

Diagnosis and field management strategies to improve the size and uniformity of the mango fruit in Peru

- Final report of research project -

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June 2026

Abstract: A research project was conducted to identify the main factors limiting fruit growth, fruit size, and productivity in commercial 'Kent' mango orchards in Piura, Peru. The project was structured in three phases: (1) diagnostic evaluation of soil, plant nutrition, and orchard conditions; (2) implementation of management strategies to improve nutrient-use efficiency, root functioning, and fruit development; and (3) identification of the most effective practices based on nutritional, physiological, and productive responses. The diagnostic phase revealed contrasting limitations between production systems. The Intensive Management System (IMS) was characterized by extremely sandy soils, low organic matter, high pH, and limited nutrient retention, whereas the Conventional Management System (CMS) exhibited high soil firmness, elevated electrical conductivity, soil acidity, low biological activity, and restricted root development. In both orchards, deficiencies of phosphorus, potassium, boron, and manganese were identified, while limited irrigation during fruit development further restricted crop performance. Under IMS conditions, T4 (soil base equilibrium + amino acids) produced the highest fruit yield and fruit number, whereas T2 (crop-demand fertilization) generated the most favorable fruit size distribution and highest average fruit mass. T3 (crop-demand fertilization + amino acids) provided the most balanced overall response. Under CMS conditions, management strategies based on nutrient-demand fertilization and organic amendments consistently improved soil fertility, plant nutrition, fruit growth, and productivity. Among them, T3 (nutrient-demand fertilization + organic amendments + soil conditioners) produced the highest yield, greatest fruit mass, and best overall performance. Overall, the results demonstrated that improving soil quality, root activity, and nutrient acquisition efficiency was more effective than simply increasing fertilizer inputs. For orchards with characteristics similar to the IMS system, T3 is recommended as the most balanced strategy, while T4 is recommended when maximizing productivity is the primary objective. For orchards with characteristics similar to the CMS system, T3 is recommended as the most effective approach for simultaneously improving fruit yield, fruit quality, and orchard sustainability.

keywords: *Mangifera indica* L.; orchard management; fertilization strategies, biostimulation

Nutrient abbreviations used in this study:

N – nitrogen; P – phosphorus; K – potassium; Ca – calcium; Mg – magnesium; S – sulfur; B – boron; Zn – zinc; Cu – copper; Mn – manganese; Fe – iron; Mo – molybdenum.

1. Introduction

Mango (*Mangifera indica* L.) is one of the most important tropical fruit crops worldwide and plays a strategic role in the agricultural economy of several countries, while Peru is currently among the leading mango exporters (FAOSTAT, 2024), with the Piura region representing one of the main production areas due to its favorable climatic conditions and strong integration with international markets. The profitability of mango production is highly dependent on fruit quality attributes, particularly fruit size and uniformity, which directly influence market classification, export value, and grower returns (Galán Saúco, 2009).

Despite advances in crop management, the occurrence of small fruits remains a recurring challenge in commercial orchards in many mango producer countries, including Peru. Reduced fruit size and poor caliber distribution can result from a complex interaction of factors, including nutritional imbalances, inadequate synchronization between nutrient supply and crop demand (Bally & Cavalcante, 2026), limitations in soil physical and biological quality, water availability, environmental stresses, and orchard management practices. Consequently, the identification of factors limiting fruit growth has become a priority for improving orchard yield and fruit marketability (Davenport, 2007; Bally, 2009; Cavalcante, 2023).

Conventional fertilization programs are often based on generalized recommendations that may not adequately reflect crop nutrient requirements throughout the production cycle, but recent studies, such as Cavalcante (2023) and Rodrigues et al. (2025), conducted in commercial mango orchards have demonstrated that nutrient partitioning, nutritional balance, and nutrient-use efficiency are closely associated with fruit growth, dry matter accumulation, yield, and fruit quality, highlighting the importance of synchronizing nutrient supply with plant demand during critical phenological stages. Therefore, fertilization strategies based on nutrient exportation and crop demand have been proposed as effective approaches to improve nutrient-use efficiency and optimize fruit development, especially based on Silva et al. (2022) nutrient mango partition.

In addition to mineral nutrition (Bally & Cavalcante, 2026), soil quality has been increasingly recognized as an important and determinant of mango orchard fruit yield (no published data). Low organic matter content, poor soil structure, reduced biological activity, and nutrient losses may restrict root growth and nutrient uptake, ultimately affecting fruit size and uniformity. Therefore, the incorporation of organic amendments, soil conditioners, amino acids, and biostimulants has been investigated as a strategy to improve soil functioning, nutrient availability, physiological performance, and fruit development under commercial production systems as reported by Cavalcante et al. (2025), Carvalho et al. (2025), Rodrigues et al. (2025) and Carvalho et al. (2026).

Among these strategies, fertilization based on nutrient exportation and crop demand seeks to synchronize nutrient supply with plant requirements throughout the phenological cycle (Bally & Cavalcante, 2026), while the use of organic residues, soil conditioners, amino acids, and foliar applications may contribute to improved soil functioning, nutrient availability, physiological performance, and fruit development. However, the effectiveness of these approaches under contrasting production systems remains insufficiently documented under the environmental conditions of northern Peru, particularly regarding their impact on fruit size distribution and the occurrence of small fruits.

Therefore, this study was carried out in two commercial mango orchards in Piura, Peru, managed under an Intensive Management System (IMS) and a Conventional Management System (CMS), with the objective of diagnosing the factors associated with the production of small fruits and assessing management practices designed to enhance fruit size,

2. Material and methods

The project was developed over three consecutive phases in commercial mango orchards selected from mango producers/exporters in Piura, Peru (Asociación Peruana de Productores y Exportadores de Mango - APEM) with 'Kent' mango in two farms – Camposol and Bora Bora (Sunshine Export).

The harvested fruit is a consequent characteristic of genetic factors, but influenced by different factors of climate, soil and orchard. This way, the project was developed in three different phases: First phase – Diagnosis; second phase: Conducting field; and third phase: Identification and recommendation of the best management strategy.

2.1 First phase – diagnosis

This phase involved gathering and analyzing climate variables, soil data, and the characteristics of the orchards chosen for the study.

Historical data for climatic variables were analyzed for air temperature, air humidity, cloudiness, rainfall and solar energy. Other variables were measured for orchard characterization, such as sun light intensity (Lux x100 x 50.000), leaf chlorophyll indexes (*a*, *b* and total), soil moisture (%), soil firmness (MPa) and leaf electrolyte leakage ($\mu\text{S}/\text{cm}$).

The Intensive Management System (IMS) orchard was approximately 10 years old, with a planting density of 7.0×3.0 m and irrigated through a drip irrigation system composed of three lateral lines per tree row. Emitters were spaced 0.6 m apart and provided a discharge rate of 2.0 L h^{-1} per emitter. In contrast, the Conventional Management System (CMS) orchard was approximately 28 years

old, planted at a spacing of 5.0×5.0 m, and irrigated by furrows at intervals of approximately 18–20 days.

Sun light intensity was evaluated using a luximeter (Instrutherm[®], Brazil) within mango tree rows. Leaf chlorophyll readings (*a*, *b* and total indexes) were measured using a chlorophyll meter reading (Falker[®], Brazil) in four leaves in each plant from the canopy middle part at each cardinal point, following the instructions of El-Hendawy et al. (2005). Soil moisture was measured using a soil tester measurer (Falker[®], Brazil) in the coverage area of the irrigation system. Leaf electrolyte leakage was performed following the methodology proposed by Lutts et al. (1996).

Still during the characterization phase soil and leaf samples were collected to diagnose the nutritional status of each orchard separately. Leaves of the last mature flush were collected stored in paper bags, then sent to the Plant Soil Laboratories[®] (Petrolina, Brazil) for leaf analysis according to Tedesco et al. (1995) the diagnostic leaf nutritional status. Soil samples at 0-30 cm of soil depth were collected below the mango tree canopy in the coverage area of the micro sprinkler, stored in proper plastic bags, then sent to the Plant Soil Laboratories[®] (Petrolina, Brazil) for fertility analysis. Soil texture was assessed following Donagema et al. (2011). Such analyses were performed on two separate dates, both before treatment definition and application.

The root system was also evaluated by visual identification (soil excavation at root zone).

2.2 Second phase: conducting field experiments

With the guiding results obtained in the first phase of the project, specific experiments were carried out based on the main problems faced by orchards with a focus on better.

Considering that the farms have very different production system characteristics, the following nomenclatures were adopted: the experiment at the Camposol farm is called Intensive Management System (IMS) and the experiment carried out at the Bora Bora farm (Sunhine Export) is called Conventional Management System (CMS).

Figure 1 illustrates the visual characteristics of the two management systems evaluated in this study.



Figure 1. Visual characteristics of the Intensive Management System (IMS) at Camposol Farm (A) and the Conventional Management System (CMS) at Bora Bora Farm (Sunshine Export) (B), Piura, Peru.

The treatments to be applied in each Management System were elaborated by the union of basic management factors associated with specific technological strategies for the mango crop, already used in other producing regions or results of scientific production already published.

2.2.1 Intensive Management System

Under Intensive Management System (Camposol), the experiment was arranged in randomized blocks with four treatments, five blocks and five plants per block. The treatments were defined as:

T1 - Control (traditional farm management, without alterations);

T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar;

T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids;

T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids

The amino acid source used in treatments T2 and T4 was Amino Q-50™, containing a minimum of 62.0% total amino acids and 38.0% free amino acids. The product also supplied 10.0% N, 0.80% P₂O₅, and 1.30% K₂O. The product was applied at flowering and subsequently at 15-day intervals via fertigation, following the application schedule described below, reaching a cumulative rate of 12 L ha⁻¹.

Application schedule and rates of amino acid source (Amino Q-50™) applied via fertigation during the experimental period is presented in Table 1.

Table 1. Application schedule and rates of Amino Q-50™ applied via fertigation during the experimental period.

Year	Week	Date	Rate (L ha ⁻¹)
2023	41	October 7–11	2
2023	43	October 21–25	2
2023	45	November 4–8	2
2023	47	November 18–22	1
2023	49	December 2–6	1
2023	51	December 16–20	1
2024	1	December 30 – January 3	1
2024	3	January 13–17	1
2024	5	January 27–31	1

The nutrient amounts applied in each treatment are in Table 2.

Table 2. Nutrient amounts applied in each treatment (kg/ha from flowering to fruit harvest).

Nutrient	Treatment		
	T1	T2 and T3	T4
N	23.6	12.78	28.3
P	7.1	9.66	12.4
K	15.6	88.10	190.5
Ca	12.5	14.93	16.7
Mg	3.8	6.51	-
S	31.0	41.31	68.6
B	1.6	6.80	42.9
Mn	3.4	13.73	13.3
Fe	-	9.9	9.5
Cu	1.6	0.24	0.24

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids.

While the fertilizing calendars from flowering to fruit harvest for each treatment (T2 and T3; and T4) are in Appendix 1 and 2 respectively, for T1 treatments the approximate total of fertilizers were applied through fertigation: 63.8 kg ha⁻¹ of ammonium sulfate, 49.0 kg ha⁻¹ of calcium nitrate, 26.1 kg ha⁻¹ of phosphoric acid, 37.6 kg ha⁻¹ of potassium sulfate, 38.8 kg ha⁻¹ of magnesium sulfate, 6.4 kg ha⁻¹ of copper sulfate, 8.6 kg ha⁻¹ of zinc sulfate, 11.0 kg ha⁻¹ of manganese sulfate, and 5.7 kg ha⁻¹ of boric acid.

All fertilizers were applied via a fertigation system. The recommended doses of each nutrient used for T2 and T3 were defined according to Gargantini (1999), personal recommendations of FRUTVASF (no published data criteria) and following the adequate ranges of supply defined by Rezende et al. (2022) and the nutrient exportation with fruit harvest properly defined by Torres (2019). The fertilizer rates used in treatment T4 were determined according to the Base Saturation Theory proposed by Albrecht, which emphasizes the balance among exchangeable soil cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) as a key factor for soil fertility, nutrient availability, and plant performance. Fertilizer recommendations were established to adjust soil base saturation toward the target proportions recommended by this approach.

Although modifications to the irrigation management strategy were initially proposed, their implementation was not feasible because of the restricted water availability observed throughout the experiment. Therefore, irrigation management was identical across all treatments. Irrigation was initially applied at 35 m³ ha⁻¹ during pruning and the subsequent weeks, reduced to 30 m³ ha⁻¹ following paclobutrazol (PBZ) application, and further decreased to 22 m³ ha⁻¹ during flowering induction. Irrigation was then gradually increased to 40 and 55 m³ ha⁻¹ during fruit development until harvest. These irrigation rates were defined according to the farm's standard management practices and may have limited the full productive potential of the orchard during the experimental period.

Evaluations

The evaluations consisted of:

- i) Soil fertility at 0-30 cm soil depth (Donagema et al., 2011);
- ii) Leaf nutritional status (Tedesco, 1995);
- iii) Fruit caliper according to distribution (Table 3) following the classification as: < 200 g, 200 – 250 g, 250 – 300 g and > 300 g.

Table 3. Fruit caliper classification according to US demand.

Fruit size (caliper)	Fruit mass (g)	
	Minimum	Maximum
5	799	899
6	667	799
7	572	667
8	490	572
9	450	490
10	380	450
12	320	380
14	270	320

- iv) Fruit mass (g);
- v) Visual root system evaluation;
- vi) At the end of the experiment, root samples were collected to determine reserve carbohydrate (starch) concentrations, following the methodology described by Dubois et al. (1956);
- vii) Number of fruits per plant and fruit yield (t/ha);
- viii) Proportional distribution between number fruits per plant and fruit mass (g), which is a base for treatment efficiency.

All soil, plant tissue, and starch analyses were conducted at PlantSoil Laboratórios, Petrolina, Pernambuco, Brazil.

Statistical analyses included analysis of variance (ANOVA) for the separation of treatments in each experiment using Tukey or Scott-Knott test. All calculations were performed using the ‘R’ software.

2.2.2 Conventional Management System

Under Conventional Management System (Bora Bora – Sunshine Exporter), the experiment was arranged in randomized blocks with four treatments, five blocks and five plants per block. The treatments were defined as:

T1 - Control (traditional farm management, without alterations);

T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure;

T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner;

T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations.

The organic amendments used in the different treatments were applied in trenches at rates of 40 L plant⁻¹ of cattle manure, 45 L plant⁻¹ of rice husk, and 75 L plant⁻¹ of sugarcane bagasse. Figure 2 illustrates the trenches opened for the application of organic amendments, as well as the visual appearance of the treated area following their incorporation into the soil.



Figure 2. Trench preparation for organic amendment application (A) and field appearance following soil incorporation (B).

Treatment T3 included the application of the soil conditioners Promesol™ and RadiGrow XL™. Promesol™ is a product based on ECCA Carboxy I™ extracts derived from agricultural residues,

whereas RadiGrow XL™ contains ECCA Carboxy I™ extracts and 1.34% P₂O₅. Promesol™ was applied in November at a rate of 20 L ha⁻¹, followed by RadiGrow XL™ in December at 2 L ha⁻¹. Both products were applied to the soil using a total spray volume of 800 L ha⁻¹. For each application, 70 L of solution were prepared, corresponding to approximately 3.5 L of solution per plant.

Treatment T4 received foliar applications consisting of gibberellic acid (GA₃; 12.5 mg L⁻¹), potassium nitrate (KNO₃; 15 g L⁻¹), sodium molybdate (0.5 g L⁻¹), and boric acid (2.0 g L⁻¹). Applications were performed using a spray volume equivalent to 4 L plant⁻¹ and were repeated two times during the production cycle beginning at first stage of mango fruit development.

Regarding nutritional management, the amounts of nutrients applied in each treatment are presented in Tables 4 and 5, respectively.

Table 4. Nutrient amounts applied in each treatment (kg/tree from flowering to fruit harvest).

