Effects of foliar biostimulant formulation and dose on fruit development and quality of sweet granadilla (*Passiflora ligularis* Juss.)

Efecto de la formulación y la dosis de bioestimulantes foliares sobre el desarrollo y la calidad del fruto de granadilla dulce (*Passiflora ligularis* Juss.)

Efeito da formulação e da dose de bioestimulantes foliares sobre o desenvolvimento e a qualidade dos frutos de maracujá-doce (*Passiflora ligularis* Juss.)

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Abstract

Plant biostimulants represent a promising alternative for improving production efficiency and fruit quality; however, limited information is available regarding their application to sweet granadilla (*Passiflora ligularis* Juss.). This study evaluated the effects of formulation and dose of two foliar biostimulants on sweet granadilla fruit development and quality under Andean conditions. Crop+Plus and Kelan Complex were applied at 0.0, 1.0, 1.5, and 2.0 mL·L⁻¹ in a randomised complete block design with split plots. Ten fruits were selected from each experimental unit, and their polar and equatorial diameters were measured at 0, 24, and 50 days after the first application. Total soluble solids, individual fruit weight, and weight-based estimated yield were determined at harvest. Greater polar and equatorial diameters were observed when Crop+Plus was applied, with significant effects of time and their interaction. At 50 days, Crop+Plus at 2.0 mL·L⁻¹ produced the largest polar and equatorial diameters, reaching 7.70 and 7.43 cm, respectively. Total soluble solids were affected by formulation and dose, whereas fruit weight was mainly influenced by dose. The most favourable results were obtained with Crop+Plus at 2.0 mL·L⁻¹, which produced 20.90 °Brix, a mean fruit weight of 120.0 g, and an estimated yield of 6,720 kg·ha⁻¹. In conclusion, Crop+Plus exerted the most consistent effects on fruit growth and quality, and 2.0 mL·L⁻¹ was the most promising concentration within the range evaluated.

Keywords: Andean crops, foliar application, fruit quality, plant biostimulants, total soluble solids.

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Resumen

Los bioestimulantes vegetales constituyen una alternativa para mejorar la eficiencia productiva y la calidad de los cultivos frutales; sin embargo, existe poca información sobre su aplicación en granadilla (*Passiflora ligularis* Juss.). El objetivo de este estudio fue evaluar los efectos de la formulación y la dosis de dos bioestimulantes foliares sobre el desarrollo y la calidad del fruto de granadilla en condiciones andinas. Se evaluaron Crop+Plus y Kelan Complex a concentraciones de 0,0; 1,0; 1,5 y 2,0 $mL \cdot L^{-1}$ mediante un diseño de bloques completos al azar con arreglo de parcelas divididas. En cada unidad experimental se seleccionaron diez frutos por planta, cuyos diámetros polar y ecuatorial se midieron a los 0, 24 y 50 días después de la primera aplicación. En la cosecha se determinó el contenido de sólidos solubles totales, el peso individual del fruto y el rendimiento estimado con base en el peso. Se observó una mayor expansión polar y ecuatorial en frutos tratados con Crop+Plus, con efectos significativos de la formulación, el tiempo y su interacción. A los 50 días, Crop+Plus a 2,0 $mL \cdot L^{-1}$ alcanzó los mayores diámetros polar y ecuatorial, con 7,70 y 7,43 cm, respectivamente. Los sólidos solubles totales fueron afectados por la formulación y la dosis, mientras que el peso del fruto estuvo determinado principalmente por la dosis, con los mejores resultados con la aplicación de Crop+Plus a 2,0 $mL \cdot L^{-1}$ (20,90 °Brix, frutos de 120,0 g y rendimiento estimado de 6.720 kg ha^{-1}). En conclusión, Crop+Plus mostró el efecto más consistente sobre el crecimiento y la calidad del fruto, y 2,0 $mL \cdot L^{-1}$ fue la concentración más prometedora dentro del intervalo evaluado.

Palabras clave: aplicación foliar, bioestimulantes vegetales, calidad del fruto, cultivos andinos, sólidos solubles.

