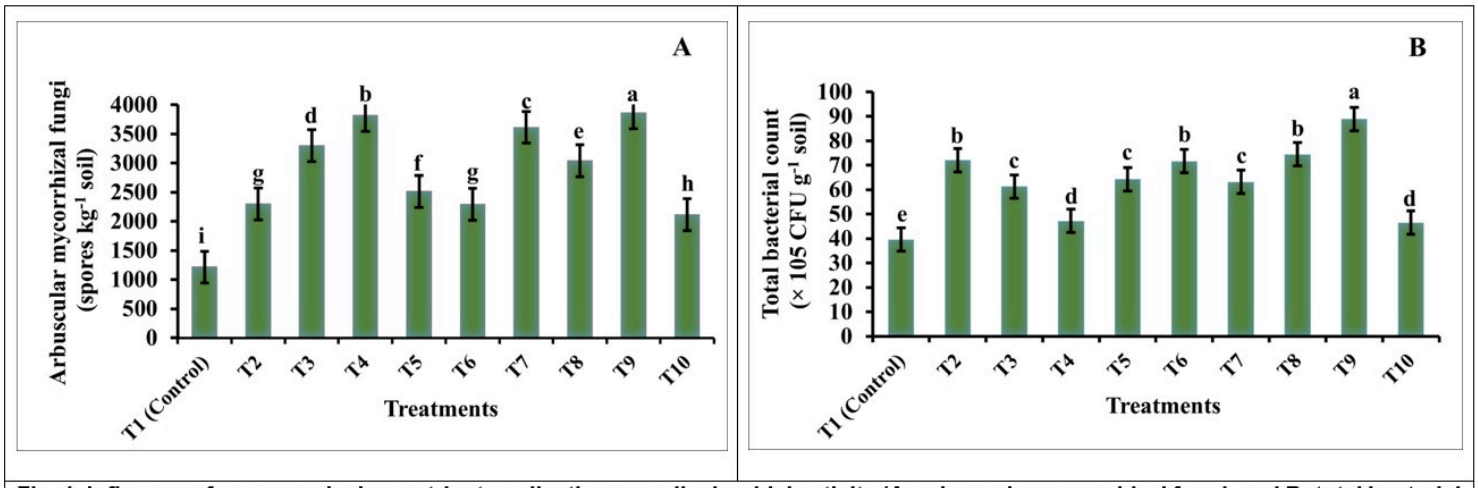

Fig. 1. Influence of macro and micronutrient application on soil microbial activity (A: arbuscular mycorrhizal fungi, and B: total bacterial count) in the mango orchard.

Figure 1

See image above for figure legend.

