

Article

Impact of Organic Fertilizers on the Quality of Mango var. ‘Kent’ During Physiological and Commercial Maturity

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Abstract

Mango (*Mangifera indica* L.) is a key fruit crop in Peru; however, its reliance on chemical fertilizers raises concerns regarding fruit quality and environmental sustainability. This study evaluated the effects of soil-applied compost and foliar-applied biol on the quality of ‘Kent’ mango fruits at physiological and commercial maturity stages. Conducted during the 2022–2023 season, the experiment used a 3 × 3 factorial design with compost applied at 0, 5, and 15 t/ha and biol at 0, 5, and 10%, plus a chemically fertilized control. Results revealed significant compost–biol interactions. At physiological maturity, treatments 5-10, 15-5 and 15-10 improved pulp color, soluble solids, titratable acidity, and dry matter content, achieving a desirable yellow pulp (2.0 on the scale), 9.29 °Brix, 1.23% acidity, and 20.96% dry matter—surpassing the control. At commercial maturity, these treatments also enhanced fruit firmness (0.42 MPa), reduced acidity (0.47%), increased pulp pH (4.69), and intensified orange pulp color. Overall, organic fertilization, particularly higher compost and biol doses, significantly improved fruit quality parameters compared to conventional chemical management. These findings highlight the potential of integrating organic amendments to promote sustainable mango cultivation while maintaining or enhancing fruit quality, thus providing a viable alternative for eco-friendly nutrient management in mango orchards.

Keywords: *Mangifera indica*; crop productivity; fruit quality; nutrient management; sustainable farming



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1. Introduction

Mango (*Mangifera indica* L.) is a seasonal tropical fruit with growing global demand due to its unique sensory attributes and well-documented health benefits [1,2]. However, in recent years, climate change has exacerbated phytosanitary challenges and disrupted key physiological processes, adversely affecting mango production and marketability [3,4]. Among the most commercially significant mango cultivars is ‘Kent’, developed in Florida, USA, in 1932 from seeds of the ‘Brooks’ variety [5]. This cultivar is recognized for its oval

shape, sweet flavor, low fiber content, and dark green skin with red hues that intensify as ripening progresses [6].

Mango ripening involves two critical stages: physiological maturity and commercial maturity. These stages are accompanied by a series of morphological, physiological, and biochemical changes that ultimately influence fruit quality [7–9]. Physiological maturity in mango corresponds to BBCH scale stage 87 [10], marked by growth cessation, lenticel formation, purine coating, and starch accumulation [11,12]. In contrast, commercial maturity aligns with stage 89 of the BBCH scale [10] and is characterized by chlorophyll degradation, carotenoid accumulation, cell wall softening, and polysaccharide breakdown [13–15]. While fruit maturity is traditionally assessed through subjective criteria such as shoulder width, shape, lenticel size, and skin color [16–18], these methods are prone to errors due to varietal variability [19]. Consequently, objective approaches based on physical, physiological, and biochemical parameters are necessary to reliably assess fruit quality [20–22].

In the “Kent” cultivar, fruit quality is linked to both qualitative traits, such as internal color and pulp hue and quantitative traits like weight, volume [18], pulp firmness [23], soluble solids content, titratable acidity [16], ethylene production, and dehydration rates [23]. Fruit maturation is influenced by intrinsic factors like genotype and extrinsic factors including water availability, temperature, light, hormone production, and nutrient supply [4,24]. Nutrient availability, in particular, plays a key role during fruit development, helping to prevent physiological disorders and nutritional imbalances that compromise harvest and postharvest quality [25,26].

In Peru, nutrient management in mango production is traditionally based on synthetic N-P-K-Mg-Ca fertilizers, often supplemented with foliar applications of micronutrients and synthetic hormones to ensure high yields and acceptable fruit quality [27,28]. However, recent increases in fertilizer prices have led to yield declines and reduced profitability [29,30]. As a result, many growers have turned to organic fertilizers as cost-effective alternatives that can mitigate the adverse impacts of chemical inputs [31,32].

Organic fertilizers, derived from decomposed plant and animal residues, typically have lower nutrient concentrations [33] but offer a broader spectrum of nutrients and compounds that are released gradually, enhancing soil physical, chemical, and biological properties [34,35]. Their use not only reduces dependence on synthetic fertilizers [36] but also improves crop yield and fruit quality [37,38]. Among the most common organic inputs in mango cultivation are compost—applied to the soil in solid form [39]—and biol, a liquid biofertilizer applied either to the soil or foliage [40].

Soil-applied compost enhances the soil–plant system by increasing root hair density, stimulating soil biota activity, reducing pathogen incidence, and supporting gradual nutrient mineralization [41–43]. Foliar-applied biol contributes micronutrients, phytohormones, and aromatic compounds that trigger morphological and physiological changes in plants, promote tissue elongation, and exert pest-repellent effects [44–46]. Previous studies have demonstrated that partial substitution of chemical fertilizers with organic inputs enhances soil properties, improves mango yield, and enriches fruit nutritional quality, including vitamin C content and favorable sugar-to-acid and soluble solids-to-acid ratios [47–49]. Accordingly, the objective of this study was to evaluate the effects of soil- and foliar-applied organic fertilizers—compost and biol—on the quality of ‘Kent’ mango fruits at physiological and commercial maturity. This study was conducted in Tambogrande, Peru, for two years during the 2022–2023 growing season.

2. Materials and Methods

2.1. Study Area and Plant Material

This study was conducted from September 2022 to March 2023 (2022–2023 growing season) in an experimental mango plot located in the village of Las Mónicas, Tambogrande district, Piura region, Peru (latitude 4°54'45" S, longitude 80°16'9" W, and elevation 96 m above sea level; Figure 1).