Resumo

Os bioestimulantes vegetais constituem uma alternativa promissora para melhorar a eficiência produtiva e a qualidade dos frutos; entretanto, ainda são escassas as informações sobre sua aplicação no maracujá-doce (*Passiflora ligularis* Juss.). Este estudo teve como objetivo avaliar os efeitos da formulação e da dose de dois bioestimulantes foliares sobre o desenvolvimento e a qualidade dos frutos do maracujá-doce em condições andinas. Crop+Plus e Kelan Complex foram avaliados nas concentrações de 0,0; 1,0; 1,5 e 2,0 mL·L⁻¹, utilizando-se um delineamento em blocos completos casualizados, em esquema de parcelas subdivididas. Em cada unidade experimental, foram selecionados dez frutos, cujos diâmetros polar e equatorial foram medidos aos 0, 24 e 50 dias após a primeira aplicação. Na colheita, determinaram-se o conteúdo de sólidos solúveis totais, o peso individual dos frutos e a produtividade estimada com base no peso. Crop+Plus promoveu maior expansão polar e equatorial que Kelan Complex, com efeitos significativos da formulação, do tempo de avaliação e da interação entre ambos. Aos 50 dias, Crop+Plus a 2,0 mL·L⁻¹ apresentou os maiores diâmetros polar e equatorial, de 7,70 e 7,43 cm, respectivamente. Os sólidos solúveis totais foram influenciados pela formulação e pela dose, enquanto a massa dos frutos foi afetada principalmente pela dose. Os melhores resultados foram obtidos com Crop+Plus a 2,0 mL·L⁻¹: 20,90 °Brix, massa média de 120,0 g e produtividade estimada de 6.720 kg·ha⁻¹. Conclui-se que Crop+Plus apresentou os efeitos mais consistentes, sendo 2,0 mL·L⁻¹ a concentração mais promissora no intervalo avaliado.

Palavras-chave: aplicação foliar, bioestimulantes vegetais, culturas andinas, qualidade dos frutos, sólidos solúveis totais.

Introduction

Andean fruit crops are a key component of regional agrobiodiversity and have considerable potential to diversify global supplies of nutritious, high-value foods. Among them, the genus *Passiflora* stands out for its particular importance, comprising approximately 520 species, nearly 96 % of which occur in the Americas, with major diversity centres in tropical South America [1]. Although numerous species produce edible fruits, commercial cultivation is concentrated mainly on yellow passion fruit (*Passiflora edulis* f. *flavicarpa*), purple passion fruit (*P. edulis* f. *edulis*), banana passion fruit (*P. tripartita* var. *mollissima*) and sweet granadilla (*P. ligularis* Juss.) [2].

Sweet granadilla is native to the tropical Andes and is well adapted to mild highland environments, making it a distinctive crop within Andean fruit-production systems Among cultivated *Passiflora* species, sweet granadilla is regarded as one of the most economically important after *P. edulis* in Andean regions of Colombia, Peru and Ecuador where contributes to the income of small- and medium-scale farmers. Its commercial value is largely associated with its pleasant flavour, aromatic pulp, attractive appearance and suitability for fresh consumption. Recent characterisation of Ecuadorian germplasm has revealed substantial variation in fruit weight, polar and equatorial diameters, soluble-solids concentration and pulp characteristics, demonstrating both the productive potential of the species and the importance of agronomic practices capable of improving the consistency of marketable fruit quality [3].

The productivity and fruit quality of sweet granadilla are shaped by genotype and growing environment, while nutritional status and production cycle further modulate crop performance [3], [4]. Accordingly, stage-specific nutrient management is essential during reproductive development and fruit filling, when nutrient accumulation and export to developing fruits intensify [5], [6]. Mineral fertilisers remain important inputs in intensive fruit production; however, their inefficient or excessive use can reduce nutrient-use efficiency and increase greenhouse-gas emissions, soil acidification, nitrate leaching, surface-water contamination, and downstream eutrophication [7], [8]. These environmental costs highlight the need for complementary agronomic technologies that improve nutrient acquisition and crop performance without relying solely on increasing conventional fertiliser inputs [7].

Plant biostimulants have attracted increasing attention as complementary inputs for improving nutrient-use efficiency, maintaining crop productivity and strengthening resilience to abiotic stress, particularly under resource-limited or otherwise suboptimal growing conditions [9], [10]. According to the current regulatory framework, a plant biostimulant is defined as a product that stimulates plant nutrition independently of its nutrient content to improve nutrient-use efficiency, tolerance to abiotic stress, crop-quality traits, or nutrient availability in the soil or rhizosphere [11]. Major categories of plant biostimulants include humic and fulvic substances, seaweed and botanical extracts, protein hydrolysates and amino acids, chitosan-based compounds, beneficial fungi, and plant-growth-promoting bacteria (PGPB), representing both non-microbial and microbial biostimulants[12], [13]. When applied to foliage, biostimulants may interact directly with leaf tissues and influence nutrient assimilation, photosynthetic activity, hormonal signalling, antioxidant metabolism and assimilate partitioning [14], [15]. Nevertheless, their effectiveness is not universal and depends on the biological origin and composition of the formulation, application method, concentration, crop species, developmental stage and environmental conditions. A meta-analysis of open-field experiments reported an average yield benefit of 17.9 %, but also demonstrated marked variability among crops, application strategies, soils and climatic regions [16].