Nutrient	T1	T2, T3 and T4
N	0.370	0.138
P ₂ O ₅	0.260	0.0
K ₂ O	0.250	0.600
CaO	0.322	0.0
Mg	0.0	0.029
S	0.737	0.269
Fe	0.030	0.0
B	0.0	0.09
Zn	0.0	0.013
Cu	0.0	0.015

Table 5. Fertilizer amounts applied in each treatment (kg/tree from flowering to fruit harvest).

Fertilizer	T1		T2, T3 and T4	
	Sept. 2025	Jan. 2026	Nov. 2025	Dec. 2025
Potassium sulfate	0.50		0.60	0.60
Ammonium sulfate	0.50	1.0	-	-
Monoammonium phosphate	0.50		-	-
Iron sulfate	0.15		-	-
Urea	-		0.15	0.15
Magnesium sulfate	-		0.15	0.15
Boric acid	-		0.05	-
Zinc sulfate	-		0.06	-
Copper sulfate	-		0.06	-
Agricultural gypsum		1.0		

All fertilizers were applied via a fertigation system. The recommended doses of each nutrient used for T2 and T3 were defined according to Gargantini (1999), personal recommendations of

FRUTVASF (no published data criteria) and following the adequate ranges of supply defined by Rezende et al. (2022) and the nutrient exportation with fruit harvest properly defined by Torres (2019).

A higher irrigation frequency was initially planned; however, water availability during the experimental period was more limited than anticipated. As a result, only two furrow irrigation events could be carried out during fruit development, which may have constrained the full productive potential of the orchard.

Evaluations

The evaluations consisted of:

i) Soil fertility at 0-30 cm soil depth (Donagema et al., 2011). During the characterization phase, soil biological activity was assessed through the determination of arylsulfatase ($\mu\text{g p-nitrophenol g}^{-1} \text{ h}^{-1}$) and β -glucosidase ($\mu\text{g p-nitrophenol g}^{-1} \text{ h}^{-1}$) activities. Arylsulfatase activity was quantified according to the method described by Tabatabai (1994), and β -glucosidase activity was determined following the procedure proposed by Eivazi & Tabatabai (1988). Both enzyme activities were expressed as $\mu\text{g p-nitrophenol released per gram of soil per hour}$;

ii) Leaf nutritional status (Tedesco, 1995);

iii) Fruit growth dynamics were monitored through measurements of polar diameter (mm), equatorial diameter (mm), fruit width (mm), and fruit weight (g) at successive evaluation dates until harvest.

iv) Fruit yield was determined on a per-plant basis and expressed as kg plant^{-1}

v) Trade-off between fruit production and fruit mass.

All soil, plant tissue, and soil enzymes analyses were conducted at PlantSoil Laboratórios, Petrolina, Pernambuco, Brazil.

Statistical analyses included analysis of variance (ANOVA) for the separation of treatments in each experiment using Tukey or Scott-Knott test. All calculations were performed using the 'R' software.

2.3 Third phase – Identification and recommendation of the best management strategy

In the third and final stage of the project, the most effective management strategies for producing larger fruits were identified, taking into account the specific conditions of each Management System. The factors influencing fruit size were analyzed, and a suitable management approach was proposed.

3. Results and discussion

3.1 Characterization of the orchards studied

Table 6 summarizes the historical climatic conditions of Piura, Peru, which is characterized by a hot desert climate (BWh according to the Köppen–Geiger classification). Air temperatures remain high throughout the year, with average monthly temperatures ranging from 21 to 27 °C and maximum temperatures reaching 33 °C during the summer months. Rainfall is highly seasonal, being concentrated between January and April, particularly in March (111 mm), while the remaining months are characterized by very low precipitation. Relative humidity remains relatively stable throughout the year, ranging from 62 to 66%.

Table 6. Average historical data for average air temperature [maximum (Max), minimum (Min) and average Ave), percentage of time spent in each cloud band (cloudiness), categorized by the percentage of sky covered by clouds (most cloudy and least cloudy), average rainfall and solar energy in Piura (PERU). Climate: BWh (Köppen-Geiger)

Month	Air temperature (°C)			Cloudiness (% of time)		Rainfall (mm)	Air humidity (%)	Solar energy (kWh/m ² per day)
	Max	Min	Ave	Most	Least			
Jan	32	22	26	68	32	38	62	6.3
Feb	33	23	27	75	25	66	64	6.1
Mar	33	23	27	72	28	111	64	6.1
Apr	32	22	26	55	45	40	63	6.1
May	30	20	24	40	60	7	63	6.0
Jun	28	19	23	32	68	3	66	5.9
Jul	27	18	21	27	73	1	66	6.2
Aug	27	17	21	27	73	0	66	6.6
Sep	28	18	21	34	66	2	65	6.9
Oct	28	18	22	48	52	5	64	6.9
Nov	29	19	23	56	44	9	64	6.9
Dec	31	20	25	61	39	20	64	6.6

Historical data is available at Climate Data (2024) and Weather Spark (2024).

As can be seen in Table 6, despite seasonal variations in cloudiness, solar radiation availability remains consistently high, with daily solar energy values ranging from 5.9 to 6.9 kWh m⁻² day⁻¹.

The period from June to December is particularly important for commercial mango production in northern Peru, as floral induction, flowering, fruit set, and most of the fruit growth phase occur during this interval. During these months, rainfall is negligible and crop water requirements must be supplied almost entirely through irrigation. In addition, the combination of high solar radiation, elevated temperatures, and increasing fruit sink demand during the second semester intensifies the need for adequate nutrient availability and efficient nutrient uptake to sustain fruit growth and dry matter accumulation (Davenport, 2007; Bally & Cavalcante, 2026).

Despite seasonal variations in cloudiness, solar radiation remains consistently high throughout the year, with daily solar energy values ranging from 5.9 to 6.9 kWh m⁻² day⁻¹, and these conditions

favor photosynthetic activity and fruit development but may also increase evapotranspiration rates and the risk of nutritional limitations when irrigation and fertilization programs are not synchronized with crop demand. Therefore, efficient water and nutrient management during the flowering and fruit development periods are critical to maximize fruit size, improve caliber distribution, and achieve high commercial yields, as preconized by Silva et al. (2022), Cavalcante (2023) and Rodrigues et al. (2025).

Table 7 presents the initial soil physical conditions and selected physiological indicators of mango trees under the Intensive Management System (IMS) and Conventional Management System (CMS). Light intensity was similar between orchards, indicating that both production systems were exposed to comparable radiation conditions during the characterization phase, likewise leaf chlorophyll a, chlorophyll b, and total chlorophyll indices showed small differences between systems initially.

Table 7. Soil moisture, soil firmness, sun light intensity, leaf chlorophyll a index, leaf chlorophyll b index, leaf total chlorophyll and leaf electrolyte leakage of both Intensive Management System and Conventional Management System during the characterization phase.

	Sun light intensity	Soil firmness	Soil moisture	Leaf chlorophyll index			Leaf electrolyte leakage
	Lux x 100 x 50.000	Mpa	%	<i>a</i>	<i>b</i>	Total	μ/cm
Intensive Management System	837.7	1.0	7.0	36.7	10.5	47.2	64.2
Conventional Management System	840.1	4.5	*	35.2	9.2	44.4	99.1

*Due to the high soil firmness recorded, it was not possible to determine the soil moisture in this orchard.

On the other hand, in relation to the soil physical conditions, the CMS orchard presented a soil firmness of 4.5 MPa, which was more than four times higher than that recorded in the IMS orchard (1.0 MPa). According to Bowen (1981), the soil firmness measured in the CMS orchard (>3 MPa) corresponds to a level of penetration resistance capable of severely restricting root growth. Because this classification relates soil resistance directly to root development, the elevated soil firmness observed in the CMS orchard suggests a reduced capacity for root expansion and soil exploration, which may limit water and nutrient uptake.

Although chlorophyll indices were relatively similar, electrolyte leakage was substantially higher in the CMS orchard (99.1 $\mu\text{S cm}^{-1}$) than in the IMS orchard (64.2 $\mu\text{S cm}^{-1}$), indicating greater cellular membrane damage and physiological stress. When compared with the electrolyte leakage classification proposed by Ferraz (unpublished data), the value observed in the IMS orchard corresponds to the threshold associated with the onset of leaf yellowing, whereas the value recorded in the CMS orchard approached the range typically associated with severe stress and the appearance of sunburn symptoms.

According to this classification, electrical conductivity values range from 40 to 45 $\mu\text{S cm}^{-1}$ in healthy green leaves, from 65 to 70 $\mu\text{S cm}^{-1}$ in leaves beginning to yellow, and exceed 100 $\mu\text{S cm}^{-1}$ in leaves showing sunburn damage.

According to the soil physical characteristics contained in Table 8 the IMS orchard was established on an extremely sandy soil, composed predominantly of fine sand (92.5%) and containing only trace amounts of clay (0.1%), whereas the CMS orchard was classified as a sandy loam soil, with higher proportions of silt (21.35%) and clay (11.43%).

Table 8. Characterization of the soil physical characteristics (0-30 cm depth) the experimental area before the application of treatments.

Soil characteristics	Finca Camposol	Finca Bora Bora
Fine sand (%)	92.5	58.69
Coarse sand (%)	-	8.53
Silt (%)	7.48	21.35
Clay (%)	0.1	11.43
Soil classification	Sandy	Sandy loam
Soil density (g/cm^3)	-	1.39
Particle density (g/cm^3)	-	2.86
Clay dispersed in water (%)	-	9.68
Total porosity (%)	-	51.40
Degree of dispersion (%)	-	84.7
Flocculation degree (%)	-	15.3

The very low clay content of the IMS soil suggests a limited capacity for water and nutrient retention, making crop performance highly dependent on efficient irrigation and fertilization management. In contrast, the higher silt and clay contents in the CMS soil would generally favor greater water-holding capacity and nutrient retention, but the CMS orchard also exhibited high soil density, elevated clay dispersion, and a low flocculation degree, indicating structural limitations that may impair soil physical quality and restrict root growth.

The high degree of clay dispersion (84.7%) and the low flocculation degree (15.3%) observed in the CMS soil indicate poor aggregate stability and a greater susceptibility to structural degradation. Under such conditions, dispersed clay particles may clog soil pores, reduce pore continuity, and impair both water infiltration and gas exchange, resulting in unfavorable conditions for root development (Brady & Weil, 2017). These characteristics are consistent with the high soil firmness recorded during

orchard characterization (4.5 MPa), a value considerably above the critical threshold commonly associated with restrictions to root elongation and soil exploration (Taylor & Gardner, 1963; Bengough et al., 2011). Consequently, even though the CMS soil presented relatively high concentrations of several nutrients, the restricted root system may have reduced the efficiency of water and nutrient acquisition. This interpretation is supported by the nutritional deficiencies observed in the leaves despite the chemically fertile status of the soil. Furthermore, the combination of structural degradation, elevated electrical conductivity, and low biological activity likely created a restrictive rhizosphere environment, limiting root functioning and nutrient cycling processes (Dexter, 2004; Brady & Weil, 2017). Therefore, the results suggest that physical constraints, rather than nutrient availability alone, were among the major factors limiting fruit growth and final fruit size in the CMS orchard.

There were contrasting conditions in soil chemical properties between the two production systems during the characterization phase (Tables 9 and 10), i.e., the IMS orchard exhibited an alkaline soil (pH 8.09) with low electrical conductivity (0.42 dS m^{-1}), whereas the CMS orchard presented an acidic soil (pH 4.84) associated with considerably higher electrical conductivity (3.59 dS m^{-1}).

Table 9. Soil chemical analysis of both Intensive Management System (IMS) and Conventional Management System (CMS) during the characterization phase.

	Soil depth	EC	pH	M.O	P	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	(H ⁺ + Al ³⁺)	SB	V	Sat. Ca	Sat. Mg	Sat. K	Sat. Na
	cm	dS/m	H ₂ O	g/kg	mg dm ⁻³	cmol _c dm ⁻³								%			
IMS	0-30	0.42	8.09	3.7	142.8	0.30	0.61	3.33	1.07	0.00	0.02	5.31	99.62	62.5	20.1	5.6	11.4
CMS	0-30	3.59	4.84	2.71	133.8	0.58	0.14	9.0	2.32	0.16	2.62	12.05	82.12	61.3	15.8	4.0	1.0

EC: electrical conductivity; SB: sum of bases; Sat.: saturation. Extractors: P, K e Na: Resin (HCl + H₂SO₄); Ca, Mg e Al: KCl 1 M.

Table 10. Soil chemical analysis for micronutrients both Intensive Management System (IMS) and Conventional Management System (CMS) during the characterization phase.

Management system	Soil depth	Fe ²⁺	Mn ²⁺	Cu ²⁺	Zn ²⁺	B
		mg/dm ³				
IMS	0-30	33.5	36.5	6.5	20.5	0.19
CMS	0-30	74.0	32.7	1.1	4.1	0.36

Despite the differences in pH, both orchards presented low organic matter contents, indicating limited biological activity and nutrient cycling, while high phosphorus (P) concentrations reflected a history of fertilizer application. In contrast, the exchangeable cation composition differed markedly between systems, with the CMS orchard presenting higher concentrations of potassium (K), calcium (Ca), and magnesium (Mg) and consequently a greater sum of bases, whereas the IMS orchard was characterized by elevated sodium saturation (>11%), which may adversely affect soil structure and water infiltration.

The acidic conditions observed in the CMS orchard were accompanied by the presence of exchangeable aluminum and a lower base saturation than that recorded in the IMS orchard. Conversely, the IMS orchard exhibited a very high base saturation and no detectable exchangeable aluminum, although the elevated soil pH may reduce the availability of certain micronutrients. Overall, the results indicate that both production systems presented distinct soil fertility constraints: the IMS orchard was characterized primarily by alkalinity and sodium accumulation, whereas the CMS orchard was characterized by a lower pH soil, aluminum presence, and elevated salinity. These factors likely influenced nutrient uptake efficiency and should be considered when interpreting plant nutritional status, fruit growth, and treatment responses throughout the production cycle.

According to the fertility ranges proposed by Tropical Horticultural Consulting and updated by Torres (2019), Lobo et al. (2019), and Nogueira e Silva & Cavalcante (2021), the IMS orchard presented generally adequate levels of K, Ca, and Mg, as well as a balanced distribution of these cations in the exchange complex. However, important chemical imbalances were identified, including an alkaline pH (8.09), P concentration substantially above the recommended range, base saturation close to 100%, and sodium saturation exceeding 11%, despite exchangeable sodium remaining below the critical threshold. These results indicate that nutrient deficiency was not the main limitation in this orchard; rather, the combination of high pH, excessive P accumulation, and elevated sodium dominance in the exchange complex may have reduced nutrient availability and use efficiency, particularly in a sandy soil with low organic matter content.

To provide an integrated assessment of soil fertility status, the chemical attributes of the CMS were classified according to reference ranges proposed for mango cultivation and summarized in a heatmap (Figure 3). Based on recommendations from Tropical Horticultural Consulting and updated according to Torres (2019), Lobo et al. (2019), and Nogueira e Silva & Cavalcante (2021), this graphical approach facilitates the identification of potential nutritional imbalances and soil-related constraints associated with root functioning, nutrient uptake, and fruit development, thereby supporting the diagnosis of factors potentially involved in the production of small fruits.

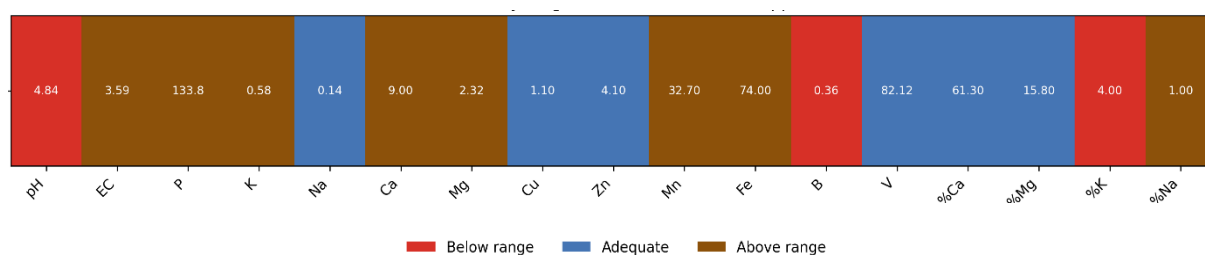


Figure 3. Heat map of the initial soil fertility status (0–30 cm depth) before treatment application in ‘Kent’ mango cultivated under a Conventional Management System (CMS).