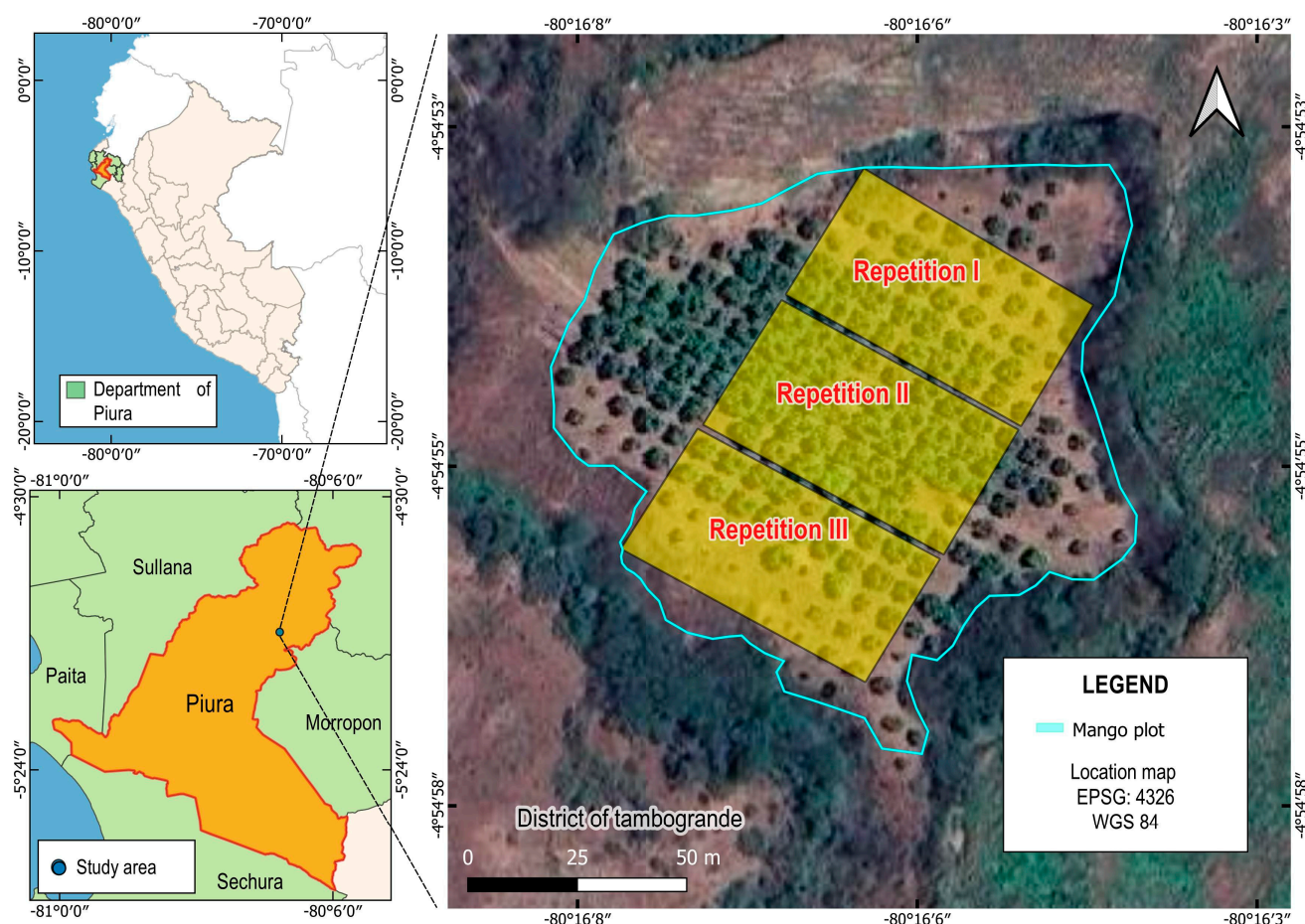


Figure 1. Research area on organic fertilizers and postharvest fruit quality management of mango (*Mangifera indica* L.) var. 'Kent' in Tambogrande, Piura region. Coordinates: 4°54'45" S, 80°16'9" W.

Climatic conditions during the study period were characterized by minimum temperatures of 14 °C, recorded in October 2022, and maximum temperatures reaching up to 37.5 °C in February 2023. The highest monthly precipitation was also observed in February 2023, with an accumulation of 147.7 mm, which coincided with the highest relative humidity (67.91%). In contrast, the lowest relative humidity (57.94%) occurred in January, aligning with the period of peak temperature (Figure 2).

The physical and chemical properties of the soil at the study site were characterized by a sandy texture (68% sand, 16% silt, and 16% clay), a pH of 7.51, organic matter content of 0.96%, and electrical conductivity of 0.18 dS/m. Soil nutrient levels included 480 mg/kg of nitrogen, 25.9 mg/kg of phosphorus, and 268 mg/kg of potassium, with a cation exchange capacity of 10.88 cmol/kg.

The plant material consisted of eight-year-old 'Kent' mango (*Mangifera indica* L.) trees, exhibiting vigorous growth, high flowering intensity, good phytosanitary condition, and no signs of alternate bearing. The trees were spaced at 7 × 7 m and originated from grafted 'Kent' scions onto 'Criollo de Chulucanas' rootstocks.

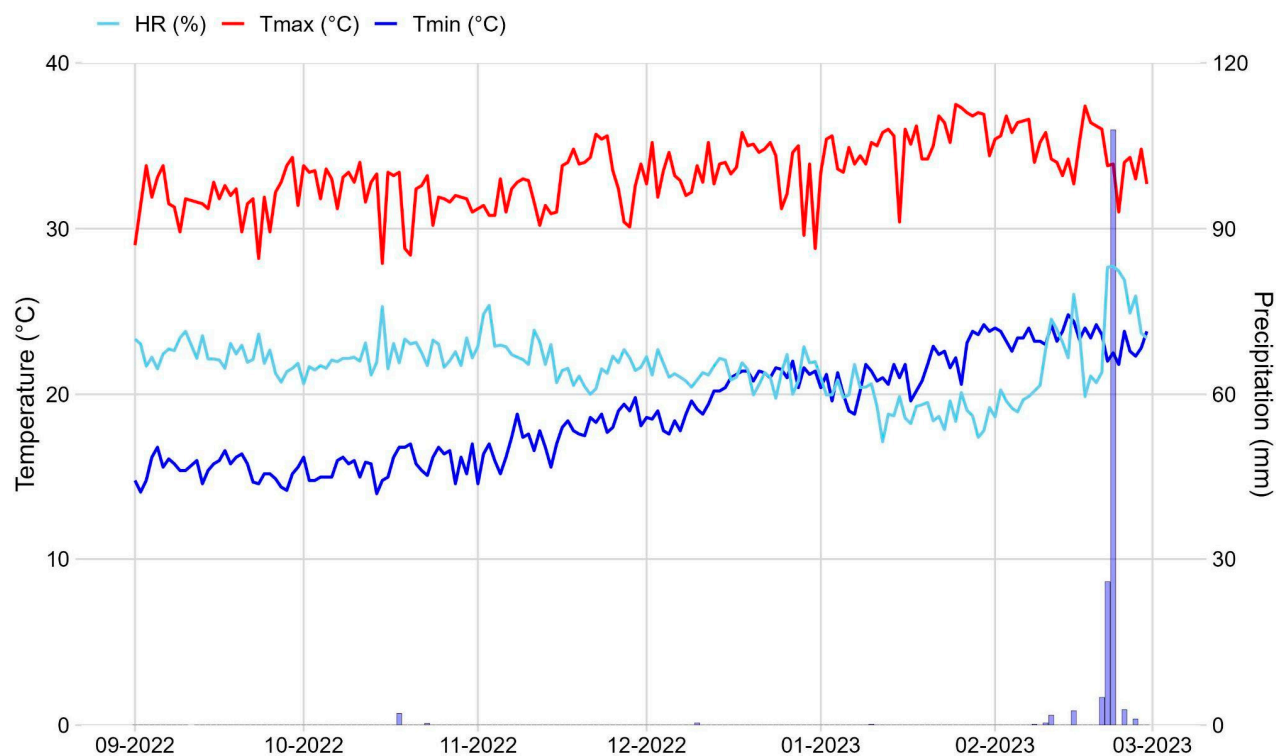


Figure 2. Weather conditions during the experiment of organic fertilizers on the quality and postharvest management of mango (*Mangifera indica* L.) Var. 'Kent', Located in the District of Tambogrande, Piura Región. Source: SENAMHI.

2.2. Experimental Treatments

The experiment was conducted using a 3×3 factorial design arranged in a completely randomized block design (CRBD) with three replications. The first factor was the application of compost at rates of 0, 5, and 15 t/ha, and the second factor was the application of biol at concentrations of 0, 5, and 10%, resulting in a total of nine treatment combinations (Table 1). Each treatment consisted of five trees, of which three were selected for evaluation. In addition, treatments were compared against a control group, which received conventional fertilization practices commonly used by local farmers in Tambogrande (Table 2). The control regimen involves the application of synthetic fertilizers to the soil (230 kg/ha N, 220 kg/ha P_2O_5 , 280 kg/ha K_2O , 36 kg/ha Ca, and 60 kg/ha MgO) and foliar sprays (90 mg/ha N, 28 mg/ha P_2O_5 , 380 mg/ha K_2O , 98 mg/ha Ca, and 100 mg/ha MgO).

Table 1. Summary of compost and biol treatments applied to *Mangifera indica* L. var. 'Kent' mango trees during the 2022–2023 season. Control treatment involves the common fertilization practices used by local farmers.

Treatment	Compost Dose (t/ha)	Biol Concentration (%)	Code
Control Treatment	0	0	0-0
Treatment 1	5	0	5-0
Treatment 2	15	0	15-0
Treatment 3	0	5	0-5
Treatment 4	0	10	0-10
Treatment 5	5	5	5-5
Treatment 6	5	10	5-10
Treatment 7	15	5	15-5
Treatment 8	15	10	15-10

Table 2. Nutrient contributions per hectare by treatment and application method in the study of *Mangifera indica* L. var. ‘Kent’.