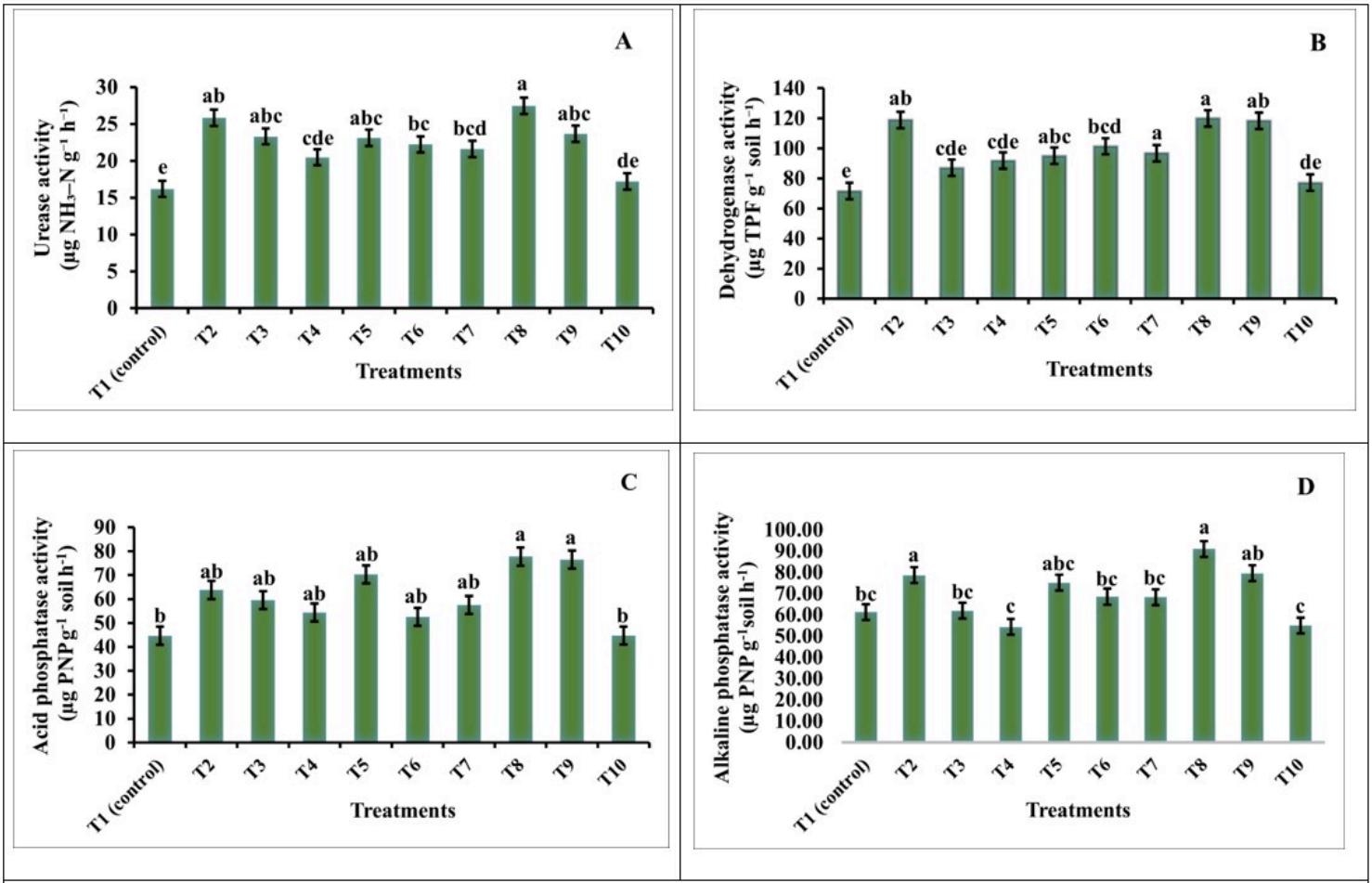

Fig. 2. Influence of macro and micronutrient application on soil enzymatic activity (A: urease activity, B: dehydrogenase activity, C: acid phosphate activity, and D: alkaline phosphatase activity) in the mango orchard.

Figure 2

See image above for figure legend.