Evidence regarding the use of biostimulants in *Passiflora* crops has focused on *P. edulis* rather than sweet granadilla. Biostimulant treatments have been associated with the activation of defence-related and phytohormone-associated genes in passion fruit plants, indicating that these products may regulate physiological pathways beyond their effects on mineral nutrition [17]. Seaweed-derived biostimulants have also shown some capacity to mitigate physiological disturbances caused by salinity in purple passion fruit, although the magnitude of the response depended on plant and management conditions [18]. More recently, a field study using a composite biostimulant based on humic substances and plant-growth-promoting bacteria increased passion-fruit yield by approximately 50 %; however, soluble-solids concentration, acidity and juice pH were not significantly altered, demonstrating that greater yield does not necessarily correspond to improved fruit quality [19].

Despite these advances, evidence concerning the response of *P. ligularis* to foliar biostimulants remains limited, particularly with respect to dose-dependent changes in fruit development, maturation, physicochemical quality and yield. Moreover, direct comparisons between commercial formulations are needed because differences in their composition may produce contrasting responses even when they are applied at equivalent concentrations. Accordingly, the present study evaluated the dose-dependent effects of two foliar biostimulants on petiole and fruit development, time to harvest, fruit weight, total soluble-solids concentration and estimated yield of established sweet granadilla plants under Andean field conditions. It was hypothesised that both biostimulant formulation and application dose would influence the magnitude of the agronomic response. This objective reflects the treatments and response variables described in the original thesis experiment.

Materials and methods

Study site and environmental conditions

The field experiment was conducted in an established commercial orchard located in San Pedro de Pelileo Canton, Tungurahua Province, in the central Ecuadorian Andes. The experimental site was situated at approximately 2,183 m above sea level (1°18'28.12"S 78°31'28.56"W).

The study area has a temperate Andean climate, with temperatures ranging from 8 to 20 °C throughout the year. Irrigation water was supplied through the Shushuri irrigation canal. Except for the experimental foliar treatments, irrigation and routine orchard-management practices were applied uniformly across all experimental plots.

Plant material and biostimulant formulations

The trial was established in a two-year-old sweet granadilla orchard, including plants of comparable vigour and reproductive development.

Two commercial foliar biostimulants were evaluated: Crop+Plus and Kelan Complex. Crop+Plus is described commercially as a soluble formulation containing metabolites derived from microbial fermentation and seaweed extracts, with glycine betaine, carboxylic acids, carbohydrates and amino acids among its declared constituents. Kelan Complex is an amino-acid-based formulation containing short-chain peptides, free amino acids and mineral nutrients (15 % free amino acids and 22 % total amino acids).

Experimental design and treatments

The experiment was arranged as a randomised complete block design with a split-plot treatment structure. Blocks were established along the slope of the field to account for potential variation associated with terrain inclination. Biostimulant formulation was assigned to the main plots, whereas application dose was assigned to the subplots.

Both biostimulants were evaluated at four concentrations (1.0; 1.5; and 2.0-mL L^{-1}). The experiment therefore comprised eight biostimulant-dose combinations, each replicated in three blocks, resulting in 24 experimental units. The 0.0 mL L^{-1} treatment served as the untreated control within each main plot.

Each experimental unit measured 5.8 × 8.75 m, corresponding to an area of 50.75 m^2. The total experimental area was approximately 1,225 m^2 and was divided into two main-plot areas of approximately 612.5 m^2 each. The small difference between the summed experimental-unit area and total field area was presumably associated with access paths or plot boundaries and should be confirmed from the original field layout.

Foliar application and trial management

Biostimulant solutions were applied to the foliage using a manually operated backpack sprayer. Applications were made at 15-day intervals. At the beginning of the experiment, recently set fruits with an approximate polar diameter of 5 cm were selected and labelled for repeated assessment.