Treatment	Application Method	N	P	K	Ca	Mg	Organic Matter (%)
0-0	Soil	230 kg	220 kg	280 kg	36 kg	60 kg	0
	Foliar	90 mg	28 mg	380 mg	98 mg	100 mg	0
5-0	Soil	104.5 kg	100.5 kg	128 kg	222.5 kg	140 kg	28.5
	Foliar	0 mg	0 mg	0 mg	0 mg	0 mg	%
15-0	Soil	313.5 kg	301.5 kg	384 kg	667.5 kg	420 kg	28.5
	Foliar	0 mg	0 mg	0 mg	0 mg	0 mg	0
0-5	Soil	0 kg	0 kg	0 kg	0 kg	0 kg	0
	Foliar	57.16 mg	18.605 mg	256.2 kg	62 mg	72.25 mg	2.14
0-10	Soil	0 kg	0 kg	0 kg	0 kg	0 kg	0
	Foliar	114.32 mg	37.21 mg	512.4 mg	124 mg	144.5 mg	2.14
5-5	Soil	104.5 kg	100.5 kg	128 kg	222.5 kg	140 kg	28.5
	Foliar	57.16 mg	18.605 mg	256.2 kg	62 mg	72.25 mg	2.14
5-10	Soil	104.5 kg	100.5 kg	128 kg	222.5 kg	140 kg	28.5
	Foliar	114.32 mg	37.21 mg	512.4 mg	124 mg	144.5 mg	2.14
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15-10	Soil	313.5 kg	301.5 kg	384 kg	667.5 kg	420 kg	28.5
	Foliar	114.32 mg	37.21 mg	512.4 mg	124 mg	144.5 mg	2.14

The compost and biol application rates were calibrated based on the nutrient equivalence of NPK inputs used in the conventional fertilization system of Tambogrande. For compost, the conventional soil fertilization rate was reduced and increased by 50%, then replaced with equivalent nutrient content in compost, resulting in rates of 5 t/ha and 15 t/ha. Similarly, for biol, the foliar fertilization rate was adjusted by $\pm 50\%$ and replaced with its equivalent concentration in biol, yielding the 5% and 10% application treatments (Table 2).

The compost used in this study was a commercial product named Compost Nutri Suelo 3M, produced by Soluciones Orgánicas Loma Fértil® in Las Mónicas-CP7, Piura, Peru. It was obtained through aerobic composting of crop residues from maize, sheep or goat manure, fossilized marine algae, rock phosphate, and charcoal husks. The composting process lasted three months and included periodic inoculation with native microorganisms from the Tambogrande region, activated with sugarcane molasses (*Saccharum officinarum*).

The biol was prepared manually following the methodology described by Chanduví-García et al. [50], with slight modifications intended to accelerate fermentation. A 200 L plastic container with a lid and a 60 L metal pot were used. A 25 kg sack of compost was submerged in 70 L of irrigation water inside the plastic container. Simultaneously, 6 kg of leaves from native plant species—*Ambrosia peruviana* (altamisa), *Ricinus communis* (castor bean), and *Azadirachta indica* (neem)—were cut into 2 × 2 cm pieces and placed in the metal pot, along with 4 kg of *Allium sativum* (garlic), 4 kg of *Allium cepa* (onion), and 3 kg of *Capsicum annuum* (chili pepper). The mixture was topped with water up to 50 L and boiled for eight hours, or until partial degradation of the plant materials was observed. Water was periodically added to maintain the original volume during evaporation.

Once cooking was complete, both the supernatant and the residual plant materials were transferred into the plastic container containing the compost mixture. Two liters of chicha de jora (a traditional Peruvian fermented maize beverage) were added, and the volume was adjusted to 200 L with additional water. The container was sealed and left to ferment for 20 days. The chemical composition of the biol used in the experiment is presented in Table 3.

The chemical fertilizers used for soil application included diammonium phosphate, potassium sulfate, ammonium sulfate, calcium nitrate, and magnesium sulfate. These were applied in specific proportions to supply the required amounts of nitrogen (N), phosphorus

(P), potassium (K), calcium (Ca), and magnesium (Mg) as outlined in Table 2. For foliar applications, liquid formulations containing N, P, K, Ca, and Mg were used.

Table 3. Physicochemical composition and microbial count of biol applied in the mango orchard.

Parameter	Unit	Value
pH	–	3.10
Electrical conductivity (EC)	dS/m	10.54
Total solids	g/L	29.22
Organic matter in solution	g/L	21.40
Total nitrogen (N)	mg/L	1143.16
Total phosphorus (P)	mg/L	181.40
Total potassium (K)	mg/L	1975.0
Total calcium (Ca)	mg/L	440.0
Total magnesium (Mg)	mg/L	145.0
Total sodium (Na)	mg/L	248.8
Total iron (Fe)	mg/L	1.5
Total copper (Cu)	mg/L	0.8
Total boron (B)	mg/L	7.2
Total manganese (Mn)	mg/L	3.5
Aerobic mesophilic microorganisms count	CFU/g	7.8×10^7

Soil fertilization was performed once, during fruit development, corresponding to phenological stage 71 (ovary growth or first fruit drop) of the BBCH scale for stone fruits [10]. Foliar applications were carried out in three stages: the first coincided with the compost application, the second occurred 15 days later, and the third was performed 20 days after the second. Soil fertilizers were incorporated into the topsoil around the canopy projection of each tree, while foliar fertilizers were applied via foliar spraying, ensuring full leaf coverage.

Fruit harvesting was performed once, following the completion of phenological stage 73 (second fruit drop), based on the BBCH scale [10]. Ten fruits per tree were randomly selected and labeled using two different colors to distinguish between stages: five fruits were designated for evaluation at physiological maturity and five for commercial maturity, totaling 15 fruits per treatment. Fruit selection prioritized those located on the outer canopy at heights above 1.5 m from the ground. Harvesting was conducted between 06:00 and 10:00 a.m. to avoid post-harvest exposure to direct sunlight.

2.3. Study Variables

The study evaluated a set of quantitative parameters to assess fruit quality at two critical developmental stages: physiological maturity (BBCH stage 87 for stone fruits) and commercial maturity (BBCH stage 89). These objective measurements were preferred over subjective criteria—such as shoulder width, size, and skin color—which are often error-prone. To assess the quality of ‘Kent’ mango fruit, the evaluation criteria were based on the Peruvian Technical Standard NTP 011.010:2020.

According to this standard, fruits at physiological maturity should meet the following criteria: weight between 167 and 1250 g, color coverage (blush) greater than 50%, firmness between 1.078 and 1.569 MPa (equivalent to 11–16 kgf/cm²), soluble solids content > 7 °Brix, yellow pulp color, titratable acidity < 4.0%, and dry matter content > 18.0% [51]. For commercial maturity, benchmarks were based on the export requirements of Peruvian agro-export companies for air-shipped mangoes, which require pulp firmness between 0.196 and 0.490 MPa (equivalent to 2–5 kgf/cm²), soluble solids content > 12 °Brix, titratable acidity < 1.0%, and pulp color ranging from yellow to orange [52,53].

At the physiological maturity stage, several key quality variables were assessed. Peel color coverage (FCC, %) was estimated using a custom-developed color reference chart (Figure 3), which quantified the percentage of carotenoid expression on the mango peel. Fruit firmness (FF, MPa) was measured using a Facchini FT 327 penetrometer (Facchini

SRL, Alfonsine, Italy) equipped with a 1 cm² plunger [54]. Firmness values originally expressed in kgf/cm² were converted to SI units and reported as penetration stress (MPa), using a conversion factor of 1 kgf/cm² = 0.09807 MPa. Pulp color (FPC) was evaluated based on a visual color scale specifically developed for this study (Figure 4). Additional biochemical parameters, including soluble solids content (SSC, °Brix), pulp pH (FpH), titratable acidity (TA, %), and dry matter percentage (FDM, %), were determined following standard protocols outlined by the Association of Official Analytical Chemists [55], specifically methods 932.12, 981.12, 942.15, and 963.15. Lastly, the physiological maturity index (FPMI) was calculated by dividing the soluble solids content by titratable acidity, serving as an integrated indicator of fruit ripeness and flavor balance.