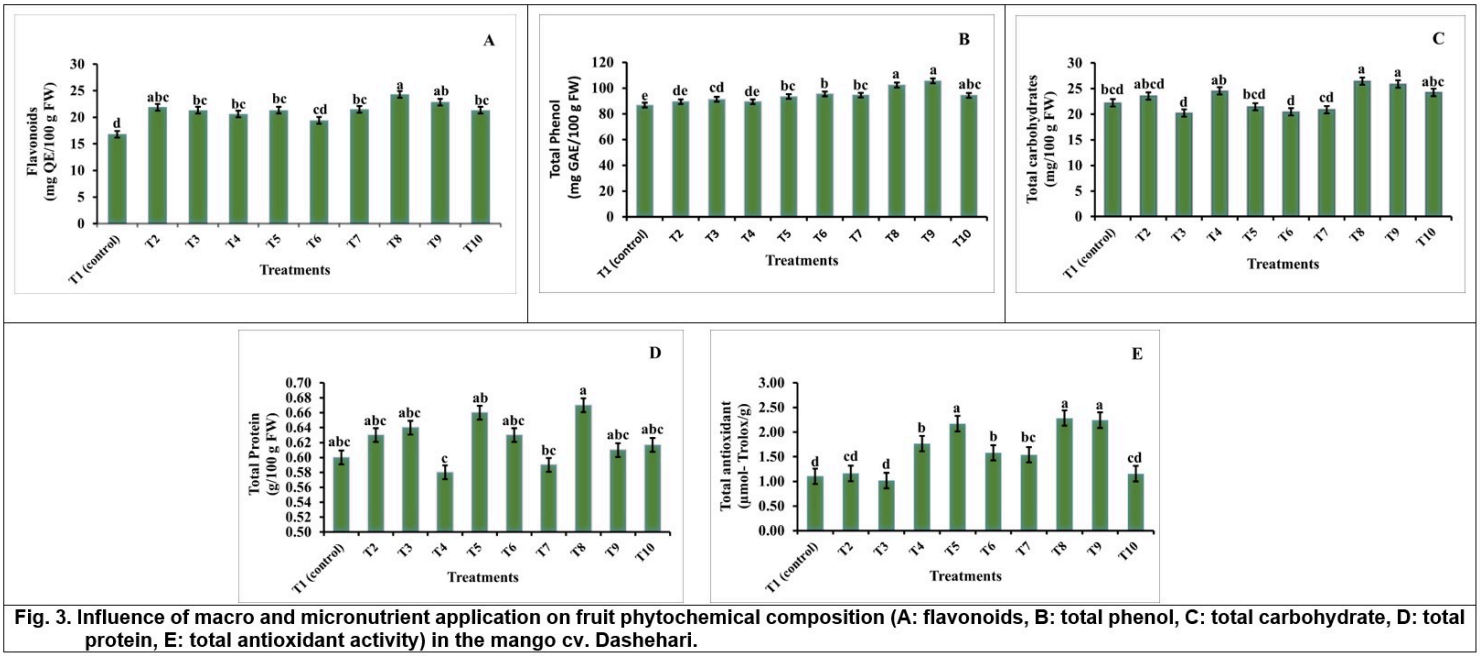

Fig. 3. Influence of macro and micronutrient application on fruit phytochemical composition (A: flavonoids, B: total phenol, C: total carbohydrate, D: total protein, E: total antioxidant activity) in the mango cv. Dashehari.

Figure 3

See image above for figure legend.

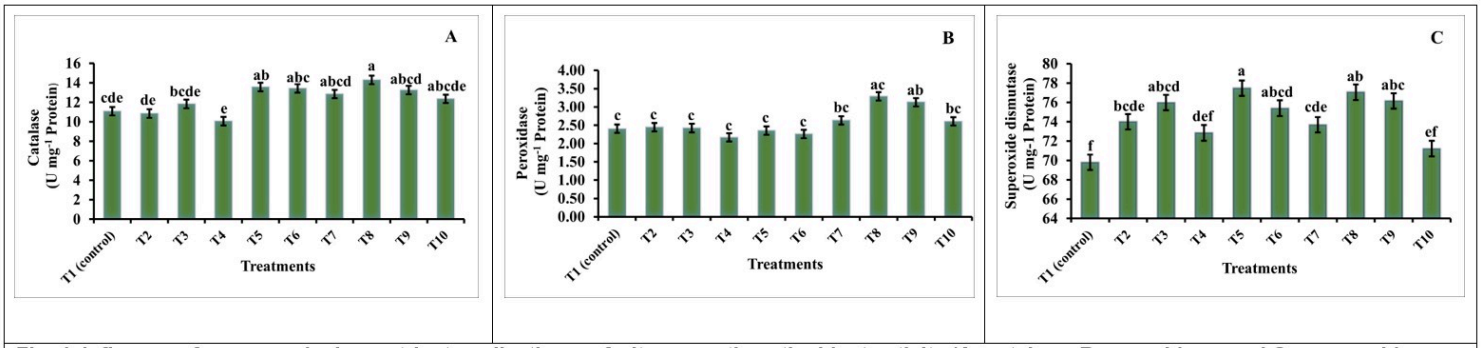

Fig. 4. Influence of macro and micronutrient application on fruit enzymatic antioxidant activity (A: catalase, B: peroxidase, and C: superoxidase dismutase) in the mango cv. Dashehari.

Figure 4

See image above for figure legend.