The treatments were applied separately to the designated experimental units according to the randomisation scheme. Care was taken to prevent spray drift between adjacent subplots. All other agronomic practices were maintained consistently across treatments throughout the experimental period.

Sampling procedure

Within each experimental unit, ten productive plants were selected as sampling plants. One reproductive branch was identified on each plant, and one fruit per plant was labelled and monitored. Thus, ten fruits were assessed per experimental unit and 30 fruits were evaluated for each biostimulant-dose combination across the blocks. The experimental unit was the subplot, whereas plants and fruits represented subsamples within each experimental unit.

Fruit and petiole development were assessed non-destructively during the experiment considering the following response variables:

Fruit polar diameter: The distance between the basal and apical ends of each fruit was measured using a Vernier calliper and expressed in centimetres.

Fruit equatorial diameter: Fruit width at the widest equatorial position was measured using a Vernier calliper and expressed in centimetres.

Petiole length: The distance from the fruit base to the point of attachment with the supporting branch was measured using a flexible measuring tape or ruler. The term employed in the original methodology should be checked botanically, because this structure may correspond to the fruit peduncle rather than the leaf petiole.

Petiole or peduncle diameter: Diameter was measured approximately 1 cm from the fruit base using a Vernier calliper and expressed in millimetres.

Harvest maturity and fruit-quality assessment

Fruits were harvested when they reached commercial maturity, defined by the development of a uniform, intense yellow peel colour across the entire fruit surface. The number of days to harvest was calculated as the interval between the initial evaluation, when fruits had reached approximately 5 cm in polar diameter, and the date on which commercial maturity was attained.

At harvest, individual fruit weight was determined using a calibrated digital balance and expressed in grams. Total soluble solids were measured in juice extracted from each fruit using a handheld refractometer and expressed as °Brix.

Results

Effects on the polar and equatorial diameters of sweet granadilla fruit

Fruit polar diameter increased progressively throughout the evaluation period under both biostimulant formulations (Figure 1). At the initial assessment, fruits treated with Crop+Plus and Kelan Complex had an identical mean polar diameter of approximately 5.60 cm. By day 24 after the first application, values had increased to 6.46 and 6.15 cm, respectively, and the difference widened by day 50, reaching 7.02 and 6.35 cm. Over the evaluation period, polar diameter increased by 25.3 % with Crop+Plus and 13.4 % with Kelan Complex as compared to non-treated plants. Differences were supported by significant effects of evaluation time ($F_{2,32}$=43.07, P<0.001), biostimulant formulation ($F_{1,2}$=20.28, P=0.046), and the biostimulant × time interaction ($F_{2,32}$=3.97, P=0.029).

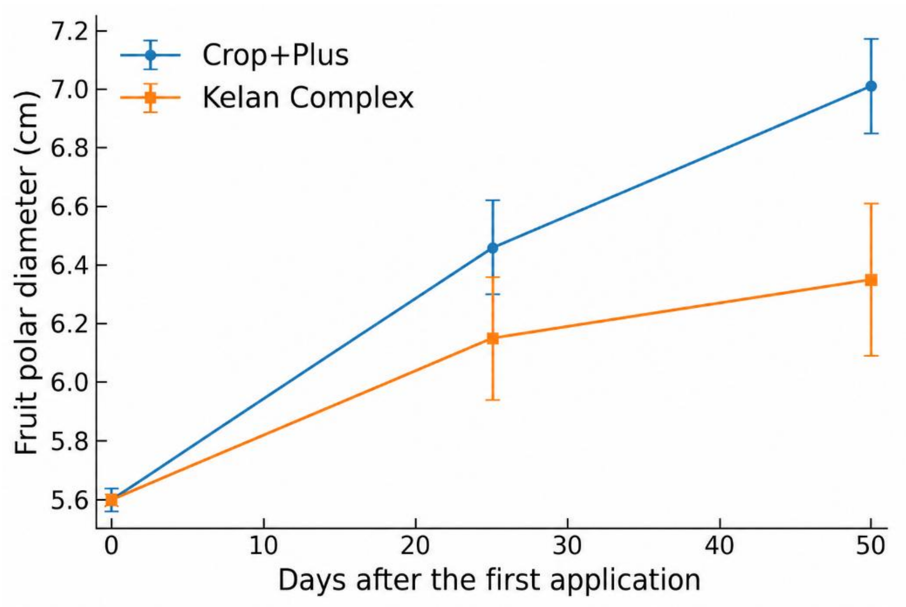

Figure 1. Effects of foliar application of Crop+Plus and Kelan Complex on the polar diameter of sweet granadilla fruit at 0, 24 and 50 days after the first application, averaged across application doses. Values represent means ± standard errors.