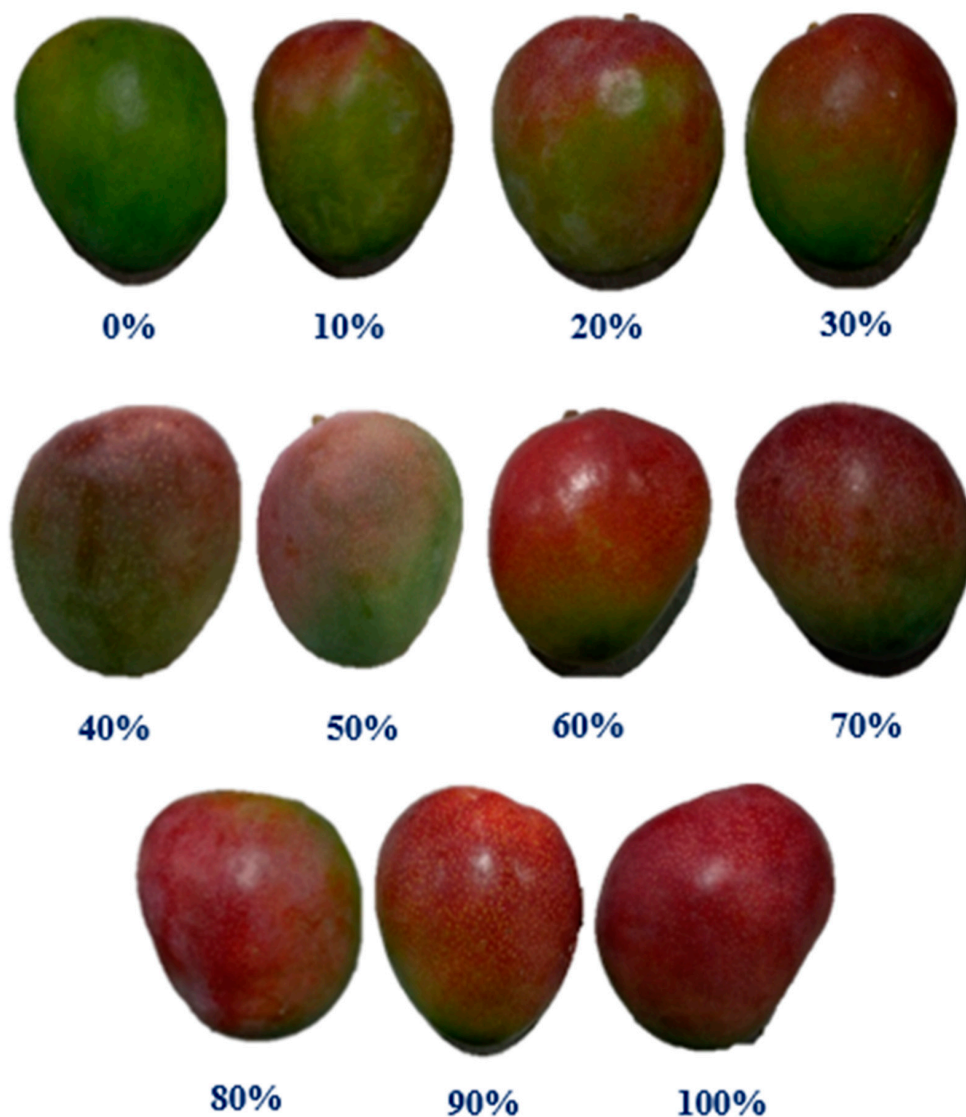


Figure 3. Scale for percentage values of carotenoids, referred to as fruit blush, where 0% indicates the absence of carotenoids in the fruit, whereas values of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100% indicate the presence of carotenoids. These percentages are based on the portion of the mango fruit located between the ventral shoulder and the dorsal shoulder, with 100% referencing the total region located between the aforementioned parts.

Variables at commercial maturity were evaluated after subjecting the fruits to a standardized postharvest ripening process, adapted from Zamora-Cienfuegos et al. [56]. In this method, fruits were ripened without continuous refrigeration or ethylene application. Initially, mangoes were stored at 13 ± 1 °C for two days. They were then transferred to a

closed ripening room for 12 h, where ambient temperatures rose above 26 ± 2 °C. After this period, the room was ventilated for 12 h to release the CO₂ emitted by the fruits. This cycle was repeated daily for five days until the fruits reached commercial maturity.



Figure 4. Scale for values of the pulp color of ripe fruit when subjected to a longitudinal cut between the poles, where the values correspond to a specific color: 1.0 white and green, 1.5 green, 2.0 green and yellow, 2.5 yellow, 3.0 yellow-orange, 3.5 orange, and 4.0 deep orange.

Upon completion of the ripening process, the Fruit Dehydration Percentage (FD, %) was calculated by comparing fruit weight before and after ripening. In addition, the following quality parameters were reassessed using the same protocols as for physiological maturity: Firmness (FF, MPa), Pulp Color (FPC), Soluble Solids Content (SSC, °Brix), pH (FpH), Titratable Acidity (TA, %), and the Commercial Maturity Index (FCMI), calculated as the SSC/TA ratio.

2.4. Statistical Analysis

A linear mixed-effects model was employed to evaluate treatment effects, providing increased robustness against potential deviations from the assumptions of normality and homogeneity of variances [57]. Subsequently, a univariate analysis of variance (ANOVA) was conducted under a factorial design to identify significant differences among treatment combinations. Compost and biol applications were evaluated as predefined combined fertilization treatments, and fruit quality was assessed separately at the physiological and commercial maturity stages. Independent analyses were performed for each maturity stage. Mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at a significance level of $\alpha = 0.05$, implemented via the *emmeans 2.0.0 package* [58]. To explore multivariate relationships among the measured variables, principal component analysis (PCA) was conducted using the *FactoMineR 2.12 package* [59]. with visualizations generated using *factoextra 1.0.7* [60]. Correlation matrices were visualized with the *corrplot package* [61]. All statistical analyses were performed using R software, version 4.4.1 [62]. The code and the reproducible analysis are provided in Supplementary File S1.

3. Results

3.1. Fruit Quality Traits at Physiological Maturity

To assess the fruit quality characteristics at the physiological maturity stage (Figure 3), a univariate analysis was performed on key variables, including fruit firmness (FF), percentage of fruit canopy color (FCC), internal fruit color (FPC), soluble solids content (SSC), titratable acidity (TA), and dry matter percentage (FDM). These variables are essential for determining physiological maturity at harvest, as outlined in the Peruvian Technical Standard NTP 011.010:2020. Their evaluation also plays a critical role in reducing the risk of postharvest damage during handling, transportation, and processing [63,64].

For FF, no statistically significant interaction was observed between compost and biol treatments ($p > 0.05$; Figure 5a). However, significant differences were detected for each factor individually. Among biol concentrations, the 10% application resulted in the highest firmness values across all compost levels, with a mean of 1.22 MPa. Similarly, the 15 t/ha compost dose produced slightly higher firmness compared to other compost treatments, averaging 1.219 MPa. Although the interaction was not significant, Treatment 15-10 yielded the highest firmness at 1.274 MPa, significantly outperforming the control (0-0), which recorded 1.118 MPa (Figure S1).

Regarding FCC, no significant interaction was found between compost and biol ($p > 0.05$; Figure 5b). Nonetheless, both factors independently influenced FCC. The 10% biol treatment produced the highest peel color coverage across compost levels, with an average of 73.86%. Similarly, the 15 t/ha compost treatment resulted in an average FCC of 73.73%. The highest recorded value was in Treatment 15-10 (78.70%), which was statistically superior to the control (0-0), which had 56.40% (Figure S1).

In contrast, a significant interaction effect was observed for FPC ($p < 0.05$; Figure 5c), indicating that the effect of one factor depended on the level of the other (non-parallel lines). Treatment 15-10 achieved a pulp color score of 2.5, corresponding to a yellow hue on the custom color scale (Figure 4), and was statistically superior to the control (Figure S1).

A significant interaction was also detected for SSC ($p < 0.05$; Figure 5d). Treatments 5-10 and 15-5 both reached 9.29 °Brix, significantly higher than the control (0-0), which recorded 8.57 °Brix (Figure S1). The confidence intervals for 5-10 and 15-5 partially overlapped, indicating statistical equivalence between these two treatments.

For TA, a significant interaction between compost and biol was also found ($p < 0.05$; Figure 5e). Treatment 15-10 exhibited the lowest acidity at 1.24%, significantly less than 0-0, which recorded the highest acidity at 1.37% (Figure S1). Notably, fruits treated with 10% biol showed consistently lower acidity across compost levels.

Finally, for FDM, no significant interaction was observed ($p > 0.001$; Figure 5f). Nonetheless, Treatment 15-10 again demonstrated statistical superiority, with a dry matter content of 21.00%, compared to 19.76% in the control (0-0) (Figure S1). It is worth noting that fruits treated with 10% biol exhibited higher dry matter content regardless of compost application rate.

To further analyze the relationships among the quality variables and organic fertilizer treatments at physiological maturity, a principal component analysis (PCA) was conducted, accompanied by a Pearson correlation matrix (Figure 6).