Sources used for comparison: Tropical Horticultural Consulting; atualizado com base em Torres (2019); Lobo et al. (2019); Nogueira e Silva & Cavalcante (2021)

Overall, the CMS orchard exhibited a chemically fertile soil characterized by high concentrations of P, K, Ca, and Mg, as well as elevated base saturation; however, these favorable attributes coexisted with low pH, the presence of exchangeable aluminum, high electrical conductivity, and elevated soil firmness, suggesting that nutrient availability was not the primary constraint in this orchard. Instead, soil salinity, acidity, and physical restrictions to root growth likely reduced the efficiency of water and nutrient acquisition, thereby limiting plant performance and potentially contributing to the occurrence of smaller fruits.

For the CMS orchard, soil enzyme analyses were performed and revealed arylsulfatase and β -glucosidase activities of 5 and 22 $\mu\text{g p-nitrophenol g}^{-1} \text{ h}^{-1}$, respectively (Table 7). Arylsulfatase is directly associated with sulfur mineralization, whereas β -glucosidase plays a key role in carbon cycling through the decomposition of organic residues and the release of energy sources for soil microorganisms (Tabatabai, 1994; Dick et al., 1996). The low activities observed for both enzymes are consistent with the low organic matter content and the physical and chemical limitations previously identified in the CMS orchard (Tables 8 and 9). According to Bandick & Dick (1999), soils with greater organic matter accumulation and biological activity generally present higher β -glucosidase and arylsulfatase activities, reflecting a greater capacity for nutrient cycling and ecosystem functioning.

In a global evaluation, the reduced enzymatic activity observed in the CMS orchard suggests limited biological functioning and nutrient turnover, which, when considered together with the elevated soil firmness (Table 7), high electrical conductivity, and nutritional imbalances identified in the soil (Table 9), indicates that physical, chemical, and biological constraints may have simultaneously affected root activity and nutrient-use efficiency.

Tables 11 and 12 show the leaf nutritional status of ‘Kent’ mango trees during the characterization phase and the corresponding sufficiency ranges proposed by Rezende et al. (2022), respectively. It is important to note that the IMS samples were separated according to leaf appearance, with IMS1 corresponding to normal-looking leaves and IMS2 to leaves exhibiting chlorosis symptoms. In addition, values reported as <LQ indicate concentrations below the method quantification limit.

Table 11. Nutritional analysis of ‘Kent’ mango leaves of both Intensive Management System (IMS) and Conventional Management System (CMS) during the characterization phase (before the application of treatments).

	N	P	K ⁺	Ca ²⁺	Mg ²⁺	S	B	Cu ²⁺	Fe ²⁺	Mn ²⁺	Zn ²⁺	Mo	Na	Si
	g kg ⁻¹						mg kg ⁻¹							
IMS ¹	14.8	1.3	12.3	29.0	2.5	1.9	61.2	14.0	124.9	30.1	65.3	0.01	182.5	625.3
IMS ²	12.2	1.0	14.3	26.1	2.3	1.4	75.6	40.3	152.2	35.8	58.0	0.33	484.5	677.8
CMS	11.1	0.9	8.9	32.6	2.6	1.2	65.0	20.2	263.4	320.0	82.5	<LQ	273.8	770.7

IMS¹: Normal-looking leaves; IMS²: leaves identified with chlorosis; <LQ: above the method quantifier limit.

Table 12. Optimal leaf mineral concentration ranges for a minimum fruit yield of ‘Kent’, suggested by (Rezende et al., 2022).

N	P	K ⁺	Ca ²⁺	Mg ²⁺	S	B	Fe ²⁺	Mn ²⁺	Zn ²⁺	Cu ²⁺	Mo
g kg ⁻¹						mg kg ⁻¹					
13.4 - 16.7	1.7 - 2.1	14.0 - 17.9	18.0 - 30.6	2.2 - 2.8	1.0 - 2.1	128.1 - 297.7	93.1 - 213.5	495.2 - 873.6	43.7 - 108.9	8.8 - 9.2	0.02 - 3.4

When compared with the sufficiency ranges (Table 11), the nutritional status differed among production systems. In IMS1, N, Ca, Mg, S, Fe, Zn, and Cu were within the recommended ranges, whereas P, K, B, Mn, and Mo were below the optimal concentrations. In IMS2, K, Ca, Mg, S, Fe, Zn, Cu, and Mo remained within the sufficiency ranges, while N, P, B, and Mn were below the recommended levels. The lower N concentration observed in IMS2 compared with IMS1 is consistent with the chlorosis symptoms identified during sampling. The CMS orchard exhibited the greatest nutritional imbalance, with N, P, K, B, Mn, and Mo below the sufficiency ranges, whereas Ca exceeded the upper limit of the adequate range.

A comparison among orchards revealed that P and B were consistently below the sufficiency ranges in all production systems, indicating widespread limitations in the supply or utilization of these nutrients (Table 10). Likewise, Mn concentrations remained below the optimal range despite the substantially higher concentration recorded in the CMS orchard. Potassium deficiency was particularly evident in IMS1 and CMS, while N deficiency was observed in IMS2 and CMS. In contrast, Ca and Mg concentrations were generally adequate, suggesting that nutritional limitations potentially associated with reduced fruit growth were more closely related to N, P, K, B, and Mn than to secondary macronutrients. These results indicate that, despite the contrasting soil conditions observed between orchards, nutritional imbalances affecting key nutrients involved in photosynthesis, assimilate transport, and fruit development were already present before the implementation of the management strategies.

3.2 Second phase: conducting field experiments

3.2.1. Results for the Intensive Management System

The management strategies promoted distinct changes in soil chemical properties when compared with the initial characterization (Table 13). One of the most notable responses was the reduction in soil pH, particularly in T2, which decreased from 8.09 to 7.01 and approached the range considered optimal for mango cultivation. Electrical conductivity remained relatively low in all treatments, indicating that none of the management strategies induced salinity problems, while exchangeable Al remained absent throughout the study, confirming that soil acidity was not a limiting factor under the Intensive Management System. Although most cation concentrations remained relatively stable, significant treatment effects were detected for EC, pH, organic matter, P, Na, and Ca. In practical terms, T2 stood out for its ability to reduce soil alkalinity, whereas T4 produced the most favorable improvements in soil quality by increasing organic matter and Ca concentration while simultaneously reducing Na accumulation in the exchange complex.

Table 13. Soil chemical properties (0–30 cm depth) before and after the application of different management strategies in ‘Kent’ mango under an Intensive Management System in Piura, Peru.

	EC	pH	M.O	P	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	(H ⁺ + Al ³⁺)	SB	V	Sat. Ca	Sat. Mg	Sat. K	Sat. Na
	dS/m	H ₂ O	g/kg	mg dm ⁻³	cmol _c dm ⁻³								%			
Before	0.42	8.09	3.7	142.8	0.30	0.61	3.33	1.07	0.00	0.02 ^a	5.31	99.62	62.5	20.1	5.6	11.4
T1	0.31 ^b	7.72 ^b	0.9 ^b	139.9 ^{ab}	0.53 ^a	0.89 ^a	3.46 ^b	1.09 ^a	0.0	0.02 ^a	5.98	99.67 ^a	57.6	18.2	8.9	15.0
T2	0.37 ^b	7.01 ^c	1.9 ^b	124.2 ^b	0.43 ^a	0.78 ^a	2.72 ^b	1.01 ^a	0.0	0.02 ^a	4.94	99.60 ^a	54.8	20.3	8.6	16.0
T3	0.33 ^b	7.96 ^a	1.0 ^b	111.6 ^b	0.42 ^a	0.86 ^a	3.21 ^c	0.93 ^a	0.0	0.02 ^a	5.41	96.63 ^a	59.0	17.0	7.7	15.0
T4	0.47 ^a	7.86 ^a	4.3 ^a	148.4 ^a	0.49 ^a	0.58 ^b	3.90 ^a	1.13 ^a	0.0	0.02 ^a	6.11	99.67 ^a	63.7	18.5	7.9	9.6

SB: sum of bases; Sat.: saturation. Extractors: P, K e Na: Resin (HCl + H₂SO₄); Ca, Mg e Al: KCl 1 M. T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids. Average values with the same letter do not differ among them (p > 0.05).

According to the reference soil ranges proposed by Tropical Horticultural Consulting and updated by Torres (2019), Lobo et al. (2019), and Nogueira e Silva & Cavalcante (2021), P concentrations remained above the sufficiency range in all treatments (Table 13), reflecting the high initial fertility status of the orchard previously identified during the characterization phase (Table 9), although lower values were observed in T2 and T3. Potassium, Ca and Mg concentrations remained within the ranges considered adequate for mango production, with T4 exhibiting the highest Ca concentration and the greatest sum of bases (Table 13), whereas sodium saturation remained above the recommended level in all treatments, indicating that sodicity continued to be one of the main chemical constraints of this orchard despite the reductions observed in T4.

Although exchangeable sodium levels in the CMS soil were not considered excessive, the high degree of clay dispersion suggests that soil structural stability may have already been compromised. Sodicty-related processes are known to promote the separation of clay particles, resulting in aggregate breakdown, pore obstruction, and reduced hydraulic conductivity (Rengasamy, 2010). These effects are frequently associated with increased soil mechanical resistance, reduced root proliferation, and lower efficiency of water and nutrient acquisition

Among the evaluated strategies, T4 promoted the most favorable overall changes in soil chemical quality by increasing organic matter content from 3.7 to 4.3 g kg⁻¹ and maintaining adequate levels of K, Ca, and Mg while reducing sodium saturation relative to the other treatments (Table 13), which is consistent with the adoption of a fertilization strategy based on soil base equilibrium, and seeks to optimize the balance among exchangeable cations and improve soil chemical functioning, particularly in soils affected by excessive sodium saturation. Greater Ca availability may also contribute to mitigating the adverse effects of Na on the exchange complex by promoting cation balance and improving soil structural stability (Brady & Weil, 2017). In contrast, T2 was the most effective treatment in reducing soil alkalinity, lowering pH from 8.09 during the characterization phase (Table 9) to 7.01, a value much closer to the range considered optimal for mango cultivation (Torres, 2019; Lobo et al., 2019; Nogueira e Silva & Cavalcante, 2021). This response may be associated with the adoption of fertilization practices based on crop nutrient demand and nutrient exportation, which tend to improve nutrient-use efficiency and reduce the accumulation of excess nutrients in the soil (Silva et al., 2022; Cavalcante, 2023). Overall, the results indicate that the management strategies were more effective in improving soil chemical balance than in correcting the excessive P accumulation and elevated sodium saturation already present before treatment implementation, although T4 showed the greatest potential for mitigating the main chemical constraints identified during the characterization phase.

According to the reference ranges proposed by Tropical Horticultural Consulting and updated by Torres (2019), Lobo et al. (2019), and Nogueira e Silva & Cavalcante (2021), soil micronutrient concentrations remained generally adequate throughout the experimental period (Table 14). Iron (Fe), manganese (Mn), and copper (Cu) concentrations did not differ among treatments and remained within their respective ranges observed after treatment implementation, indicating that the management strategies had little influence on the availability of these nutrients. In contrast, significant differences were detected for zinc (Zn) and boron (B), with T2 and T3 exhibiting the highest Zn concentrations and T3 presenting the highest B concentration. Despite these differences, Zn concentrations remained above the recommended range in all treatments, whereas B remained close to or slightly above the upper limit of the sufficiency range. Overall, the results indicate that micronutrient availability was not a major limiting factor in the orchard, although the consistently low Mn concentrations and the accumulation of Zn observed across treatments should be considered when interpreting plant nutritional status and treatment responses.

Table 14. Soil chemical properties (0–30 cm depth) for micronutrients (mg dm⁻³) before and after the application of different management strategies in ‘Kent’ mango under an Intensive Management System in Piura, Peru.

	Fe ²⁺	Mn ²⁺	Cu ²⁺	Zn ²⁺	B
Before	14.8	1.3	12.3	29.0	2.5
T1	12.7 ^a	1.2 ^a	6.7 ^a	24.9 ^b	2.2 ^{bc}
T2	13.6 ^a	1.1 ^a	6.0 ^a	27.1 ^a	2.4 ^b
T3	12.6 ^a	1.2 ^a	6.1 ^a	27.2 ^a	2.7 ^a
T4	11.5 ^a	1.2 ^a	6.6 ^a	21.4 ^c	2.0 ^c

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids. Bars with the same letter do not differ among them ($p > 0.05$).

The observed responses are consistent with both the management strategies adopted and the initial soil conditions of the orchard, since the IMS was established on an extremely sandy soil with very low clay content and low organic matter levels (Tables 8 and 9), characteristics that reduce nutrient retention and increase the susceptibility of micronutrients, particularly B, to leaching losses (Brady & Weil, 2017). Under these conditions, fertilization programs based on crop nutrient demand and nutrient exportation are expected to improve nutrient-use efficiency and maintain a more balanced nutrient supply throughout the production cycle (Silva et al., 2022; Cavalcante, 2023). Consequently, the greater Zn and B concentrations observed in T2 and T3 (Table 14) likely reflect the combined effects of increased nutrient inputs and more efficient nutrient management. Furthermore, the alkaline soil conditions identified during the characterization phase (Table 9) may reduce the availability of several micronutrients in the soil solution, reinforcing the importance of continuous micronutrient

replenishment to sustain adequate nutrient availability and support fruit growth and development (Havlin et al., 2014; Brady & Weil, 2017).

As can be seen in Table 15 the management strategies had a soft effect on the leaf concentrations of N, P, K, S, and Cu, for which no significant differences were observed among treatments for such nutrients. Similarly, Mg showed only minor variations, although T3 exhibited higher concentrations than T4, but significant treatment effects were detected for Ca, B, Fe, Mn, and Zn. The lowest Ca concentration was observed in T4, whereas T3 promoted the highest B concentration, indicating that the combination of fertilization based on crop nutrient demand and amino acid application favored B leaf accumulation. On the other hand, Fe concentrations were highest in T4, while Mn concentrations increased in T2 and T4 relative to T1; and Zn exhibited the greatest variation among treatments, with the highest concentrations recorded in T1 and the lowest in T2.

Table 15. Leaf nutritional status before and after the application of different management strategies in ‘Kent’ mango under an Intensive Management System in Piura, Peru.

	N	P	K ⁺	Ca ²⁺	Mg ²⁺	S	B	Cu ²⁺	Fe ²⁺	Mn ²⁺	Zn ²⁺	Mo
	g kg ⁻¹						mg kg ⁻¹					
Before	14.8	1.3	12.3	29.0	2.5	1.9	61.2	14.0	124.9	30.1	65.3	0.01
T1	12.7 ^a	1.2 ^a	6.7 ^a	24.9 ^a	2.2 ^{ab}	1.4 ^a	168.0 ^{ab}	6.6 ^a	117.3 ^{ab}	39.4 ^b	50.1 ^a	0.08
T2	13.6 ^a	1.1 ^a	6.0 ^a	27.1 ^a	2.4 ^{ab}	1.5 ^a	152.5 ^b	7.5 ^a	93.1 ^b	52.7 ^a	13.8 ^c	<LQ
T3	12.6 ^a	1.2 ^a	6.1 ^a	27.2 ^a	2.7 ^a	1.5 ^a	184.7 ^a	6.1 ^a	97.5 ^b	44.0 ^{ab}	32.9 ^{bc}	0.01
T4	11.5 ^a	1.2 ^a	6.6 ^a	21.4 ^b	2.0 ^b	1.4 ^a	133.5 ^b	7.0 ^a	167.6 ^a	51.0 ^a	42.3 ^{ab}	<LQ

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids. Average values followed by the same letter in columns do not differ among them ($p > 0.05$).