Despite this apparent high-dose response, the pattern was not strictly monotonic. Crop+Plus at 1.5 mL·L^{-1} produced a lower mean than both the control and the 1.0 mL·L^{-1} treatment, while Kelan Complex at 1.0 mL·L^{-1} was slightly below its control. The split-plot analysis detected a significant overall effect of biostimulant formulation ($F_{1,2}$=25.00, P=0.038), but the dose effect ($F_{3,12}$=2.70, P=0.092) and biostimulant × dose interaction did not show significant effects ($F_{3,12}$=0.70, P=0.571).

Between days 24 and 50, polar diameter increased by a further 0.56 cm under Crop+Plus but by only 0.20 cm under Kelan Complex. Therefore, the main difference between formulations appears to have occurred during the later stage of fruit growth.

At the final evaluation, fruit polar diameter varied according to both biostimulant formulation and nominal application dose (Figure 2). For Crop+Plus, mean polar diameter was 6.77 cm in the untreated control, 7.03 cm at 1.0 mL·L^{-1}, 6.57 cm at 1.5 mL·L^{-1} and 7.70 cm at 2.0 mL·L^{-1} with the highest dose producing a 13.8% increase relative to the Crop+Plus control. On the other hand, for Kelan Complex, the corresponding means were 6.03, 5.93, 6.50 and 6.93 cm in the untreated control, 1.0-, 1.5-, and 2.0-mL·L^{-1}, respectively. The 2.0 mL·L^{-1} treatment was approximately 14.9 % higher than its respective control. Thus, both formulations reached their greatest numerical polar diameter at the highest dose tested.

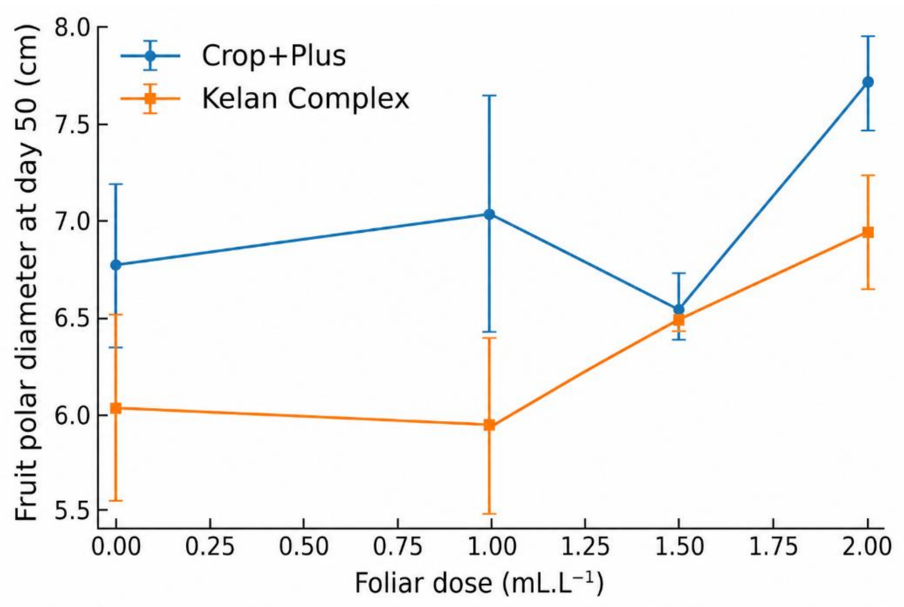

Figure 2. Effects of foliar application of Crop+Plus and Kelan Complex on the polar diameter development of sweet granadilla fruit at day 50 according to foliar dose. Values represent means ± standard errors.

Accordingly, these findings support the idea that Crop+Plus generally produced larger fruits than Kelan Complex at the final evaluation and, besides, the 2.0 mL L^{-1} dose was agronomically promising for both products; however, these current data do not demonstrate a statistically conclusive or uniformly increasing dose response.