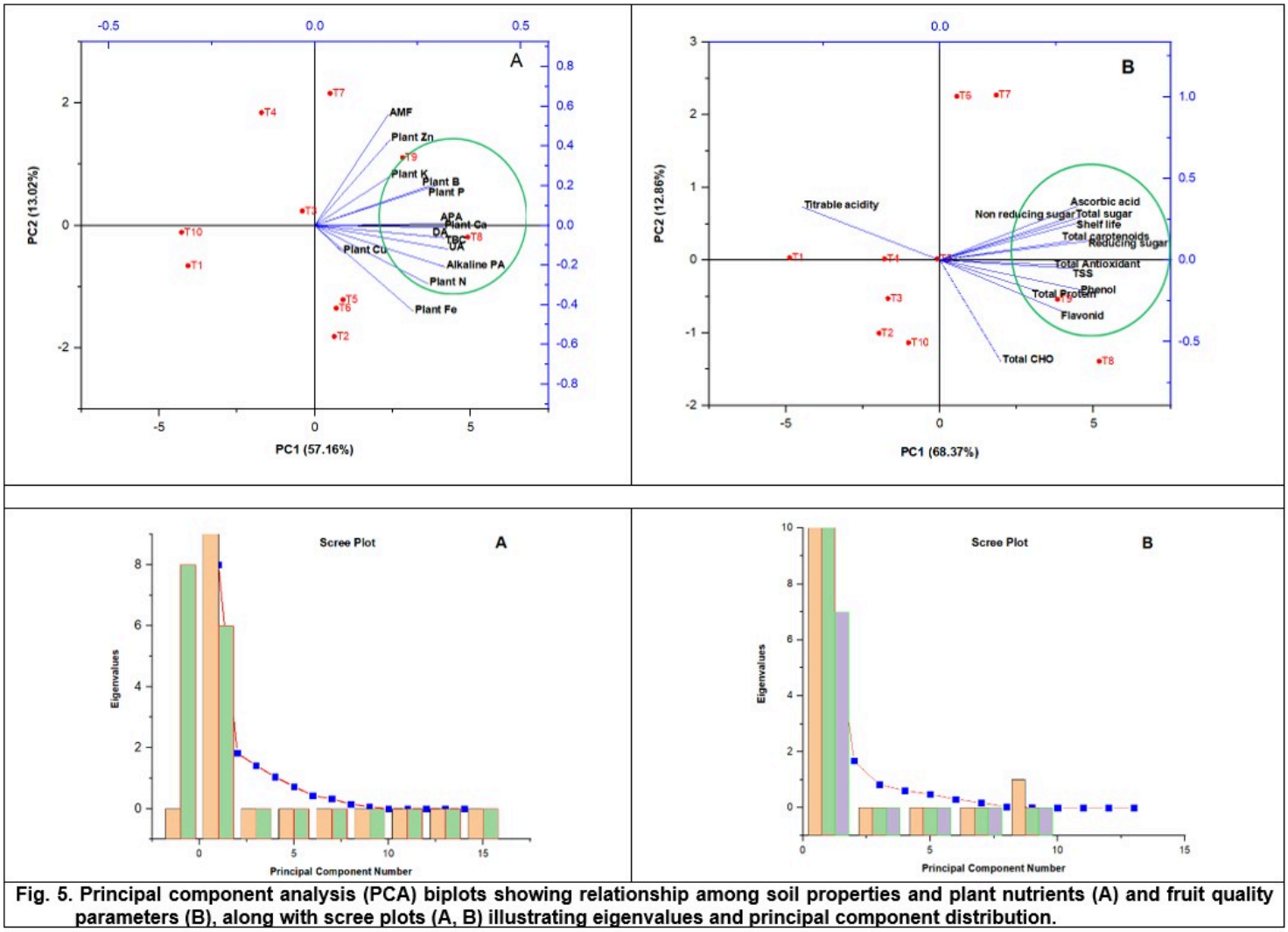

Fig. 5. Principal component analysis (PCA) biplots showing relationship among soil properties and plant nutrients (A) and fruit quality parameters (B), along with scree plots (A, B) illustrating eigenvalues and principal component distribution.

Figure 5

See image above for figure legend.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Fig.S1.ExperimentalResearchUnit.jpg
- Fig.S2.Plantinglayoutofmango.jpg
- floatimage1.png
- Fig.S3.OverviewofSoilSampleCollection.jpg
- Fig.S4.RDA.png
- Graphicalabstract.png
- SupplementryTable.docx