When compared with the initial nutritional status (before) and the sufficiency ranges proposed by Rezende et al. (2022) (Table 12), P and K concentrations remained below the recommended levels regardless of the management strategy adopted, suggesting that the extremely sandy nature of the soil (Table 8), combined with its low organic matter content and limited nutrient retention capacity (Table 9), continued to restrict leaf nutrient accumulation. In contrast, the substantial increases observed for B, Fe, and Mn, particularly in T2, T3, and T4, indicate that the management strategies improved micronutrient availability and uptake.

Indeed, the positive responses recorded in T3 and T4 may be partially attributed to the application of amino acids, which have been reported to enhance nutrient absorption, stimulate root growth, increase membrane transport activity, and improve plant tolerance to abiotic stress, ultimately contributing to greater nutrient-use efficiency, as previously reported by Colla et al. (2015), Rouphael & Colla (2020) and Moura et al. (2025), this last specifically for mango crop. Furthermore, the fertilization programs based on crop nutrient demand and nutrient exportation likely promoted a more balanced nutrient supply throughout the production cycle, reducing nutritional limitations associated with micronutrient availability.

Similar responses were reported by Moura et al. (2025) in ‘Kent’ mango cultivated under tropical semiarid conditions, where the application of proline associated with *Ascophyllum nodosum* extract enhanced leaf concentrations of P, K and S and improved the overall nutritional status of the trees. The authors attributed these effects to improvements in osmotic adjustment, nutrient translocation, and stress mitigation mechanisms. Such findings reinforce the hypothesis that the superior nutritional performance observed in T3 and T4 was not exclusively associated with fertilizer supply, but also with physiological improvements in nutrient acquisition and utilization efficiency promoted by amino acid-based biostimulation.

Table 16 summarizes the starch concentration in mango roots following the implementation of the management strategies under the IMS, detaching that average values ranged from 98.91 to 124.49 mg g⁻¹, with the highest value recorded in T1 and the lowest in T3, while intermediate values were observed in T2 and T4. Considering that starch stored in roots represents an important carbohydrate reserve for perennial fruit crops, the differences among treatments suggest distinct patterns of carbon allocation between storage organs and developing fruits.

Table 16. Starch concentration (mg/g) in mango roots as a function of different management strategies under an Intensive Management System in Piura, Peru.

Treatment	Starch at the root (mg/g)	Physiologic reading (remaining reserve)
T1	124.49	Higher reserve → lower fruit demand/sink (lower mobilization)
T2	115.29	Intermediate-high reserve → good tillage without depleting the roots
T3	98.91	Lower reserve → strong fruit mobilization (high sink pull)
T4	100.96	Low/intermediate → high mobilization, but with inefficiencies

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids.

The lower starch concentrations of T3 and T4 likely indicate greater mobilization of carbohydrate reserves from roots to support reproductive growth and fruit development, since roots act as major storage organs in perennial fruit crops such as mango, accumulating carbohydrates during periods of lower demand and remobilizing them when strong sinks, such as developing fruits, require assimilates (Schaffer et al., 2013). Consequently, the reduced starch concentrations recorded in these treatments suggest that a greater proportion of stored carbon was allocated to fruit growth, a response that was particularly evident in T3, where fertilization based on crop nutrient demand was combined with amino acid application. This strategy may have enhanced metabolic activity, nutrient uptake, and sink strength, thereby increasing carbohydrate mobilization toward the fruits and improving the utilization of stored reserves (Colla et al., 2015; Rouphael & Colla, 2020).

This interpretation is further supported by Rossouw et al. (2024), who described root starch in mango as a dynamic carbon reserve that buffers the balance between assimilate supply and fruit demand. According to these authors, carbohydrates stored in roots and other perennial organs are remobilized and converted into transportable sugars when developing fruits become strong sinks, particularly during periods of rapid fruit growth. Consequently, reductions in root starch concentration are often associated with greater translocation of assimilates to reproductive organs, whereas higher starch levels may indicate lower reserve utilization. Therefore, the lower starch concentrations observed in T3 and T4 provide additional physiological evidence that these treatments promoted stronger source–sink relationships and greater carbon partitioning toward fruit development.

From a practical perspective, the higher starch concentration observed in T1 should not necessarily be interpreted as a positive response, since large carbohydrate reserves may indicate that assimilates were retained in storage tissues rather than being effectively utilized for fruit growth.

Conversely, the lower starch concentrations observed in T3 and, to a lesser extent, T4 may reflect greater fruit demand and more active translocation of assimilates from reserve tissues to developing fruits.

Figure 4 illustrates the visual aspect of the root system of ‘Kent’ mango trees subjected to the different management strategies under the IMS. Although the observations are qualitative, noticeable differences were evident among treatments. T1 exhibited a relatively sparse root system and was associated with the highest starch concentration in the roots (Table 16), suggesting a greater accumulation of carbohydrate reserves and a lower mobilization of assimilates toward developing fruits. In contrast, T2 and particularly T3 displayed a greater abundance of fine roots, which coincided with lower starch concentrations and may indicate more active root metabolism and greater translocation of stored carbohydrates to support fruit growth.



Figure 4. Visual aspect of the root system of ‘Kent’ mango as a function of different management strategies under an Intensive Management System in Piura, Peru.

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids.

Figure 4 shows that the response observed in T3 is consistent with the physiological interpretation derived from the starch analyses, in which the combination of fertilization based on crop nutrient demand and amino acid application promoted the greatest depletion of root reserves, suggesting stronger sink activity by developing fruits. Treatment T4 also showed relatively low starch concentrations. Overall, the visual observations support the hypothesis that the management strategies

affected carbon allocation patterns within the trees, with T3 showing the strongest evidence of reserve mobilization from roots to reproductive sinks.

The management strategies significantly affected fruit yield, fruit number per tree, and average fruit mass of 'Kent' mango under the Intensive Management System (Figure 5). The highest fruit yield was obtained in T4 (approximately 30 t ha⁻¹), which differed significantly from the other treatments, whereas T1, T2, and T3 produced similar yields ranging from approximately 21 to 22 t ha⁻¹ (Figure 5A). A similar trend was observed for the number of fruits per tree, with T4 producing approximately 72 fruits per tree, significantly exceeding the values recorded in T1, T2, and T3, which ranged from 43 to 47 fruits per tree (Figure 5B). In contrast, the highest average fruit mass was observed in T2, followed by T3 and T1, while T4 produced the smallest fruits among the evaluated treatments (Figure 5C).

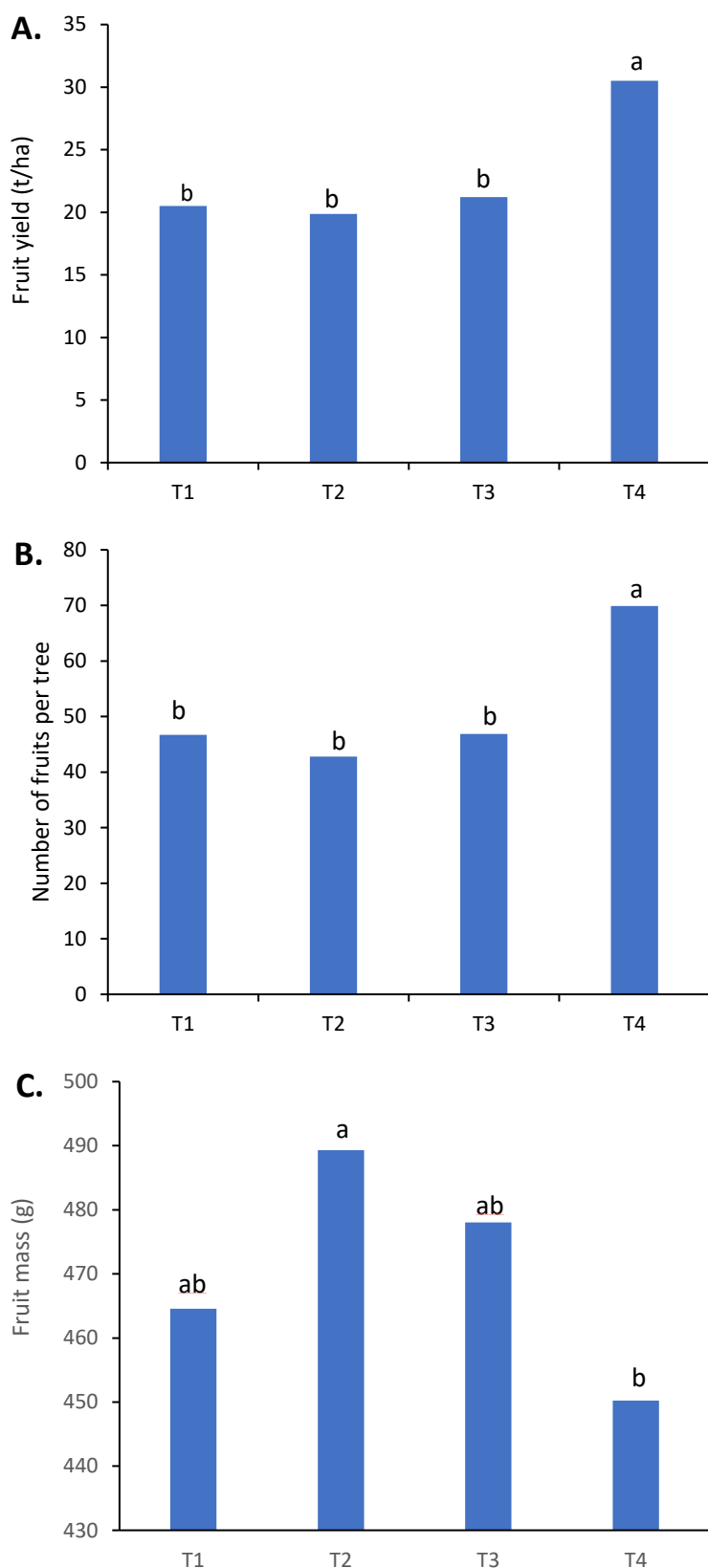


Figure 5. Fruit yield (A), number of fruits per tree and fruit mass (C) of different management strategies in 'Kent' mango under an Intensive Management System in Piura, Peru.

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids. Bars with the same letter do not differ among them ($p > 0.05$).

The contrasting responses observed among treatments suggest that the management strategies altered carbon partitioning and sink competition within the trees. The lower starch concentrations recorded in T3 and T4 (Table 16), together with the visual evidence of greater root development and activity (Figure 4), indicate a more intense mobilization of carbohydrate reserves from roots to support reproductive growth, which is consistent with the role of roots as storage organs that accumulate carbohydrates during periods of lower demand and remobilize them when developing fruits become strong sinks for assimilates (Schaffer et al., 2013; Rossouw et al., 2024). Likewise, the improvements observed in leaf nutritional status, particularly for B, Fe, and Mn (Table 15), may have enhanced photosynthetic performance, assimilate transport, and reproductive development, since these nutrients are directly involved in carbohydrate metabolism, pollen viability, fruit set, and sink activity (Marschner, 2012). The amino acid-based strategies may have further contributed to these responses by stimulating nutrient-use efficiency and plant metabolism, thereby increasing the demand for assimilates by developing fruits (Colla et al., 2015; Rouphael & Colla, 2020), suggesting that the differences observed in Figure 5 resulted not only from nutrient supply but also from changes in carbon allocation patterns within the trees, ultimately influencing the balance between fruit retention and individual fruit growth.

As can be seen in Table 17 the highest proportions of fruits were concentrated in calibers 8, 9, and 10 across all treatments, indicating that these categories represented the predominant commercial standards in the orchard, but clear differences were observed among treatments. T2 exhibited the highest proportion of caliber 8 fruits (33.14%) and one of the lowest proportions of large fruits (calibers 12 and 14), whereas T4 showed the greatest proportion of caliber 10 fruits (26.33%) and maintained a relatively balanced distribution among calibers 8, 9, 10, and 12. Treatments T1 and T3 presented intermediate distributions, with T3 showing a greater proportion of caliber 9 fruits than the other treatments. Extremely small (<5) or very large (>14) fruits represented only a minor fraction of total production in all treatments.

Table 17. Percentage distribution of fruits by size (% per treatment) as a function of different management strategies under an Intensive Management System in Piura, Peru.

Fruit caliper	T1	T2	T3	T4
5	0.00	0.00	0.00	0.18
6	3.19	1.45	0.87	0.71
7	11.17	16.57	12.21	8.13
8	21.54	33.14	27.03	24.38
9	18.09	18.31	25.00	21.73
10	22.34	20.06	21.80	26.33
12	16.49	8.43	10.17	14.84
14	6.65	2.03	2.03	3.00
<14	0.53	0.00	0.58	0.71
>5	0.00	0.00	0.29	0.00

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar; T3 - Fertilization recommendations according to nutrient plant demand in quantity (fruit yield exportation) and following a phenological calendar + amino acids; T4 - Fertilization recommendations according to soil base equilibrium and following a phenological calendar + amino acids.

The fruit size distribution observed in Table 17 is consistent with the yield components presented in Figure 5 and the carbohydrate dynamics discussed previously (Table 16). The greater concentration of caliber 8 fruits in T2 reflects the tendency of this treatment to promote individual fruit growth while maintaining a relatively lower fruit load, which is consistent with the higher average fruit mass recorded in Figure 5C. In contrast, the broader distribution observed in T4, particularly the higher proportion of caliber 10 fruits, appears to be associated with the greater number of fruits retained per tree (Figure 5B), which likely increased competition among developing fruits for assimilates. According to Whiley et al. (1996) and Schaffer et al. (2013), fruit size in mango is strongly influenced by sink competition and the balance between fruit number and assimilate availability (Rossouw et al., 2024). Consequently, treatments that favor fruit retention often increase total yield but may reduce the proportion of larger fruits, whereas treatments that reduce sink competition tend to promote greater assimilate allocation per fruit and increased fruit size.

Table 18 provides an integrated overview of the main physiological, nutritional, and productive responses observed under the different management strategies. By combining leaf nutrient status (Table 15), root starch concentration (Table 16), fruit size distribution (Table 17), and yield components

(Figure 5), the table highlights the distinct mechanisms through which each treatment influenced fruit development. Overall, T1 was characterized by greater preservation of carbohydrate reserves and lower productive performance, T2 promoted the most favorable fruit size distribution, T3 stimulated the greatest mobilization of root reserves to support fruit growth, and T4 achieved the highest fruit yield through increased fruit retention. These results demonstrate that the management strategies affected not only nutrient availability but also carbon allocation patterns within the trees, resulting in different balances between reserve conservation, fruit growth, and fruit production.

Table 18. Integrated assessment of leaf nutrient status, root starch concentration, fruit size distribution, and production responses under different management strategies for ‘Kent’ mango under an Intensive Management System in Piura, Peru.

Treatment	Declared Strategy	Leaf Nutrient Status (Summary)	Root Starch (mg g ⁻¹)	Fruit Size Standard	Integrated Interpretation
T1 – Control (traditional management)	Farm standard management without adjustments	Low K (6.7); intermediate Ca (24.9); high B (168.0); moderate micronutrient concentrations	124.49 (highest)	Sizes 8–10 fruits. The low foliar K present, but less concentrated	Carbohydrate reserves were largely maintained in the root system, suggesting lower reserve mobilization toward developing fruits. The low foliar K concentration may have limited assimilate transport and fruit filling, contributing to lower productivity and a less concentrated distribution of commercial fruit sizes.
T2 – Demand-based fertilization phenological calendar	Fertilization based on nutrient exportation and crop demand according to phenological stage	Adequate Ca (27.1); Mg (2.4); B (152.5); moderate N (13.6); balanced micronutrient status; low foliar K (6.0)	115.29	Highest proportion of size 8 fruits (33%) and strong representation of sizes 9–10	Most favorable strategy for fruit size distribution. The combination of balanced nutrition and moderate reserve mobilization promoted good fruit standardization, producing a high proportion of commercially desirable calibers without excessive depletion of root carbohydrate reserves.
T3 – Demand-based fertilization phenological calendar + amino acids	Fertilization based on nutrient exportation and crop demand combined with amino acid application	Adequate Ca (27.2); highest Mg (2.7); highest B (184.7); adequate micronutrients; low foliar K (6.1)	98.91 (lowest)	High proportion of sizes 9–10 and good representation of size 8 fruits	The lowest starch concentration indicates intense mobilization of stored reserves toward fruit development. The combination of nutrient-demand-based fertilization and amino acids may have enhanced sink strength, nutrient uptake, and assimilate utilization, resulting in good fruit size distribution but greater consumption of root carbohydrate reserves.
T4 – Soil base equilibrium phenological calendar + amino acids	Fertilization based on soil base balance + combined with amino acid application and phenological management	Lower Ca (21.4); adequate B (133.5); highest Fe (167.6); elevated Mn and Zn concentrations; low foliar K (6.6)	100.96	Broad distribution across sizes 8–12, with the highest proportion of size 10 fruits	This strategy produced the highest fruit yield and fruit number, indicating strong sink establishment and fruit retention. Although improvements in soil chemical quality were observed, these responses were not fully reflected in leaf nutrient balance. The high fruit load likely increased competition among fruits for assimilates, resulting in a wider distribution of fruit sizes and greater demand on carbohydrate reserves.