To evaluate the overall interactions among fruit quality traits and their responses to organic fertilizer treatments, a principal component analysis (PCA) was conducted (Figure 6). The first two principal components explained a cumulative variance of 94.50%, with Dimension 1 accounting for 83.00% and Dimension 2 for 11.50% of the total variability (Figure 6a). Within Dimension 1, the variables FF, FPMI, and FCC showed the highest contributions—14.49%, 14.21%, and 14.00%, respectively—while FPC contributed less (4.97%). In Dimension 2, FPC was the dominant contributor at 71.87%, while FCC and TA

had the lowest contributions, at 0.31% and 2.06%, respectively. The variables FF, FPMI, FDM, SSC, and TA were identified as the most influential in explaining fruit quality at physiological maturity.

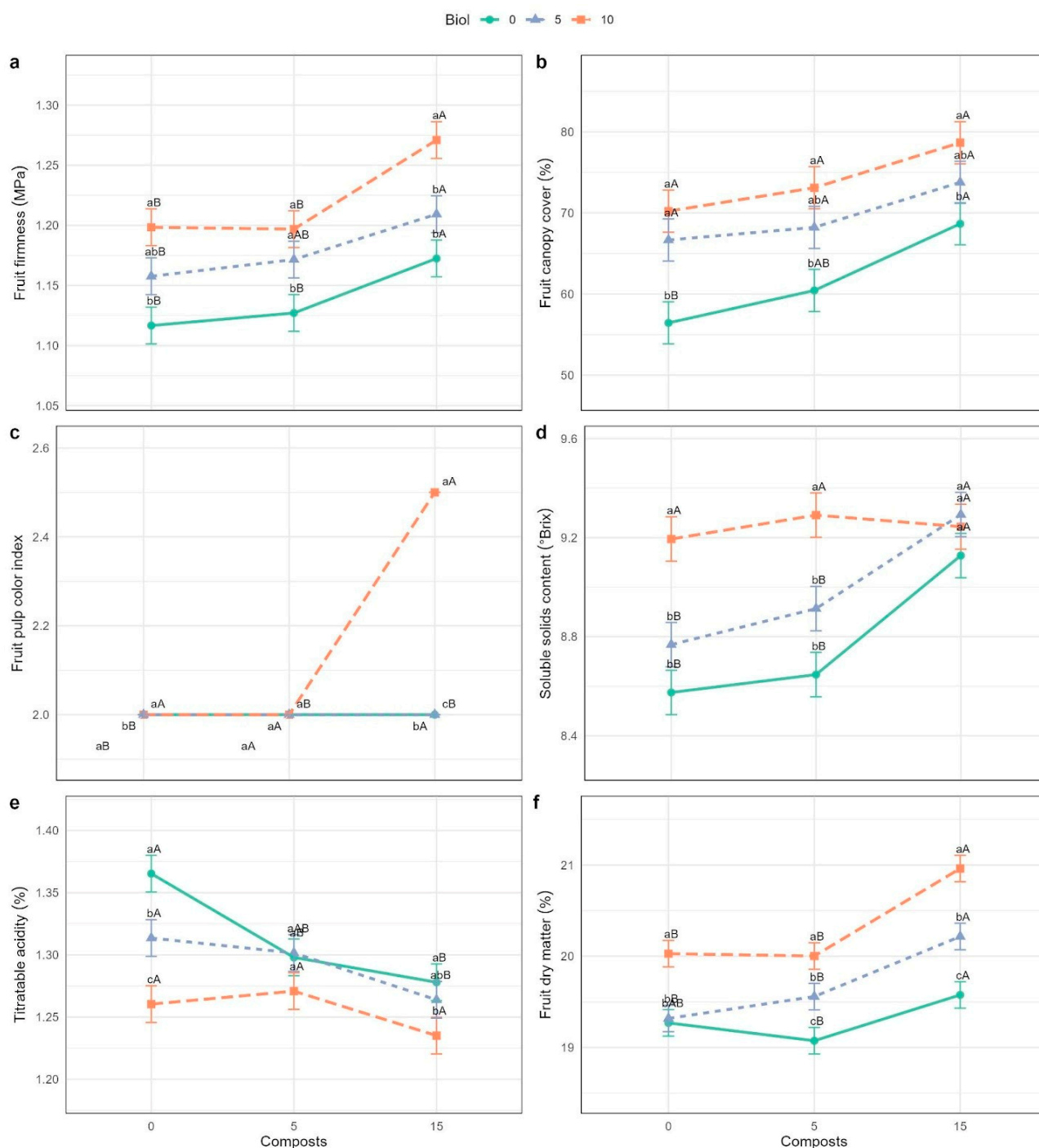


Figure 5. Quality traits of *Mangifera indica* L. var. 'Kent' mango fruits at physiological maturity. (a) FF, (b) FCC, (c) FPC, (d) SSC, (e) TA, and (f) FDM. Different uppercase letters indicate statistically significant differences among compost treatments, while different lowercase letters indicate significant differences among biol treatments, based on Tukey's multiple comparison test ($p < 0.05$). Error bars represent standard errors from post hoc analysis. Treatments represent combinations of compost (t/ha) and biol (%) as follows: 0-0, 5-0, 15-0, 0-5, 0-10, 5-5, 5-10, 15-5, and 15-10. Data analysis was based on 405 individual fruit samples ($n = 405$).

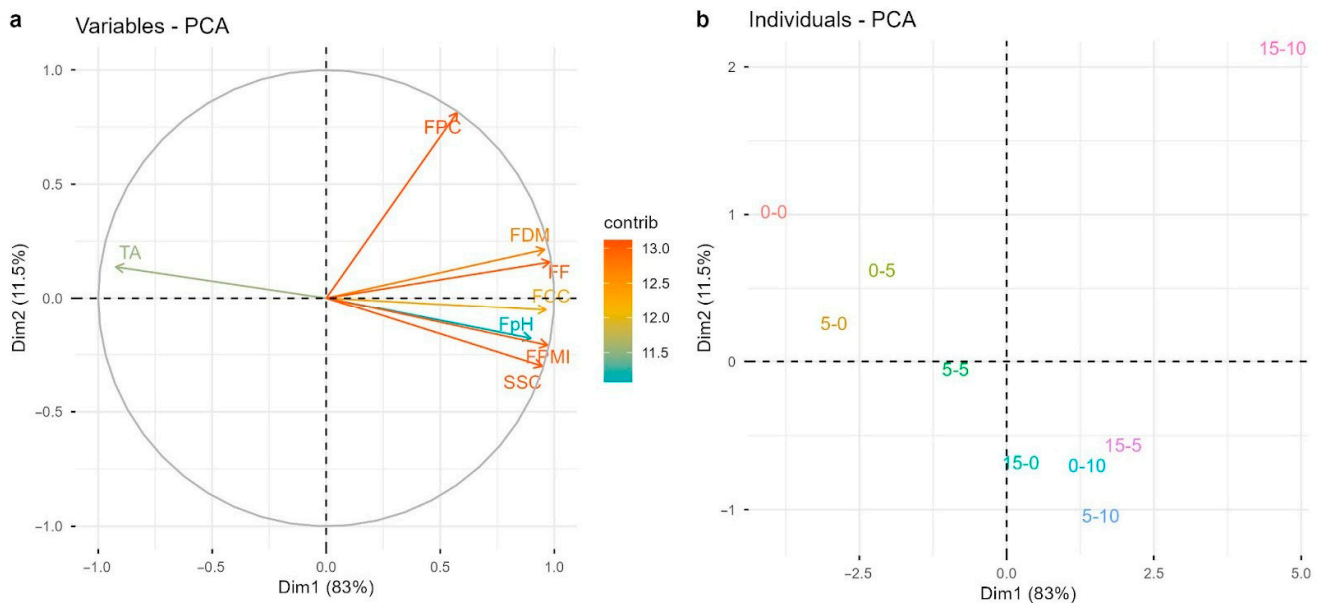


Figure 6. Principal Component Analysis (PCA) of quality traits for mango fruits at physiological maturity from compost and biol applications. **(a)** Distribution of physicochemical traits: FCC, FF, FPC, SSC, FpH, TA, FDM, FPMI. The first two principal components explained 94.50% of the total variance, with Dimension 1 accounting for 83.00% and Dimension 2 for 11.50%. **(b)** Distribution of treatments based on combinations of compost (t/ha) and biol (%), including: 0-0, 5-0, 15-0, 0-5, 0-10, 5-5, 5-10, 15-5, and 15-10. Analysis was based on 405 samples ($n = 405$).