3.2.2. Results for the Conventional Management System

Significant treatment effects were detected for electrical conductivity (EC), pH, organic matter (M.O.), K, and Mg, whereas P, Na, Ca, Al, potential acidity (H+Al), sum of bases (SB), and base saturation (V) remained statistically unchanged (Table 19). The highest pH values were observed in T2, T3, and T4, indicating a partial reduction in soil acidity relative to T1. Likewise, organic matter concentrations increased substantially in these treatments, reaching values between 4.1 and 4.8 g kg⁻¹ compared with 2.8 g kg⁻¹ in T1. Potassium and Mg concentrations also tended to increase in response to the management strategies, with T3 exhibiting the highest concentrations of both nutrients, but, in contrast, EC remained high in all treatments, although lower values were recorded in T2, T3, and T4 than in T1.

Table 19. Soil chemical properties (0–30 cm depth) before and after the application of different management strategies in ‘Kent’ mango under a Conventional Management System in Piura, Peru.

	EC	pH	M.O	P	K ⁺	Na ⁺	Ca ²⁺	Mg ²⁺	Al ³⁺	(H ⁺ + Al ³⁺)	SB	V	Sat. Ca	Sat. Mg	Sat. K	Sat. Na
	dS/m	H ₂ O	g/kg	mg dm ⁻³	cmol _c dm ⁻³								%			
Before	3.59	4.84	2.71	133.8	0.58	0.14	9.0	2.32	0.13	2.62	12.05	82.12	61.3	15.8	4.0	1.0
T1	4.10 ^a	4.75 ^b	2.80 ^b	155.0 ^a	0.78 ^b	0.15 ^a	8.9 ^a	2.25 ^b	0.18 ^a	2.75 ^a	12.08 ^a	81.50 ^a	60.1	15.2	5.3	1.0
T2	3.85 ^{bc}	5.05 ^a	4.20 ^a	145.0 ^a	0.92 ^{ab}	0.13 ^a	9.4 ^a	2.70 ^{ab}	0.10 ^a	2.30 ^a	13.11 ^a	85.10 ^a	60.8	17.5	6.0	0.8
T3	3.65 ^c	5.20 ^a	4.80 ^a	148.0 ^a	0.95 ^a	0.12 ^a	9.7 ^a	2.85 ^a	0.08 ^a	2.10 ^a	13.62 ^a	86.60 ^a	61.7	18.1	6.0	0.8
T4	3.90 ^b	5.00 ^a	4.10 ^a	143.0 ^a	0.90 ^{ab}	0.13 ^a	9.3 ^a	2.65 ^{ab}	0.11 ^a	2.35 ^a	12.98 ^a	84.70 ^a	60.7	17.3	5.9	0.8

SB: sum of bases; Sat.: saturation. Extractors: P, K e Na: Resin (HCl + H₂SO₄); Ca, Mg e Al: KCl 1 M. T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations. Bars with the same letter do not differ among them (p > 0.05).

The observed responses are consistent with the management practices adopted in T2, T3, and T4, which included the incorporation of sugarcane bagasse, rice husks, and bovine manure into the soil. Organic amendments are known to increase soil organic matter, improve cation retention, stimulate microbial activity, and contribute to the gradual release of nutrients such as K and Mg (Brady & Weil, 2017; Havlin et al., 2014). The particularly favorable response observed in T3 may also be associated with the application of Promesol™ and RadiGrow XL™, products designed to improve soil chemical and biological functioning and potentially enhance nutrient availability in the rhizosphere.

The increase in pH observed in T2, T3, and T4 is especially relevant because the initial characterization identified the CMS orchard as acidic (Table 9), with measurable exchangeable Al and severe physical constraints, including high soil firmness (Table 7). Although soil salinity remained elevated throughout the experiment, the reductions in EC together with the increases in organic matter, K, and Mg suggest that the management strategies improved soil fertility and nutrient availability under the challenging conditions of the orchard. Considering that only two irrigation events were possible during fruit development, these improvements may have been particularly important for sustaining root activity and nutrient acquisition under water-limited conditions.

No significant differences were observed for Fe and Mn, whose concentrations remained relatively stable across treatments (Table 20). In contrast, significant increases were detected for Cu, Zn, and B in T2, T3, and T4 compared with the conventional management (T1). The highest concentrations of Cu, Zn, and B were generally observed in T3, although differences among T2, T3, and T4 were small. When compared with the initial characterization, all management strategies promoted increases in Zn and B concentrations, whereas Fe and Mn remained close to their original levels.

Table 20. Soil chemical properties (0–30 cm depth) for micronutrients (mg dm⁻³) before and after the application of different management strategies in ‘Kent’ mango under a Conventional Management System in Piura, Peru.

	Fe ²⁺	Mn ²⁺	Cu ²⁺	Zn ²⁺	B
Before	74.0	32.7	1.1	4.1	0.36
T1	90.0 ^a	34.0 ^a	1.1 ^b	4.2 ^b	0.36 ^b
T2	78.0 ^a	33.5 ^a	1.8 ^a	6.2 ^a	0.55 ^a
T3	80.0 ^a	34.0 ^a	1.9 ^a	6.5 ^a	0.58 ^a
T4	78.5 ^a	33.8 ^a	1.8 ^a	6.1 ^a	0.56 ^a

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations. Bars with the same letter do not differ among them ($p > 0.05$).

The observed responses are consistent with the management practices adopted in T2, T3, and T4, which combined nutrient-demand-based fertilization with the incorporation of organic

amendments. The application of cattle manure, sugarcane bagasse, and rice husks likely contributed to increasing micronutrient availability through gradual nutrient release and improvements in soil organic matter content (Table 19), which can enhance nutrient retention and reduce losses in the root zone (Brady & Weil, 2017). The increases in Zn and B are particularly relevant because these nutrients were supplied directly through fertilization (Tables 4 and 5), while the higher Cu concentrations observed in T2, T3, and T4 are consistent with the application of copper sulfate. The absence of significant changes in Fe and Mn suggests that their availability was more strongly influenced by the original soil characteristics than by the management interventions. Overall, the results indicate that the adopted strategies were effective in increasing the availability of key micronutrients involved in flowering, fruit set, and reproductive development, particularly Zn and B, while maintaining adequate concentrations of the remaining micronutrients.

Table 21 demonstrates that the management strategies improved the nutritional status of ‘Kent’ mango trees under the CMS. Significant treatment effects were observed for N, P, K, Mg, S, B, Cu, and Zn, whereas Ca, Fe, and Mn remained relatively stable among treatments. Overall, T2, T3, and T4 consistently outperformed the conventional management (T1), indicating that the combination of nutrient-demand-based fertilization and organic amendments enhanced nutrient uptake and accumulation in the canopy. Among the evaluated strategies, T3 generally promoted the most favorable nutritional balance, while T2 and T4 produced similar responses for most nutrients.

Table 21. Leaf nutritional status before and after the application of different management strategies in ‘Kent’ mango under a Conventional Management System in Piura, Peru.

	N	P	K ⁺	Ca ²⁺	Mg ²⁺	S	B	Cu ²⁺	Fe ²⁺	Mn ²⁺	Zn ²⁺	Mo
	g kg ⁻¹						mg kg ⁻¹					
Before	11.1	0.9	8.9	32.6	2.6	1.2	65.0	20.0	263.4	320.0	82.5	<LQ
T1	12.0 ^b	1.1 ^b	10.2 ^c	31.5 ^a	2.5 ^b	1.5 ^b	66.0 ^b	20.5 ^b	285.0 ^a	325.0 ^a	83.0 ^b	<LQ
T2	13.5 ^a	1.3 ^{ab}	12.8 ^b	30.8 ^a	3.1 ^a	1.8 ^a	82.0 ^a	26.0 ^a	250.0 ^a	300.0 ^a	105.0 ^a	<LQ
T3	14.2 ^a	1.4 ^a	13.5 ^a	31.0 ^a	3.3 ^a	1.9 ^a	86.0 ^a	28.0 ^a	255.0 ^a	305.0 ^a	112.0 ^a	<LQ
T4	13.8 ^a	1.3 ^{ab}	13.0 ^{ab}	30.5 ^a	3.2 ^a	1.8 ^a	90.0 ^a	27.0 ^a	252.0 ^a	302.0 ^a	108.0 ^a	0.08

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations. Average values followed by the same letter in columns do not differ among them ($p > 0.05$).

The improvements observed in leaf nutrient concentrations presented in Table 21 are consistent with the changes in soil fertility previously identified in Tables 19 and 20. The incorporation of cattle manure, sugarcane bagasse, and rice husks increased soil organic matter and improved the availability of K, Mg, Zn, B, and Cu, which was reflected in greater nutrient accumulation in the leaves.

In addition, the particularly favorable response observed in T3 may be associated with the combined effects of organic amendments and the soil conditioners Promesol™ and RadiGrow XL™, which may have enhanced nutrient availability and root activity in a soil characterized by high firmness and restricted root growth during the characterization phase (Table 7). The increases in B and Zn are especially relevant because these nutrients play key roles in reproductive development, carbohydrate transport, pollen viability, and fruit set (Marschner, 2012), while the higher concentrations of N, K, and Mg may have contributed to improved photosynthetic activity and assimilate production. Although leaf concentrations of P and K remained below the sufficiency ranges proposed by Rezende et al. (2022), the substantial increases observed in T2, T3, and T4 indicate that the management strategies were effective in reducing nutritional limitations and improving nutrient acquisition under the challenging soil and irrigation conditions of the orchard.

Figure 6 provides a visual summary of the nutritional diagnosis presented in Table 21 by comparing leaf nutrient concentrations with the optimal ranges proposed by Rezende et al. (2022). The heatmap highlights that the management strategies were particularly effective in improving the nutritional status of N, Mg, S, Zn, and Cu, especially in T2, T3, and T4, whereas P, K, B, and Mn remained below the recommended sufficiency ranges regardless of treatment. Calcium, Fe and Mg generally remained within or close to the optimal ranges, indicating that these nutrients were not major limitations under the evaluated conditions. Among the treatments, T3 exhibited the most balanced nutritional profile, showing the highest number of nutrients approaching their respective sufficiency ranges, while T1 consistently presented the greatest nutritional limitations.

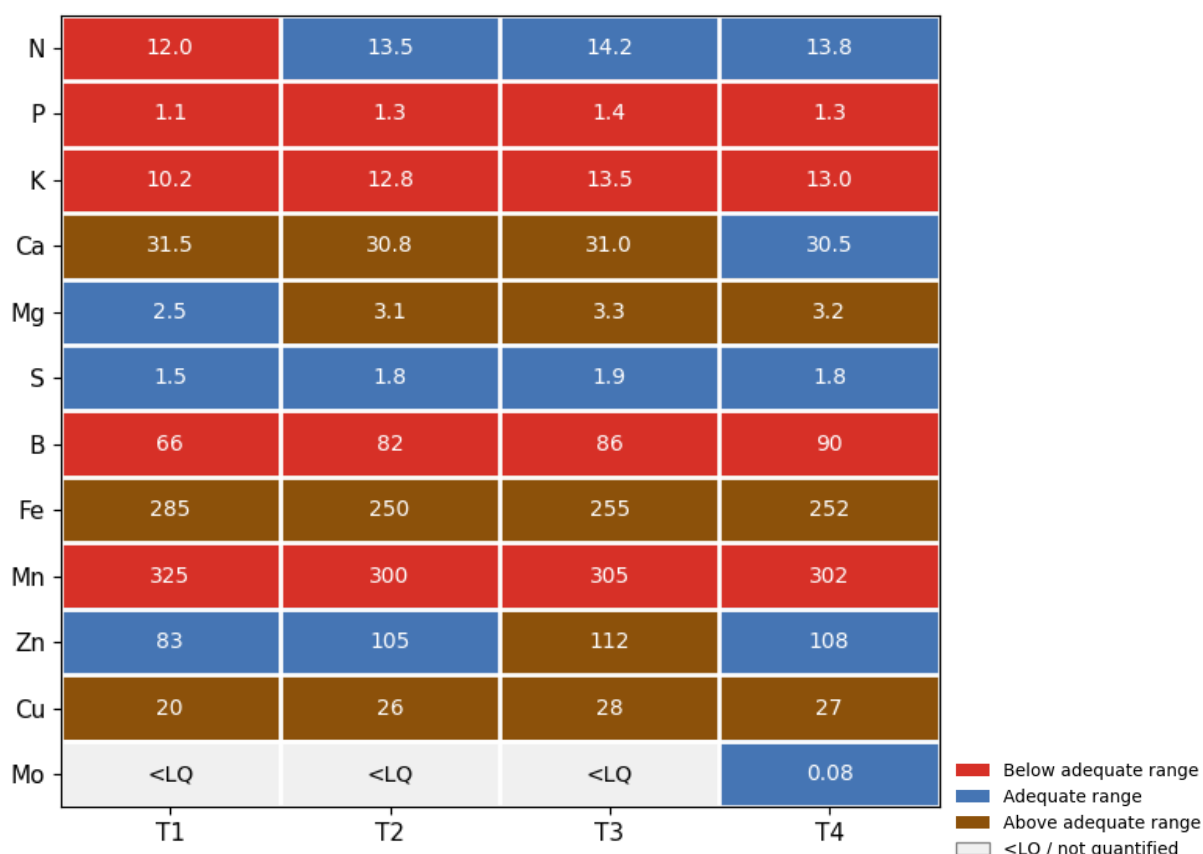


Figure 6. Nutritional diagnosis of ‘Kent’ mango leaves grown in a Conventional Management System under different fertilization strategies based on optimal nutrient concentration ranges proposed by Rezende et al. (2022).

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations.

The nutritional patterns observed in Figure 6 reflect the combined effects of soil conditions, nutrient supply, and environmental constraints throughout the production cycle. Although the management strategies improved soil fertility (Tables 19 and 20) and promoted greater nutrient accumulation in the leaves (Table 21), plant responses were strongly influenced by the restrictive conditions of the orchard, particularly the high soil firmness identified during the characterization phase (Table 7) and the limited water availability during fruit development. Soil mechanical impedance is recognized as a major factor limiting root elongation and soil exploration, thereby reducing root-soil contact and restricting nutrient acquisition (Bengough et al., 2011). Likewise, Valentine et al. (2012) demonstrated that increasing soil strength reduces root proliferation and limits the volume of soil explored by roots, directly affecting plant access to water and nutrients. These constraints become even more pronounced under water-limited conditions, as nutrient transport to the root surface depends largely on mass flow and diffusion processes that are strongly affected by soil moisture (Marschner,

2012). According to Lambers et al. (2008), reductions in soil water availability decrease nutrient mobility and uptake efficiency, particularly for nutrients whose movement is closely associated with the soil solution. Therefore, the superior nutritional balance observed in T3 suggests that the combination of organic amendments, nutrient-demand-based fertilization, and soil conditioners not only increased nutrient availability but also improved rhizosphere functioning and root activity, enhancing nutrient acquisition efficiency despite the physical and environmental limitations of the orchard.