The PCA biplot (Figure 6a) illustrated strong positive relationships among FF, FDM, SSC, FPMI, FPC, FpH, and FCC, whereas TA showed an inverse relationship. Specifically, FF exhibited a strong positive correlation ($r = 0.97$) with Dimension 1, while TA was strongly negatively correlated ($r = -0.93$), highlighting their opposing contributions to fruit quality along the main component. For Dimension 2, FPC displayed a strong positive correlation ($r = 0.81$), further emphasizing its importance in color development at maturity.

In terms of treatment positioning within the PCA space, the conventional fertilization treatment (0-0) aligned closely with the TA vector, indicating that this treatment was associated with higher fruit acidity (Figure 6). In contrast, Treatment 15-10 showed the strongest association with FPC, reflecting the most intense pulp coloration—specifically yellow—indicative of greater ripeness and visual appeal. Similarly, 15-10 also aligned with higher values of FF and FDM, suggesting that this treatment promoted fruits with greater firmness and dry matter content, traits that are desirable for improving postharvest handling and commercial shelf-life. Furthermore, variables such as SSC, FPMI, and FpH increased progressively with treatments 5-5 through 15-10, indicating that higher compost and biol doses enhanced sweetness, maturity index, and overall flavor quality.

3.2. Fruit Quality Traits at Commercial Maturity

To assess fruit quality at the commercial maturity stage, a univariate analysis was performed on key postharvest attributes, including fruit firmness (FF), soluble solids content (SSC), titratable acidity (TA), fruit dehydration percentage (FD), pulp pH (FpH), and fruit pulp color (FPC). These variables are widely used by Peruvian mango export companies and serve as critical indicators for determining commercial maturity during postharvest handling [65,66].

Significant differences were observed in FF as a result of the interaction between compost and biol applications ($p < 0.05$; Figure 7a). Treatments 15-10, 15-5, 5-10, and

5-5 showed significantly higher firmness values compared to the control (0-0), with Treatment 15-10 exhibiting the highest mean firmness at 0.424 MPa (Figure S2).

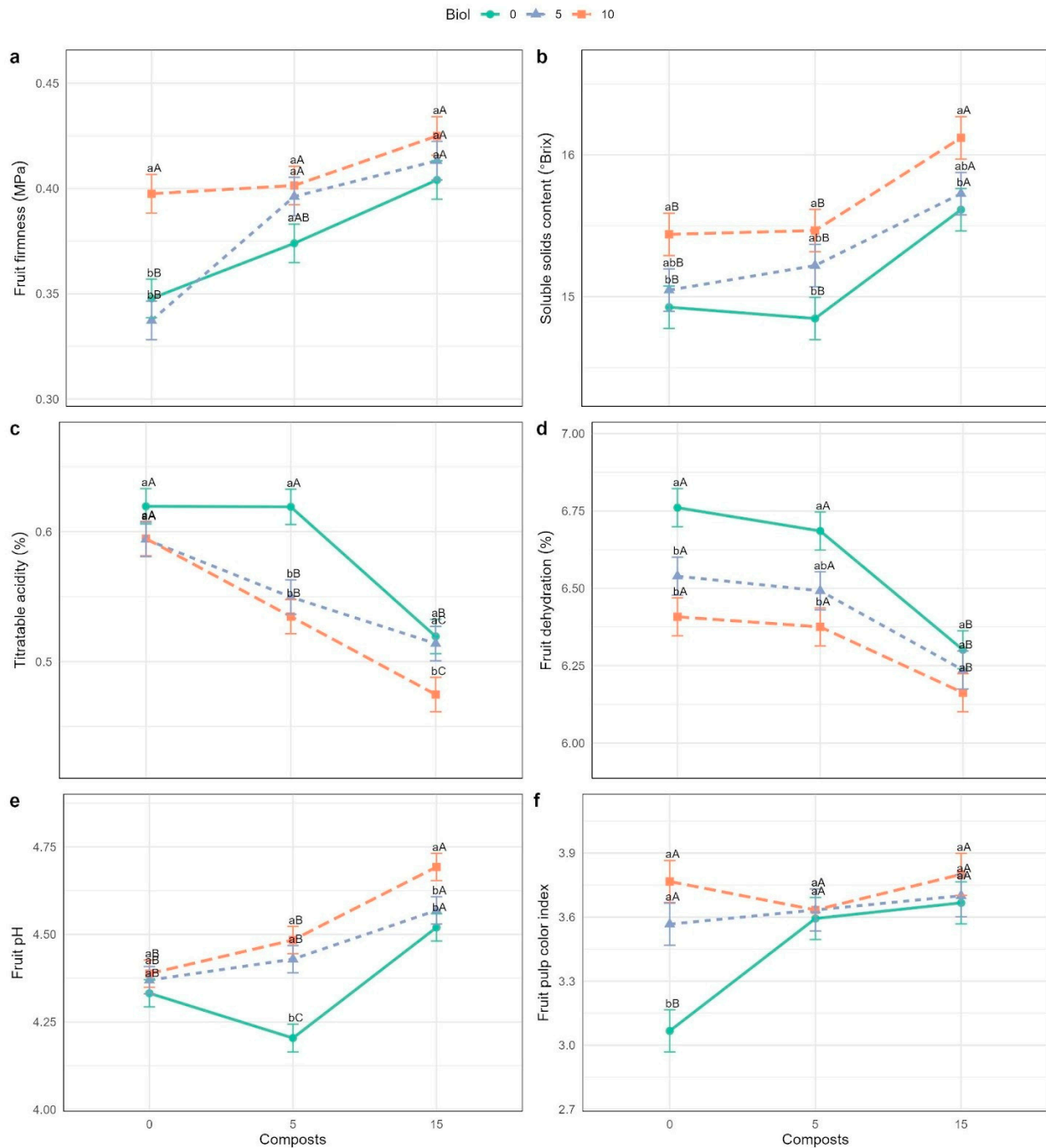


Figure 7. Quality characteristics of *Mangifera indica* L. var. 'Kent' fruit at commercial maturity. (a) FE, (b) SSC, (c) TA, (d) FD, (e) FpH, and (f) FPC. Different uppercase letters indicate statistically significant differences between compost treatments, and different lowercase letters indicate differences between biol treatments, based on Tukey's multiple comparison test at a significance level of $p < 0.05$. Error bars represent the standard error derived from post hoc analysis. Treatments represent combinations of compost (t/ha) and biol (%) as follows: 0-0, 5-0, 15-0, 0-5, 0-10, 5-5, 5-10, 15-5, and 15-10. The analysis was based on 135 fruit samples ($n = 135$).

For SSC, no significant interaction between compost and biol was detected ($p > 0.05$; Figure 7b). However, the 10% biol application consistently promoted higher °Brix values across all compost levels, and similarly, the 15 t/ha compost dose outperformed lower

compost doses across biol levels. Despite the absence of interaction, Treatment 15-10 achieved the highest SSC at 16.12 °Brix, significantly exceeding the control (0-0, Figure S2).

Regarding TA, a highly significant interaction effect was found ($p < 0.05$; Figure 7c). Treatment 15-10 produced the lowest acidity (0.47%), which was significantly lower than that of the control (0.62%; Figure S2). Compost at 15 t/ha resulted in consistently lower acidity across all biol levels, with all values statistically lower than the control.

For FD, no significant interaction was found ($p > 0.05$; Figure 7d), though differences were evident among individual treatment levels. In particular, treatments without biol 0% exhibited the highest dehydration, averaging 6.58%. Although the interaction was not significant, Treatment 15-10 had the lowest dehydration rate at 6.16%, statistically lower than the control (Figure S2).

A significant interaction was observed for FpH ($p < 0.05$; Figure 5e). Treatment 15-10 exhibited the highest mean pH value at 4.69, which was significantly greater than that of the control group (Figure S2).

Lastly, FPC also showed a highly significant interaction effect ($p < 0.05$; Figure 7f). The highest color intensity score was recorded for Treatment 15-10, with a value of 3.8 on the visual scale, corresponding to an intense orange hue. This treatment was significantly superior to the control, which had lower color development (Figure S2).

To further explore trait interrelationships and treatment effects across organic fertilizer dosages, a principal component analysis (PCA) and Pearson correlation analysis were conducted (Figure 8).