This interpretation is consistent with the findings of Santos et al. (2014) in research about mangos, who demonstrated that fine roots represent the majority of the root system and are primarily responsible for water and nutrient uptake, emphasizing the close relationship between root growth and resource acquisition. Under the conditions of the present study, the combination of high soil firmness and restricted irrigation during fruit development likely limited root proliferation and soil exploration, thereby reducing nutrient uptake efficiency. Consequently, the more balanced nutritional status observed in T3 may reflect not only improvements in soil fertility but also a greater capacity of the root system to maintain water and nutrient acquisition under adverse soil physical and environmental conditions, ultimately contributing to improved plant performance and fruit development.

The importance of improving plant nutritional status is further supported by Tenreiro et al. (2023), who reported that nutritional management based on calcium fertilization is very important for mango cultivation. Although Ca was not the primary factor evaluated in the present study, the authors demonstrated that improvements in nutritional balance can be directly reflected in fruit growth and productive performance. Therefore, the superior nutritional status observed in T3 may have contributed not only to greater nutrient accumulation in plant tissues but also to creating favorable physiological conditions for fruit development.

Figure 7 illustrates the fruit growth dynamics of ‘Kent’ mango under the different management strategies evaluated in the Conventional Management System. Regardless of treatment, fruit growth followed the typical sigmoid pattern reported for mango, characterized by a rapid increase in fruit dimensions during the first evaluations followed by a progressive stabilization as fruits approached physiological maturity (Whiley et al., 1996; Bally & Cavalcante, 2026). Differences among treatments were relatively small for polar diameter (Figure 7A), equatorial diameter (Figure 7B), and fruit width (Figure 7C), indicating that all strategies promoted similar patterns of fruit expansion throughout the production cycle. The other way, the greatest divergence among treatments was observed for fruit mass (Figure 7D), particularly during the final stages of fruit development, when T2 and T3 exhibited a more pronounced increase in fruit weight than T1 and T4.

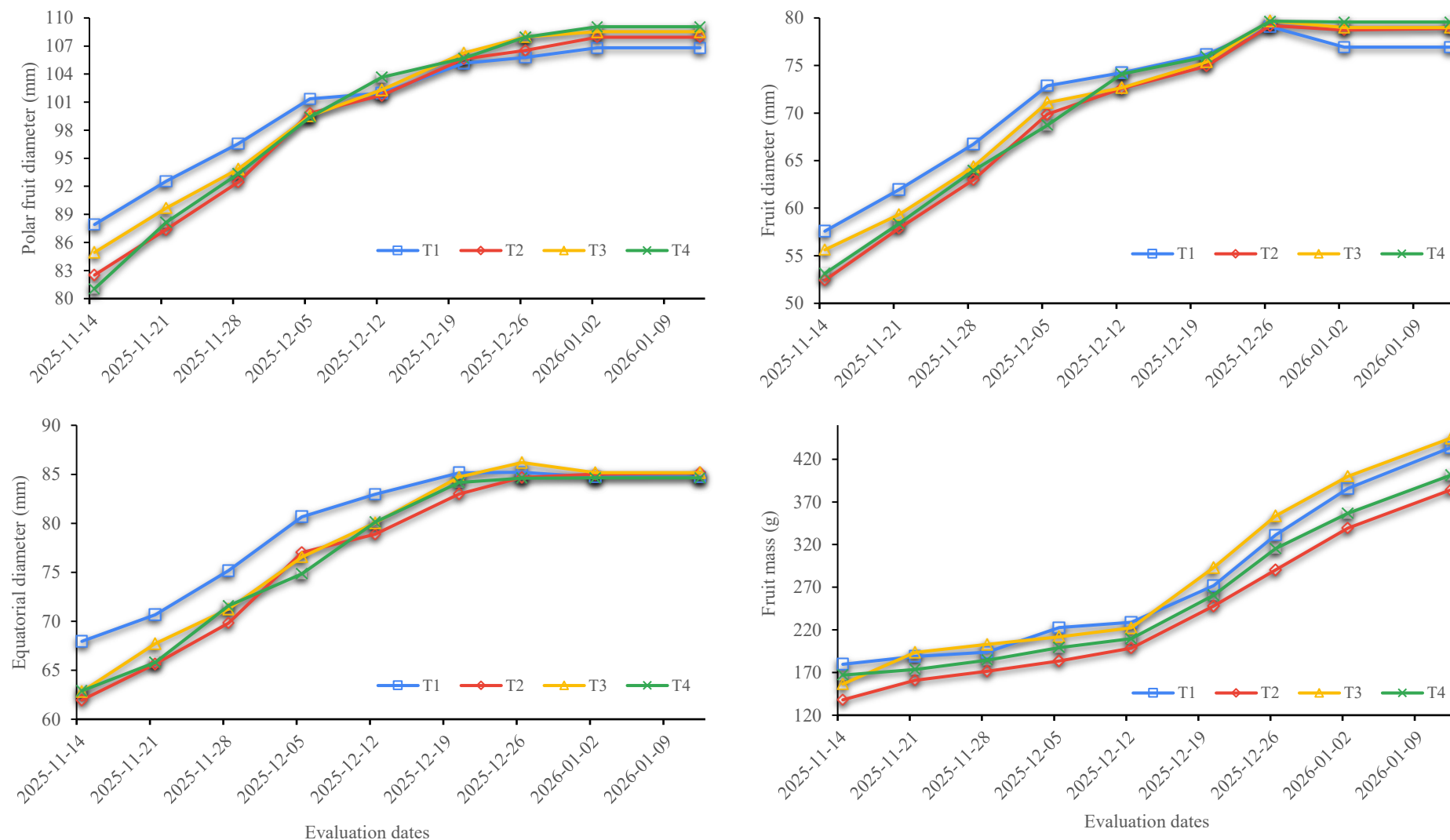


Figure 7. Fruit production of different management strategies in ‘Kent’ mango under an Conventional Management System in Piura, Peru.

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations.

The similar growth curves observed for fruit dimensions suggest that the management strategies had limited influence on the rate of cell expansion and fruit shape development, but, in contrast, the differences observed for fruit mass indicate that the treatments affected dry matter accumulation and assimilate partitioning during the fruit filling phase. This response is consistent with the improvements in soil fertility (Tables 19 and 20) and leaf nutritional status (Table 21), particularly in T2 and T3, which generally exhibited the most balanced nutritional profiles. The greater increase in fruit mass observed during the final stages of development suggests that the combination of nutrient-demand-based fertilization, organic amendments, and, in the case of T3, soil conditioners, enhanced the capacity of the trees to sustain assimilate supply to developing fruits.

The highest fruit production was obtained in T3, which differed from T1 and T4, while T2 presented an intermediate response and did not differ statistically from the remaining treatments (Figure 8).

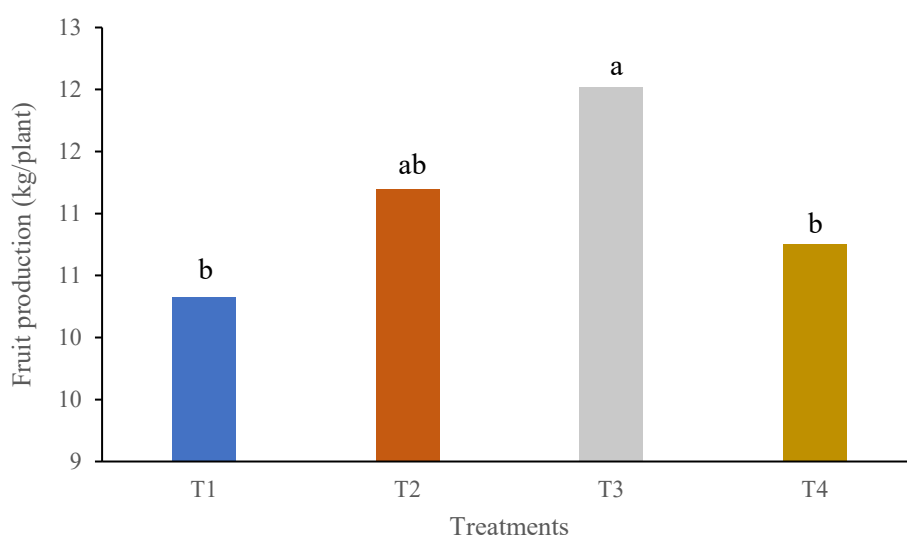


Figure 8. Fruit production of different management strategies in ‘Kent’ mango under an Conventional Management System in Piura, Peru.

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations. Bars with the same letter do not differ among them ($p > 0.05$).

The superior performance observed in T3 is consistent with the improvements previously identified in soil fertility (Tables 19 and 20) and leaf nutritional status (Table 21). This treatment combined organic amendments with the soil conditioners Promesol™ and RadiGrow XL™, which may have enhanced nutrient availability and root activity in a soil characterized by high firmness and restricted root growth during the characterization phase (Table 7). The greater concentrations of N, K, Mg, B, Cu, and Zn observed in T3 (Table 21), together with the favorable fruit growth patterns shown

in Figure 7, suggest that this strategy improved the capacity of the trees to acquire nutrients and sustain fruit filling throughout the production cycle. Considering that only two irrigation events were possible during fruit development, the yield increase observed in T3 indicates that improvements in soil and plant nutrition partially compensated for the environmental limitations imposed by restricted water availability.

Figure 9 shows that the management strategies significantly affected fruit dimensions and fruit mass under the Conventional Management System. Polar diameter (Figure 9A) was lowest in T1, whereas T4 produced the largest fruits for this variable, with T2 and T3 presenting intermediate responses, while a similar pattern was observed for fruit diameter (Figure 9B), in which T2, T3, and T4 produced significantly larger fruits than T1. In contrast, no significant differences were detected for equatorial diameter (Figure 9C), indicating that the treatments had little influence on fruit width. Fruit mass (Figure 9D) exhibited the greatest variation among treatments, with T3 producing the heaviest fruits, followed by T1, while T2 and T4 recorded the lowest fruit masses.

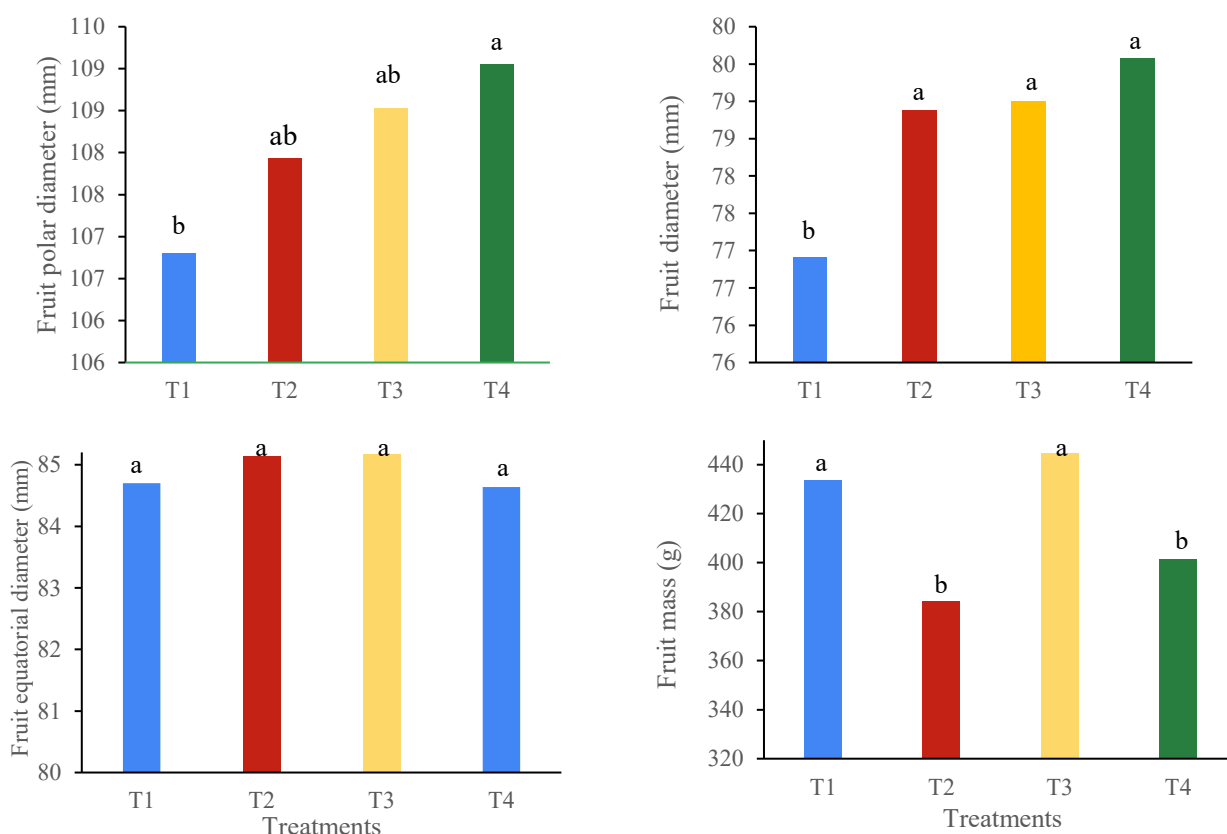


Figure 9. Fruit polar diameter (A), fruit diameter (B), equatorial diameter (C) and fruit mass (D) of ‘Kent’ mango as a function of different management strategies under a Conventional Management System in Piura, Peru.

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations. Bars with the same letter do not differ among them ($p > 0.05$).

The results quoted in Figure 9 indicate that the management strategies influenced fruit growth primarily through changes in fruit filling rather than through major alterations in fruit shape, which is supported by the relatively small differences observed for the dimensional variables compared with the larger differences detected for fruit mass. The superior performance of T3 is consistent with the improvements previously observed in soil fertility (Tables 19 and 20) and leaf nutritional status (Table 21), suggesting that the combination of organic amendments and soil conditioners enhanced nutrient acquisition and assimilate accumulation during the final stages of fruit development. The greater fruit mass observed in T3 also agrees with the fruit growth curves presented in Figure 7, which showed a more pronounced increase in fruit weight during the fruit filling phase. According to Whiley et al. (1996) and Bally & Cavalcante (2026), mango fruit mass is strongly influenced by the availability of assimilates during the latter stages of development, when dry matter accumulation becomes a major determinant of final fruit quality. Therefore, the results suggest that T3 improved the capacity of the trees to sustain assimilate supply to developing fruits, resulting in heavier fruits and ultimately contributing to the higher productivity observed in Figure 8.

Table 22 summarizes the trade-off between fruit production and fruit mass under the different management strategies, detaching that relative to the conventional management (T1), T2 and T4 increased fruit production but reduced average fruit mass, indicating that a greater proportion of assimilates was distributed among a larger number of fruits. In contrast, T3 simultaneously increased fruit production and fruit mass, demonstrating a more favorable balance between fruit load and fruit growth, suggesting that the management strategy adopted in T3 enhanced the capacity of the trees to support a larger reproductive demand without compromising individual fruit development.

Table 22. Trade-off between fruit production and fruit mass under different management strategies for ‘Kent’ mango under a Conventional Management System in Piura, Peru.

Treatment	Fruit mass (g)	Variation (%)	Fruit production (kg/tree)	Variation (%)
T1	434	—	10	—
T2	384	-11.5%	11	+10.0%
T3	445	+2.5%	12	+20.0%
T4	401	-7.6%	11	+10.0%

T1 - Control (traditional farm management, without alterations); T2 - Fertilization recommendations according to nutrient plant demand and following a phenological calendar + sugarcane bagasse + rice husks + bovine manure; T3 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + soil conditioner; T4 - Fertilization recommendations according to nutrient plant and following a phenological calendar + sugarcane bagasse + rice husk + bovine manure + foliar fumigations

The contrasting responses observed among treatments are consistent with the source-sink relationships that govern mango production (Table 22), since in fruit trees, increases in fruit number frequently intensify competition among developing fruits for water, carbohydrates, and mineral nutrients, often resulting in smaller fruits (Schaffer et al., 2013). This pattern was evident in T2 and T4, where gains in production were accompanied by reductions in fruit mass.

The contrasting responses observed among treatments are consistent with the source-sink relationships that govern mango production (Table 22), since increases in fruit number generally intensify competition among developing fruits for carbohydrates, mineral nutrients, and water, frequently resulting in reductions in individual fruit mass (Schaffer et al., 2013). This pattern was evident in T2 and T4, where gains in fruit production were accompanied by decreases in average fruit weight, suggesting that the increase in sink demand was not matched by a proportional increase in resource acquisition and assimilate supply. In contrast, T3 simultaneously increased fruit production and fruit mass, indicating that the trees were able to sustain a greater reproductive demand without compromising fruit growth, indicating that the combined improvements in soil fertility, nutrient acquisition, and plant nutritional status observed throughout the production cycle.

Indeed, the greater nutrient accumulation recorded in the leaves suggests enhanced uptake and translocation of mineral nutrients involved in photosynthesis, assimilate transport, and osmotic regulation, processes that play a central role in supporting fruit growth and sink activity (Marschner, 2012; Lambers et al., 2008). Moreover, the improved soil conditions promoted by the incorporation of organic amendments and soil conditioners may have favored root functioning and resource acquisition despite the restrictive physical conditions of the orchard, characterized by high soil firmness and limited water availability. Similar relationships between root activity, resource acquisition, and fruit production have been reported for mango by Santos et al. (2014), who demonstrated that reductions in root development can directly affect the capacity of trees to acquire water and nutrients and sustain fruit production. Therefore, the simultaneous increase in fruit number and fruit mass observed in T3 suggests that this management strategy improved not only resource availability but also the efficiency with which these resources were acquired and allocated to developing fruits, thereby overcoming the trade-off commonly observed between fruit load and fruit size in mango orchards.

Conversely, T3 was able to overcome this trade-off, producing both heavier fruits and higher yields, probably due to the improvements in soil fertility (Tables 19 and 20), leaf nutritional status (Table 21), and fruit growth (Figures 7 and 9) what suggests that the combination of organic amendments and soil conditioners enhanced nutrient acquisition and assimilate supply during fruit filling, allowing the trees to sustain a greater fruit load without reducing fruit size. From a practical

perspective, T3 represented the most efficient strategy because it improved both productivity and fruit quality, two attributes that are directly associated with orchard profitability and export market value.

3.3 Third phase – Identification and recommendation of the best management strategy

Based on the integrated evaluation of soil physical, chemical, and biological characteristics, leaf nutritional status, root carbohydrate reserves, fruit growth dynamics, fruit size distribution, and productive performance, it was possible to identify the principal constraints limiting mango production in both production systems and to recommend the most suitable management strategies for each orchard condition. The results demonstrate that the factors limiting fruit growth differed substantially between the Intensive Management System (IMS) and the Conventional Management System (CMS), requiring distinct management approaches.

In the IMS orchard, nutrient availability was generally adequate and soil fertility was not the primary limiting factor. Instead, the main constraints were associated with the extremely sandy soil texture, low organic matter content, excessive soil alkalinity, elevated sodium saturation, and limited nutrient retention capacity. These conditions reduce nutrient-use efficiency and increase the dependence of the crop on precise fertilization and irrigation management. Leaf analyses confirmed persistent deficiencies of P, K, B, and Mn, despite the relatively high nutrient availability observed in the soil, indicating that nutrient uptake efficiency rather than nutrient supply was the main challenge in this production system.

In contrast, the CMS orchard exhibited a different set of limitations. Despite the relatively high concentrations of several nutrients in the soil, high soil firmness, elevated electrical conductivity, soil acidity, exchangeable aluminum, low biological activity, and restricted root development likely reduced the efficiency of root exploration and nutrient uptake. Under these conditions, management practices aimed at improving soil physical quality, organic matter accumulation, biological activity, and root functioning appear to be more important than merely increasing fertilizer inputs.

The results also demonstrate that management strategies capable of improving nutrient-use efficiency, root activity, and assimilate allocation were generally more effective than strategies focused exclusively on nutrient supply. In both production systems, treatments designed according to crop nutritional demand and synchronized with phenological stages consistently outperformed the conventional management adopted by growers, reinforcing the importance of matching nutrient availability with crop requirements throughout fruit development.

Therefore, specific recommendations are presented below for each production system evaluated in this study.

3.3.1 Intensive Management System (IMS)

Among the evaluated strategies, T4 (fertilization based on soil base equilibrium combined with amino acids and phenological management) produced the highest fruit yield and the greatest number of fruits per tree, reaching approximately 30 t ha⁻¹ and 72 fruits per tree, respectively. This treatment also promoted important improvements in soil chemical quality, including higher organic matter content, greater Ca availability, and reduced Na saturation, indicating that correcting cation balance and improving soil chemical functioning are effective approaches for increasing fruit retention and maximizing productivity under highly sandy conditions. Nevertheless, T4 also produced the smallest average fruit mass and a greater proportion of caliber 10 fruits, suggesting that the higher fruit load intensified competition among developing fruits for assimilates. Therefore, although T4 represents the most suitable strategy when the primary objective is maximizing fruit production per hectare, it may not be the best alternative for markets that prioritize larger fruit sizes.

Treatment T2 (fertilization based on crop nutrient demand and phenological management) produced the most favorable fruit size distribution, with the highest proportion of caliber 8 fruits and the greatest average fruit mass, while also substantially reducing soil pH and bringing it closer to the range considered optimal for mango cultivation. These responses suggest that improving nutrient-use efficiency and synchronizing nutrient supply with crop demand can enhance fruit filling and increase the proportion of commercially valuable fruit sizes.

Treatment T3 (crop-demand fertilization combined with amino acids) exhibited the lowest root starch concentration, the greatest evidence of reserve mobilization, and a favorable distribution of calibers 8, 9, and 10. Together with the visual assessment of root development, these results suggest that amino acids enhanced sink strength and assimilate translocation toward developing fruits, resulting in a balanced combination of productivity and fruit growth. Consequently, T3 appears to represent the best compromise between productivity, fruit size, and physiological efficiency.

Overall, T4 is recommended when the goal is maximizing fruit yield, whereas T2 is the most suitable strategy for producers targeting premium fruit size categories. From an integrated perspective, however, T3 emerges as the most balanced management strategy because it simultaneously improved nutritional status, stimulated root activity, enhanced reserve mobilization, and maintained a favorable fruit size distribution without excessive reductions in fruit mass.

3.3.2 Conventional Management System (CMS)

Under the Conventional Management System, the strategies based on organic amendments consistently improved soil fertility, nutrient availability, and leaf nutritional status relative to the traditional management adopted by the grower. The incorporation of sugarcane bagasse, rice husks,

and bovine manure increased soil organic matter, reduced soil acidity, improved K and Mg availability, and enhanced the accumulation of several nutrients in the leaves, demonstrating the importance of restoring soil quality in orchards affected by physical and chemical limitations.

Among the evaluated strategies, T3, which combined crop-demand fertilization with organic amendments and soil conditioners, produced the most consistent overall responses. In addition to generating the highest fruit yield, average fruit mass, and fruit dimensions, this treatment promoted the highest concentrations of several nutrients in the leaves and the most balanced nutritional profile. The simultaneous increases in soil organic matter, K, and Mg further suggest that the soil conditioners enhanced the benefits provided by the organic amendments, improving soil functioning and nutrient acquisition under the restrictive conditions observed in the orchard.

Positive responses were also obtained with T2, which improved soil fertility, plant nutritional status, and fruit growth relative to the conventional management, although its performance was generally slightly inferior to that achieved with T3. While T4 produced similar improvements in leaf nutrition, these gains were not translated into comparable increases in productivity, indicating that foliar applications alone were insufficient to overcome the structural limitations affecting root development and nutrient acquisition.

Taken together, the results indicate that the principal limitation of the CMS orchard was not nutrient availability itself but rather the reduced efficiency of nutrient uptake caused by physical, chemical, and biological constraints within the soil. Under these conditions, strategies aimed at improving soil quality, root activity, and nutrient-use efficiency proved to be more effective than those relying exclusively on nutrient supplementation.

Consequently, T3 is recommended as the most suitable management strategy for orchards with characteristics similar to those observed in the CMS production system. The combination of nutrient-demand fertilization, organic amendments, and soil conditioners generated the most consistent improvements in soil quality, plant nutrition, fruit growth, and fruit yield, representing the most effective approach for simultaneously increasing fruit yield and fruit quality under the environmental conditions of northern Peru.

4. Final recommendations

Based on the results obtained throughout the diagnostic, experimental, and validation phases of the project, the following technical recommendations are proposed for mango orchards cultivated under conditions similar to those evaluated in northern Peru. It is important to emphasize that the benefits associated with the recommended management strategies should be viewed as cumulative rather than immediate. Improvements in soil fertility, soil structure, organic matter content, biological

activity, root functioning, nutrient-use efficiency, and overall tree performance are progressive processes that tend to intensify with the continuous adoption of these practices over successive production cycles. Therefore, the positive responses observed during the experimental period likely represent only part of the potential benefits that may be achieved through long-term implementation, reinforcing the importance of maintaining the recommended practices consistently from year to year.

General recommendations:

- ✓ Conduct periodic soil and leaf analyses to support fertilization programs based on crop demand, nutrient exportation, and phenological stage rather than relying exclusively on generalized fertilizer recommendations;

- ✓ Prioritize strategies that improve nutrient-use efficiency and root functioning, since the results demonstrated that nutrient availability alone does not guarantee adequate nutrient uptake and fruit development;

- ✓ Increase soil organic matter through the regular incorporation of organic amendments such as cattle manure, sugarcane bagasse, crop residues, composts, or other locally available organic materials. Improvements in soil organic matter were consistently associated with better soil fertility, nutrient availability, and plant nutritional status;

- ✓ Implement management practices aimed at stimulating root growth and root activity, particularly in orchards affected by soil compaction, salinity, or restricted water availability. Practices that improve soil structure, biological activity, and root exploration should be considered priorities;

- ✓ Improve irrigation management whenever possible. The limited number of irrigation events observed during the experimental period likely reduced the productive potential of the orchard and restricted the efficiency of nutrient uptake, especially during the fruit filling phase; and

- ✓ Monitor soil salinity and sodium accumulation regularly, particularly in sandy soils and under intensive fertigation systems, since elevated electrical conductivity and sodium saturation were identified as important risk factors for long-term soil quality.

4.1 Recommendations for orchards with characteristics similar to the Intensive Management System (IMS)

- ✓ For maximum fruit yield, adopt fertilization programs based on soil base equilibrium combined with amino acids and phenological management (T4);

- ✓ For premium fruit size categories and markets that prioritize larger fruit calibers, adopt fertilization programs based on crop nutritional demand synchronized with phenological stages (T2);

✓ For production systems seeking a balance between productivity, fruit size, nutritional efficiency, and reserve mobilization, adopt crop-demand fertilization combined with amino acid application (T3), which provided the most balanced overall response among the evaluated treatments; and

✓ In highly sandy soils, particular attention should be given to organic matter management, nutrient retention, irrigation scheduling, and potassium nutrition, since these factors were identified as critical for fruit growth and fruit filling.

4.2 Recommendations for orchards with characteristics similar to the Conventional Management System (CMS)

✓ Prioritize strategies that combine nutrient-demand fertilization with organic amendments and practices aimed at improving soil quality;

✓ Adopt management programs similar to T3, consisting of nutrient-demand fertilization combined with organic amendments and soil conditioners, as this strategy produced the highest yield, the greatest fruit mass, the most favorable nutritional status, and the most consistent improvements in soil quality;

✓ The use of organic amendments should be considered a long-term investment in soil improvement rather than merely a nutrient source, as the benefits observed in this study extended beyond nutrient supply and included improvements in soil functioning and nutrient acquisition efficiency; and

✓ Foliar fertilization programs can complement nutritional management but should not replace strategies focused on improving soil conditions and root functioning, particularly in orchards affected by compaction, salinity, or restricted biological activity.

Overall, the results demonstrate that the most successful management strategies were those capable of simultaneously improving soil quality, root activity, nutrient acquisition, and assimilate allocation. Consequently, future management programs should focus not only on fertilizer inputs but also on enhancing the efficiency with which trees acquire and utilize water and nutrients throughout the production cycle. Because many of these processes depend on gradual improvements in soil physical, chemical, and biological properties, the benefits obtained are expected to accumulate over time. Therefore, the long-term and continuous adoption of the recommended practices is essential to maximize their impact on soil functioning, tree performance, fruit quality, and orchard profitability.

5. Acknowledgments

We recognize the actions of the National Mango Board (USDA) on supporting the generation of scientific information for the mango industry and for granting this project. We also thank Dr. Vespasiano Borges de Paiva Neto for all support and help, APEM (Asociación Peruana de Productores y Exportadores de Mango – APEM), Camposol Farm (especially Ing. Arturo Marbel Garcia Garcia) and Bora Bora Farm (Sunshine Export), especially Ing. Javier Arturo Caro Alburquerque for the partnership to develop the field research of the project.

6. Declaration of interest statement

The authors report there are no competing interests to declare.

7. References

- Bally, I.S.E., Cavalcante, I.H.L. 2026. Crop Production: Mineral Nutrition. In: Bally, I.S.E. (Ed.), *The Mango: Botany, Production and Uses* (3rd ed.). Wallingford, UK: CABI. <https://doi.org/10.1079/9781800622647.0016>
- Bandick, A.K., Dick, R.P. 1999. Field management effects on soil enzyme activities. *Soil Biology and Biochemistry*, 31(11), 1471–1479.
- Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A. 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. *Journal of Experimental Botany*, 62(1): 59–68. DOI: 10.1093/jxb/erq350
- Bowen, H.D. 1981. *Alleviating mechanical impedance*. In: Arkin GF, Taylor HM, (Comp.) *Modifying the root environment to reduce crop stress*. St. Joseph, American Society of Agricultural Engineers. p. 21-57.
- Brady, N.C., Weil, R.R. 2017. *The Nature and Properties of Soils*. 15th ed. Pearson Education, New York, NY, USA. 1104 p.
- Carvalho, C.I.F.S., Coelho, B.E.S., Sousa, K.S.M., Lima, A.M.N., Cavalcante, I.H.L., Silva, R.L., Ribeiro, E.B., Nascimento, J.V.C. 2025. Effects of boron and calcium fertilization combined with amino acids and algae extract on the yield and quality of ‘Palmer’ mango. *Journal of Plant Nutrition*, 48(17), 3101–3115. <https://doi.org/10.1080/01904167.2025.2507803>
- Carvalho, L.H.M., Carvalho, C.V.R., Oliveira, R.S., Silva, G.A., Cunha, V.D.L., Henrique, J.C.G.S., Coelho, L.S., Souza, E.R., Freitas, S.T., Cavalcante, I.H.L., Moreira, B.C. 2026. Viability of bionutrition on organic carbon and microbial metabolism in soil cultivated with ‘Palmer’ mango. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v. 30, p. e293837. <https://doi.org/10.1590/1807-1929/agriambi.v30n2e293837>
- Cavalcante, Í.H.L. 2023. *Field Management Strategies to Enhance Mango Fruit Dry Mass Accumulation and Fruit Growth*. National Mango Board, Orlando, FL, USA. 37 p. Available at: <https://www.mango.org/wp-content/uploads/2024/04/field-management-strategies-enhance-mango-fruit-dry-mass-2023.pdf>. Accessed: June 19, 2026
- Cavalcante, I.H.L., Paiva Neto, V.B., Carvalho, L.H.M. 2025. Role of biostimulants in fertilization of mangoes. *Acta Horticulturae*, v. 1415, p. 305-314, 2025. <https://doi.org/10.17660/ActaHortic.2025.1415.36>