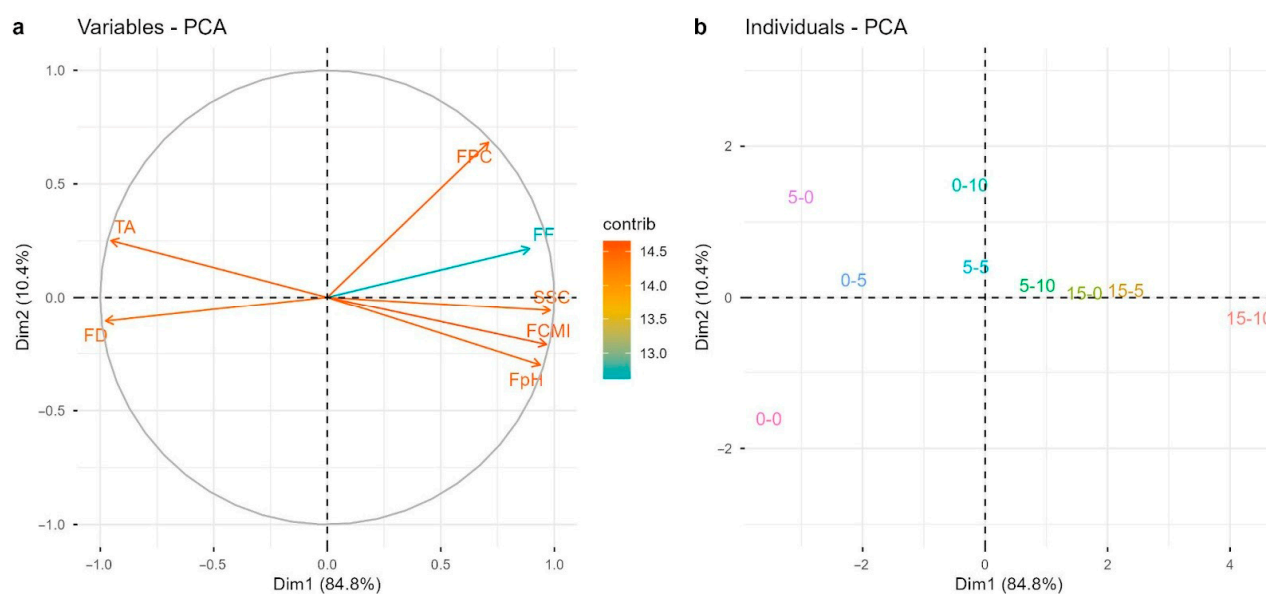


Figure 8. Principal Component Analysis (PCA) of quality traits for mango fruits at commercial maturity under compost and biol applications. (a) Distribution of physicochemical traits: FD, FF, FPC, SSC, FpH, TA, and FCMI. The first two principal components explained 95.2% of the total variance, with Dimension 1 accounting for 84.80% and Dimension 2 for 10.40%. (b) Distribution of treatments based on combinations of compost (t/ha) and biol (%), including: 0-0, 5-0, 15-0, 0-5, 0-10, 5-5, 5-10, 15-5, and 15-10. Analysis was based on 405 individual fruit measurements ($n = 135$).

To explore the interaction of fruit quality traits at commercial maturity, a principal component analysis (PCA) was performed (Figure 8). The first two dimensions explained a cumulative variance of 95.20%, with Dimension 1 accounting for 84.80% and Dimension 2 for 10.40% of the total variance (Figure 8a). Within Dimension 1, FD and SSC were the main contributors, with contributions of 16.06% and 16.24%, respectively, followed by FPC at 8.50%. In Dimension 2, FPC contributed the most (64.34%), while FD and SSC had minimal

influence, at 1.57% and 0.49%, respectively. Overall, the traits FD, SSC, FPC, TA, FpH, and FF made the most substantial contributions, reflecting their importance in defining commercial fruit maturity and market readiness.

The PCA biplot (Figure 8a). revealed strong positive correlations among SSC, FPC, FpH, and FF, indicating that these attributes tend to increase together. In contrast, FD and TA showed negative correlations with these variables. Specifically, SSC showed a strong positive correlation ($r = 0.98$) along Dimension 1, while FD had a strong negative correlation ($r = -0.98$), confirming their opposing influence on fruit quality. For Dimension 2, FPC showed a moderate positive correlation ($r = 0.68$), highlighting its relevance in explaining color variation at this maturity stage.

Treatment positioning within the PCA space reflected quality trait expression. Treatments 0-0 and 0-5 were aligned with the FD and TA vectors, indicating that fruits from these treatments had higher dehydration and acidity—traits that negatively affect commercial quality. High acidity can reduce fruit palatability, while greater dehydration is associated with weight loss and reduced firmness, as FF and FD vectors are oppositely oriented (Figure 8). Additionally, FPC was positioned opposite 0-0, suggesting that conventional fertilization results in less vibrant pulp coloration. Since orange and orange-yellow hues are associated with consumer-preferred ripe fruits, this indicates a lower visual appeal in 0-0 fruits. In contrast, treatments 5-5, 5-10, 15-5, and 15-10 clustered along the direction of FF, SSC, and FpH vectors, indicating that higher doses of compost and biol enhanced firmness, sweetness, and pH—traits that improve postharvest handling, consumer acceptance, and flavor quality.

4. Discussion

Mango is one of Peru's most important horticultural exports, with over 60% of national production destined for international markets such as the Netherlands, the United States, Spain, and the Republic of Korea [67]. Given the increasing demand for sustainable production practices, the use of organic fertilizers and bio-based molecules has gained attention for their potential to enhance yield and fruit quality [68,69]. This study evaluated the effects of soil- and foliar-applied organic fertilizers—compost and biol—on the physicochemical quality of 'Kent' mango fruit, using mature, eight-year-old trees under field conditions. Fruit quality was assessed at two critical developmental stages—physiological and commercial maturity—providing a comprehensive view of how organic inputs influence both pre- and postharvest performance.

The present study was not designed to establish strict nutrient equivalence between organic and synthetic fertilization treatments. Rather, the results should be interpreted as a comparison of fertilization strategies that differ in nutrient source, mode of application, and nutrient release dynamics. Organic inputs such as compost and biol provide a gradual and sustained nutrient supply, often associated with bioactive compounds, whereas conventional chemical fertilization ensures a more immediate nutrient availability through soil and foliar applications [70,71].

4.1. Mango Quality at Physiological Maturity

In this study, the quality of 'Kent' mango fruit at physiological maturity was assessed using key parameters, including fruit firmness (FF), peel fruit canopy color (FCC), pulp color (FPC), soluble solids content (SSC), titratable acidity (TA), and fruit dry matter percentage (FDM). Although no significant interaction was detected between compost and biol applications for FF and FCC (Figure 5a,b), treatments 15-10, 15-5, and 5-10 consistently yielded the highest values and were statistically superior to the conventional control (0-0) (Figure S1). These findings contrast with those of Marco Antonio et al. [72], who found

no significant differences in fruit firmness during physiological maturity when comparing mango trees fertilized with organic inputs, chemical fertilizers, or left unfertilized (Tukey $p < 0.05$). Nevertheless, all treatments in this study met the firmness criteria set by the Peruvian Technical Standard NTP 011.010:2020 for 'Kent' mango (1.078–1.569 MPa), suggesting compliance with quality standards regardless of treatment. The observed improvements in firmness may be attributed to the presence of potassium, calcium, and magnesium in the compost and biol treatments (Table 2), as these nutrients are known to promote homogalacturonan accumulation, pectin cross-linking, and phospholipid biosynthesis, all of which contribute to cell wall structure and firmness [73–75]. Firmer fruits are also associated with extended shelf-life and improved postharvest handling [65].

Regarding FCC, all treatments exceeded the >50% coverage threshold established by NTP 011.010:2020. Although the compost \times biol interaction was not statistically significant, treatments 15-10 through 5-5 resulted in significantly higher FCC values compared to 0-0 (Figure S1), suggesting that organic fertilizers enhance skin coloration. However, this finding diverges from Kanzaki et al. [76], who indicated that red coloration in mango peel is primarily influenced by genetic background and environmental factors such as sun exposure. Aesthetically, red coloration enhances consumer preference and marketability [76,77], and it is associated with the accumulation of anthocyanins—compounds that also improve resistance to chilling and pathogens [78–80].