- Climate Data. 2024 *Historical data for Piura, Peru*. Available at: [https:// pt.climate-data.org/americas-do-sul/peru/piura/piura-3403/#climate-graph](https://pt.climate-data.org/americas-do-sul/peru/piura/piura-3403/#climate-graph)
- Colla, G., Nardi, S., Cardarelli, M., Ertani, A., Lucini, L., Canaguier, R., Roupael, Y. 2015. Protein hydrolysates as biostimulants in horticulture. *Scientia Horticulturae*, 196: 28–38. Doi: 10.1016/j.scienta.2015.08.037
- Davenport, T.L. 2007. Reproductive physiology of mango. *Brazilian Journal of Plant Physiology*, 19(4), 363–376. <https://doi.org/10.1590/S1677-04202007000400007>
- Dexter, A.R. 2004. Soil physical quality. Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. *Geoderma*, 120(3–4): 201–214. DOI: 10.1016/j.geoderma.2003.09.004
- Dick, R.P., Breakwell, D.P., Turco, R.F. 1996. Soil enzyme activities and biodiversity measurements as integrative microbiological indicators. In: Doran, J. W., & Jones, A. J. (Eds.), *Methods for Assessing Soil Quality* (pp. 247–271). Madison, Wisconsin: Soil Science Society of America Special Publication No. 49. 410 p.
- Donagema, G.K., Campos, D.B., Calderano, S.B., Teixeira, W.G., Viana, J.M. 2011. *Manual de métodos de análise de solos*. 2. ed. Embrapa Solos, Rio de Janeiro, Brazil. 230 p.
- Dubois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.T., Smith, F. 1956. Colorimetric method for determination of sugars and related substances. *Analytical Chemistry* 28(3):350–356. <https://doi.org/10.1021/ac60111a017>
- Eivazi, F., Tabatabai, M.A. (1988). Glucosidases and galactosidases in soils. *Soil Biology and Biochemistry*, 20, 601–606.
- El-Hendawy, S.E., Hu, Y., Schmidhalter, U. 2005. Growth, ion content, gas exchange, and water relations of wheat genotypes differing in salt tolerances. *Australian Journal of Agricultural Research*, 56(2): 123-134.
- FAOSTAT. 2024. *Production and trade statistics*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. Available at: <https://www.fao.org/faostat/en/#data> (accessed 19 June 2026).
- Galán Saúco, V. 2009. *El Cultivo del Mango*. (2nd ed.). MundiPrensa, Madrid, Spain. 340 p.
- Gargantini, F. 1999. *Nutrição e adubação da manga*. In: Curso de mangicultura da região Meio Norte, 1. Teresina, Piauí, Brazil. Apostila. s.p.
- Havlin, J.L., Tisdale, S.L., Nelson, W.L., Beaton, J.D. 2014. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. 8th ed. Pearson Education, Upper Saddle River, NJ, USA. 516 p.
- Lambers, H., Chapin III, F.S., Pons, T.L. 2008. *Plant Physiological Ecology*. 2nd ed. Springer, New York, USA. 604 p.
- Lobo, J.T., Sousa, K.S.M., Paiva Neto, V.B., Pereira, R.N., Silva, L.S., Cavalcante, Í.H.L. 2019. Biostimulants on fruit yield and quality of mango cv. Kent grown in semiarid. *Journal of the American Pomological Society* 73(3): 152-160.
- Lutts, S., Kinet, J.M., Bouharmont, J. 1996. Effects of salt stress on growth, mineral nutrition and proline accumulation in relation to osmotic adjustment in rice (*Oryza sativa* L.) cultivars differing in salinity resistance. *Journal of Plant Growth Regulation*, 19: 207- 218.
- Marschner, H., 2012. *Mineral nutrition of higher plants*. 3th Ed. Academic Press, New York, USA. 684 p.

- Moura, F.M., Lobo, J.T., Cavalcante, I.H.L., Borges, M.C.R.Z., Paiva Neto, V.B., Lima, A.M.N., Félix, W.P. 2025. Ascophyllum nodosum extract and proline on the leaf-macronutrient status of mango cv. Kent. *Journal of Plant Nutrition*, v. 48, p. 3695-3705, 2025.
- Nogueira e Silva e Silva, G.J., Cavalcante, Í.H.L. 2021. *Research report presented at the Encontec 2021*. Petrolina, Brazil.
- Rengasamy, P. 2010. Soil processes affecting crop production in salt-affected soils. *Functional Plant Biology*, 37(7): 613–620. DOI: 10.1071/FP09249.
- Rezende, J.S., Freire, F.J., da Silva, S.R.V., Musser, R.D.S., Cavalcante, Í.H.L., Saldanha, E.C.M., dos Santos, R.L., Cunha, J.C. 2022. Nutritional status of mango by the boundary line and mathematical chance methods. *Journal of Agricultural Science*, 14 (8):90. doi: 10.5539/jas.v14n8p90
- Rodrigues, L.S., Souto, A.G.L., Cavalcante, I.H.L., Carvalho, L.H.M., Henrique, J.C.G.S., Silva, G.J.N., Paiva Neto, V.B., Mendonça, R.M.N., Gheyi, H.R., Lima, G.S., Batista, R.O., Sá, C.H., Silva, W.A.O., Cunha, V.D.L., Sousa Neto, A.T. 2025. Combined effects of calcium sources and water restriction on fruit yield and quality of ‘Ataulfo’ and ‘Kent’ mangoes. *Frontiers in Plant Science*, v. 16, p. 1622533. <https://doi.org/10.3389/fpls.2025.1622533>.
- Rossouw, G.C., Orr, R., Bennett, D., Bally, I.S.E. 2024. The roles of non-structural carbohydrates in fruiting: a review focusing on mango (*Mangifera indica*). *Functional Plant Biology*, 51: FP23195. 31 p. DOI: 10.1071/FP23195.
- Rouphael, Y., Colla, G. 2020. Biostimulants in agriculture. *Frontiers in Plant Science*, 11: 40. <https://doi.org/10.3389/fpls.2020.00040>
- Santos, M.R., Martinez, M.A., Donato, S.L.R., Coelho, E.F. 2014. Fruit yield and root system distribution of ‘Tommy Atkins’ mango under different irrigation regimes. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 18(4): 362–369. <https://doi.org/10.1590/S1415-43662014000400003>
- Schaffer, B., Wolstenholme, B.N., Whiley, A.W. 2013. Mango. In: Dixon, G.R., Aldous, D.E. (eds.), *Horticulture: Plants for People and Places*. Springer, Dordrecht, Netherlands, pp. 639–665. https://doi.org/10.1007/978-94-017-8578-5_19
- Silva, R.L., Fontes, R.L.F., Neves, J.C.L., Lima, A.M.N., Soares, E.M.B., Carvalho, C.I.F.S., Cavalcante, Ítalo H.L. 2022. Nutrient partition and nutritional efficiency of mango cv. Palmer as a function of plant age in São Francisco Valley, Brazil. *Semina: Ciências Agrárias*, 43(4), 1671–1694. <https://doi.org/10.5433/1679-0359.2022v43n4p1671>
- Tabatabai, M.A. 1994. *Soil enzymes*. In: Weaver, R.W. et al. (Eds.), *Methods of Soil Analysis. Part 2. Microbiological and Biochemical Properties*. SSSA Book Series No. 5. Soil Science Society of America, Madison, WI, pp. 775–833.
- Taylor, H.M., Gardner, H.R. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. *Soil Science*, 96(3): 153–156. DOI: 10.1097/00010694-196309000-00003
- Tedesco, M.J., Gianello, C., Bissani, C.A., Bohnen, H., Volkweiss, S.J. 1995. *Análises de solo, plantas e outros materiais*. 2nd ed. Federal University of Rio Grande do Sul, Porto Alegre, Brazil. 174 p.
- Tenreiro, I.G.P., SÁ, M.H. de C., de Souza, I.M., da Silva, K.A., Cavalcante, Í.H.L., de Freitas, S.T., Lima, A.M.N., Rodrigues, M.S., SOUSA, K. Dos S.M. de. 2023. Calcium fertilization strategy to improve production and quality of ‘Tommy Atkins’ mango in semi-arid conditions. *Communications in Soil Science and Plant Analysis*, 54: 3089-3100. <http://dx.doi.org/10.1080/00103624.2023.2254340>

Torres, A.P. 2019. *Effect of fulvic and humic acids on mango nutrition and productivity in the São Francisco Valley, Brazil* (in Portuguese). (M.Sc. thesis, Agronomy - Plant Production) - Federal University of São Francisco Valley, Petrolina, Brazil.

Valentine, T.A., Hallett, P.D., Binnie, K., Young, M.W., Squire, G.R., Hawes, C., Bengough, A.G. 2012. Soil strength and macropore volume limit root elongation rates in many UK agricultural soils.

Weather Spark. 2024. *Historical data for Piura, Peru*. Available at: <https://pt.weatherspark.com/y/18257/Clima-caracter%C3%ADstico-em-Piura-Peru-durante-o-ano>

Whiley, A.W., Schaffer, B., Wolstenholme, B.N. 1996. *The Mango: Botany, Production and Uses*. CAB International, Wallingford, UK. 587 p.

8. Appendix

Below are the appendixes 1 and 2 of this report.

Appendix 1: Fertilizing planning performed for T2 and T3 treatments performed in the Intensive Management System.

Mango Kent: Pré florada - Colheita (24 semanas)																										
Investigador:			Dr. Ítalo Cavalcante			Parcero:			Camposol (T23)						Área (ha):		11,01									
Total de plantas:			5241		Info. Extras:			Recomendação de adubação por extração de nutrientes																		
			Semanas																							
			Flor.	Enchimento de fruto																				Colh.		
Ferti.	Total	fert/plar	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11
Sulf. de Amo.	29,55	0,006		4,43	4,43	4,43	4,43	4,43	4,43	2,95																
				15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	10,0%																
Ácido fosfórico	206,06	0,039		20,61	20,61	20,61	20,61	20,61	20,61	20,61	20,61	20,61	20,61													
				10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%													
Sulf. K	1964,00	0,37		58,92	58,92	58,92	58,92	78,56	98,20	98,20	98,20	117,84	117,84	117,84	137,48	137,48	137,48	137,48	117,84	98,20	78,56	78,56	78,56			
				3,0%	3,0%	3,0%	3,0%	4,0%	5,0%	5,0%	5,0%	6,0%	6,0%	6,0%	7,0%	7,0%	7,0%	7,0%	6,0%	5,0%	4,0%	4,0%	4,0%			
Nitra. Ca	865,26	0,165		129,79	129,79	129,79	129,79	129,79	129,79	86,53																
				15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	10,0%																
Sulf. Mg	753,86	0,144		18,85	18,85	37,69	37,69	37,69	45,23	45,23	45,23	52,77	52,77	52,77	60,31	52,77	45,23	37,69	37,69	30,15	22,62	22,62				
				2,5%	2,5%	5,0%	5,0%	5,0%	6,0%	6,0%	6,0%	7,0%	7,0%	7,0%	8,0%	7,0%	6,0%	5,0%	5,0%	4,0%	3,0%	3,0%				
Sulf. Zn	153,93	0,029		9,24	9,24	9,24	9,24	4,62	4,62	4,62	4,62	9,24	9,24	9,24	9,24	9,24	9,24	9,24	9,24	9,24	6,16	4,62	4,62			
				6,0%	6,0%	6,0%	6,0%	3,0%	3,0%	3,0%	3,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	4,0%	3,0%	3,0%		
Acid. B	439,50	0,084		35,16	30,76	30,76	26,37	26,37	26,37	26,37	26,37	26,37	26,37	26,37	21,97	21,97	17,58	17,58	17,58	13,18	13,18	8,79				
				8,0%	7,0%	7,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	5,0%	5,0%	4,0%	4,0%	4,0%	3,0%	3,0%	2,0%				
Sulf. Mn	487,70	0,093		14,63	24,38	24,38	29,26	29,26	34,14	29,26	24,38	24,38	24,38	24,38	29,26	29,26	24,38	24,38	19,51	19,51	19,51	19,51	19,51			
				3,0%	5,0%	5,0%	6,0%	6,0%	7,0%	6,0%	5,0%	5,0%	5,0%	5,0%	6,0%	6,0%	5,0%	5,0%	4,0%	4,0%	4,0%	4,0%	4,0%			
Sulf. Fe	546,95	0,104		21,88	27,35	32,82	38,29	38,29	32,82	27,35	27,35	27,35	27,35	27,35	27,35	27,35	27,35	27,35	27,35	27,35	21,88	16,41	16,41			
				4,0%	5,0%	6,0%	7,0%	7,0%	6,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	4,0%	3,0%	3,0%		
Sulf. Cu	10,48	0,002		0,629	0,838	1,048	0,734	0,734	0,734	0,734	0,629	0,629	0,629	0,629	0,629	0,629	0,629	0,629								
				6,0%	8,0%	10,0%	7,0%	7,0%	7,0%	7,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%	6,0%							

Appendix 2: Fertilizing planning performed for T5 treatments performed in the Intensive Management System.

Mango Kent: Pré florada - Colheita (24 semanas)

Investigador:			Dr. Ítalo Cavalcante			Parceiro:										Área:													
Total de plantas:			1095	Info. Extras:			Recomendação de adubação por equilíbrio de bases																						
			Semanas																										
			Flor.	Enchimento de fruto																								Colh.	
Ferti.	Total	/planta	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47			
Ureia (N)	132,35	0,12	0	4,63	4,63	6,62	6,62	6,62	11,25	11,25	11,25	11,25	7,94	7,94	7,94	7,94	6,62	6,62	6,62	6,62	0,00	0,00	0,00	0,00	0,00	0,00			
			0,00%	3,50%	3,50%	5,00%	5,00%	5,00%	8,50%	8,50%	8,50%	8,50%	6,00%	6,00%	6,00%	6,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	0,00%	0,00%	0,00%	0,00%	0,00%		
MAP (P)	54,71	0,05	0	5,47	5,47	5,47	5,47	5,47	5,47	5,47	5,47	5,47	5,47	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			
			0,00%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%		
Sulf. K	872,89	0,80	0,00	21,82	26,19	26,19	39,28	39,28	39,28	43,64	43,64	43,64	43,64	43,64	39,28	39,28	39,28	48,01	48,01	48,01	48,01	48,01	48,01	52,37	52,37	0,00	0,00		
			0,00%	2,50%	3,00%	3,00%	4,50%	4,50%	4,50%	5,00%	5,00%	5,00%	5,00%	5,00%	4,50%	4,50%	4,50%	5,50%	5,50%	5,50%	5,50%	5,50%	5,50%	6,00%	6,00%	0,00%	0,00%		
Algen (Ca)	385,95	0,35	385,95	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			
			100%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%			
Sulf. Mg	0,00	-0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			
			0,00%	5,50%	6,00%	6,00%	6,00%	6,00%	6,00%	6,00%	6,00%	6,00%	6,00%	6,00%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	4,50%	0,00%	0,00%	0,00%		
Sulf. Zn	32,16	0,03	0,00	1,93	1,93	1,93	1,93	1,93	1,29	1,29	1,29	1,29	1,29	1,61	1,61	1,61	1,61	1,61	1,61	1,61	1,61	1,61	1,61	0,00	0,00	0,00			
			0,00%	6,00%	6,00%	6,00%	6,00%	6,00%	4,00%	4,00%	4,00%	4,00%	4,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	0,00%	0,00%	0,00%		
Acid. Br	584,77	0,53	0,00	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	29,24	0,00	0,00	0,00			
			0,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	5,00%	0,00%	0,00%	0,00%		
Sulf. Mn	101,89	0,09	0	4,585	3,057	3,057	3,0568	3,057	3,057	3,821	3,821	3,821	3,821	5,095	5,095	5,095	5,095	6,114	6,114	6,114	6,114	6,114	7,642	7,642	0	0			
			0,00%	4,50%	3,00%	3,00%	3,00%	3,00%	3,00%	3,75%	3,75%	3,75%	3,75%	5,00%	5,00%	5,00%	5,00%	6,00%	6,00%	6,00%	6,00%	6,00%	6,00%	7,50%	7,50%	0,00%	0,00%		
Sulf. Fe	114,27	0,10	0	9,142	9,142	9,142	9,1419	9,142	4,571	4,571	4,571	4,571	3,428	3,428	3,428	4,571	4,571	4,571	4,571	4,571	4,571	4,571	4,571	0	0	0			
			0,00%	8,00%	8,00%	8,00%	8,00%	8,00%	4,00%	4,00%	4,00%	4,00%	3,00%	3,00%	3,00%	4,00%	4,00%	4,00%	4,00%	4,00%	4,00%	4,00%	4,00%	4,00%	0,00%	0,00%	0,00%		
Sulf. Cu	2,19	0,00	0,000	0,219	0,219	0,219	0,219	0,219	0,219	0,219	0,219	0,219	0,219	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000				
			0,00%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%			