Significant interactions between compost and biol were observed for FPC, SSC, and FDM (Figure 5c,d,f). Treatments 15-10, 15-5, and 5-10 were statistically superior to the control (0-0) (Figure S1). These results partially contradict Marco Antonio et al. [72], who found no significant differences in SSC among fruits treated with organic, conventional, or no fertilization. In contrast, Mahadeen [81] and Kilic et al. [82] reported increased soluble solids in organically grown fruits. In the present study, the high potassium content in treatments (Table 2) likely facilitated the translocation of photoassimilates and activation of starch-hydrolyzing enzymes, thus enhancing soluble solids accumulation [83–85]. All treatments surpassed the SSC threshold of $>7.0^\circ$ Brix required by NTP 011.010:2020.

Similarly, the dry matter content (FDM) was higher in treatments 15-10 through 5-5 compared to the control (Figure S1), consistent with the findings of Okba et al. [83], who reported elevated dry matter in organically fertilized fruits. Organic fertilizers may enhance vegetative growth and carbohydrate accumulation by stimulating microbial activity and nutrient cycling [86]. As dry matter content reflects carbohydrate accumulation during fruit development, it serves as an indirect indicator of maturity and internal quality [1,87,88].

For pulp color (FPC), only Treatment 15-10 was statistically superior to the control (Figure S1), although all treatments produced fruits with yellow pulp, as required by NTP 011.010:2020. This supports findings by Maldonado-Celis et al. [1], who noted that pulp and skin color are reliable indicators of mango maturity, though they vary by cultivar. Moreover, Lechaudel et al. [89] observed that fruit position within the canopy affects pulp color, with interior fruits exhibiting greener tones compared to exterior ones.

Titrateable acidity (TA) showed a significant interaction between compost and biol (Figure 5e), with treatments 15-10 through 5-5 producing significantly lower acidity than the control (Figure S1). These results are consistent with Abdel-Sattar et al. [90] and Kilic et al. [82], who reported reduced acidity in fruits grown with organic fertilizers. All treatments in this study met the acidity requirement of $<4.0\%$ set by NTP 011.010:2020. Lower acidity is favorable for flavor development, as it facilitates the conversion of organic acids into sugars, thereby increasing SSC and improving sweetness [90,91].

4.2. Mango Quality at Commercial Maturity

At the commercial maturity stage, mango undergoes critical physicochemical changes reflected in quality parameters such as fruit firmness (FF), soluble solids content (SSC), titratable acidity (TA), fruit dehydration percentage (FD), pH (FpH), and pulp color (FPC). In this study, SSC and FD showed no significant interaction between compost and biol (Figure 5b,d), yet treatments 15-10, 15-5, and 5-10 produced the highest values, significantly outperforming the control (0-0) (Figure S2). These findings are consistent with Marco Antonio et al. [72], who reported that organically fertilized mangoes at commercial maturity had higher SSC compared to those grown with chemical fertilizers or without fertilization. In our case, all treatments exceeded the 12 °Brix minimum required by Peruvian agro-exporters, highlighting the effectiveness of organic inputs.

This aligns with Sun et al. [92], who reported that sugar accumulation in fruit is influenced by fertilization, water availability, and the translocation of photoassimilates. Other authors have noted that SSC depends on cultivar and is largely the result of starch hydrolysis into simple sugars during ripening [93,94]. Postharvest handling practices—such as temperature control, ethylene application, and edible coatings—also affect SSC and fruit quality [26,95,96].

For FD, fruits from the control treatment (0-0) experienced significantly higher dehydration compared to those treated with 15-10, 15-5, 5-10 and 5-5 (Figure S2). Although no direct relationship has been established between organic fertilization and reduced dehydration, previous studies suggest that fruit weight loss during postharvest storage is influenced by peel thickness, transpiration rate, and respiration [97,98]. Additionally, climatic conditions and postharvest practices play a major role in fruit dehydration [25,99].

FF, FpH, and FPC all showed significant compost \times biol interaction effects (Figure 5a,c,e,f), with treatments 15-10, 15-5, and 5-10 performing best (Figure S2). This contrasts with findings by Marco Antonio et al. [72], who observed greater firmness in unfertilized fruits during commercial maturity. All treatments in our study, however, fell within the optimal firmness range (0.196–0.490 MPa) required for commercial export. The presence of calcium in all fertilized treatments may explain these results, given its known role in enzymatic activity, membrane stabilization, and delayed softening [64,93]. Firmness loss and dehydration are natural outcomes of the climacteric ripening process, and when well-managed, they indicate proper fruit maturation [95].

Increased FpH and improved pulp coloration observed in organically treated fruits may be explained by potassium and calcium-mediated enzymatic activity during ripening [100,101]. However, pulp color and pH are also influenced by storage time and postharvest handling [102,103]. Edible coatings containing wax or calcium salts can enhance color development and slow senescence [84,95].

TA values were lowest in treatments 15-10, 15-5, and 5-10, statistically below the control (0-0) (Figure S2). Although the exact mechanism is not fully clear, this reduction may be attributed to increases in SSC, as sugar accumulation is often accompanied by a decline in organic acid content [93]. All treatments met the export requirement of <1.0% acidity. Other studies suggest that acidity loss may also be due to cytosolic oxidation during fruit ripening [104,105]. Conversely, Haider et al. [106] reported that calcium can delay organic acid degradation, helping preserve acidity longer. Importantly, lower acidity improves mango palatability and is valued for processed products such as juices, jams, and desserts.

Although organic fertilizers demonstrated favorable effects on fruit quality at both physiological and commercial maturity, these improvements cannot be solely attributed to organic inputs. The control treatment—based on chemical fertilization—also supplied essential nutrients such as potassium, calcium, and magnesium. In addition, fruit quality

is influenced by cultivar, climatic conditions, phytosanitary status, and broader agronomic practices [107].

Nevertheless, organic fertilization contributes to long-term sustainability, in contrast to synthetic fertilizers. Compost and biol enhance soil physical, chemical, and biological properties [108], ensuring a more stable nutrient supply [109]. Key quality-related nutrients such as potassium, calcium, and magnesium are released gradually, promoting fruit development and postharvest quality [65,75,84]. Organic fertilization also supports circular agriculture through crop residue recycling and opens new market opportunities, given the growing global demand for organic products [110,111].

Although the present study provides valuable insights into sustainable mango production practices, future research should incorporate post-harvest soil analyses to more accurately quantify nutrient uptake by mango trees from both organic amendments and chemical fertilizers. Such analyses would contribute to a more comprehensive understanding of nutrient dynamics under different fertilization regimes. Furthermore, foliar nutrient assessments conducted before and after fertilization are recommended as a complementary diagnostic tool to evaluate the crop's nutritional status. This information would support the development of more precise and efficient organic fertilization strategies, tailored to the specific nutritional requirements of the mango plant.

This study was conducted during a single growing season, which limits the assessment of interannual and spatial variability. Nevertheless, as one of the first studies reported in Peru evaluating organic fertilization effects on mango fruit quality, it provides relevant baseline evidence, and future research should include multi-year and multi-site trials to validate and expand these findings. Additionally, the application of advanced technologies to assess internal and external fruit color is encouraged, as these approaches could enhance the accuracy of maturity assessment and carotenoid accumulation monitoring under organic management systems. Finally, future studies should incorporate bromatological analyses and comprehensive evaluations of fruit nutritional composition to more clearly elucidate the effects of organic fertilization strategies on mango fruit quality.

5. Conclusions

The combined application of compost and biol significantly improved fruit quality parameters of mango cv. 'Kent' at both physiological and commercial maturity stages. Our findings indicate that treatments involving 15 t/ha of compost combined with 5% and 10% biol, as well as 5 t/ha of compost with 10% biol, were the most effective. These treatments increased soluble solids content and dry matter accumulation at physiological maturity, while enhancing fruit firmness and pulp pH at commercial maturity. In addition, they exerted positive effects on internal pulp color and fruit acidity at both maturity stages. The combined use of compost and biol proved to be a viable and effective alternative for mango production systems, capable of meeting the fruit quality standards required by international markets while reducing reliance on synthetic fertilizers. These findings are particularly relevant for mango-producing regions such as Piura, Peru, where export-oriented production requires both high fruit quality and environmentally responsible management practices. Overall, organic fertilization emerges as a viable strategy to support high-quality fruit production, preserve soil health, and reduce dependency on synthetic inputs.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18052574/s1>. Figure S1: Quality traits for 'Kent' mango fruit at physiological maturity; Figure S2: Quality characteristics for mango fruit of the 'Kent' variety at commercial maturity; Supplementary File S1: ESM.

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