Fruit equatorial diameter followed a pattern similar to that observed for polar diameter, but the separation between formulations was especially evident during the final evaluation (Figure 3). Initial values were nearly identical, averaging 5.03 cm and 5.00 cm for Crop+Plus and Kelan Complex, respectively. Consistently, Crop+Plus produced greater equatorial fruit diameters than Kelan Complex, exceeding it by 0.28 cm at day 24 (6.08 vs 5.80 cm) and by 0.59 cm at day 50 (6.75 vs 6.16 cm).

These values represented increases of approximately 34.1 % and 23.2 %, respectively, relative to the initial measurements. At day 50, the equatorial diameter of Crop+Plus-treated fruits was approximately 9.6 % greater than that of fruits treated with Kelan Complex. The repeated-measures analysis confirmed significant effects of time ($F_{2,32}$=105.06, P<0.001), biostimulant formulation ($F_{1,2}$=122.49, P=0.008), and the biostimulant × time interaction ($F_{2,32}$=3.87, P=0.031). Differences observed at days 24 and 50 provided strong evidence of the effect of treatment exposure rather than pre-existing variation in fruit size. Thus, Crop+Plus maintained a greater rate of transverse fruit expansion during the later developmental period.

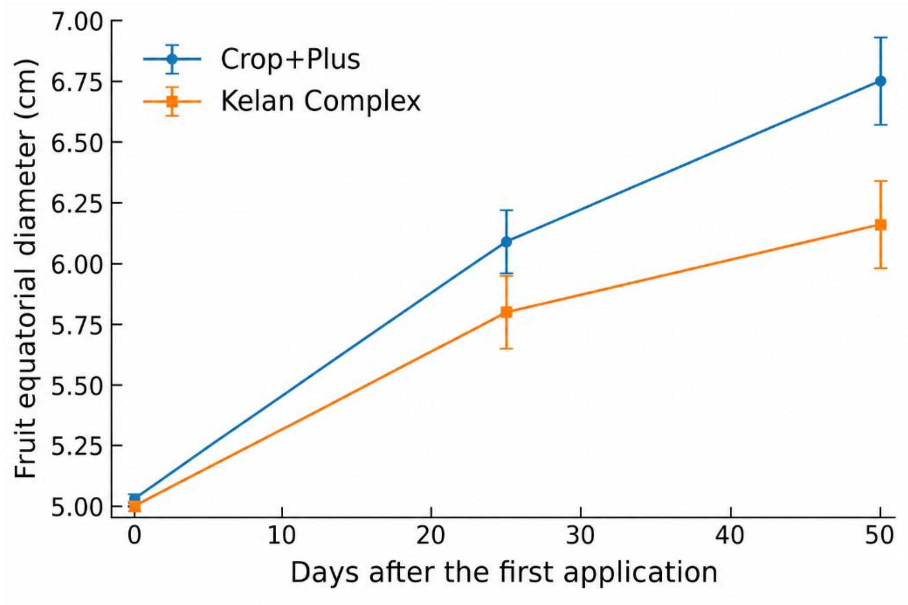

Figure 3. Effects of foliar application of Crop+Plus and Kelan Complex on the equatorial diameter of sweet granadilla fruit measured at 0, 24 and 50 days after the first application, averaged across application doses. Values represent means ± standard errors.

The simultaneous enhancement of both polar and equatorial diameters indicates that Crop+Plus promoted general fruit enlargement rather than elongation along only one axis. This fact is agronomically important because coordinated expansion in both dimensions is more likely to contribute to increased fruit calibre and fresh mass. Since fruit volume rises disproportionately as both diameters increase, even apparently moderate differences in linear dimensions may translate into appreciable differences in final fruit size. Nevertheless, this interpretation should ultimately be corroborated using individual fruit weight or directly estimated fruit volume.

The equatorial-diameter response displayed a more orderly increase across doses than the polar-diameter response, particularly for Kelan Complex (Figure 4). Under Crop+Plus, equatorial diameter averaged 6.37 cm in the control, 6.73 cm at 1.0 $mL \cdot L^{-1}$, 6.47 cm at 1.5 $mL \cdot L^{-1}$ and 7.43 cm at 2.0 $mL \cdot L^{-1}$. The highest dose increased equatorial diameter by approximately 16.8% relative to the control. Under Kelan Complex, mean values increased from 5.77 cm in the control to 6.07, 6.27 and 6.53 cm at 1.0, 1.5 and 2.0 $mL \cdot L^{-1}$, respectively. This corresponded to a 13.3 % increase at the highest dose compared with the untreated treatment, showing a more regular response across concentrations.

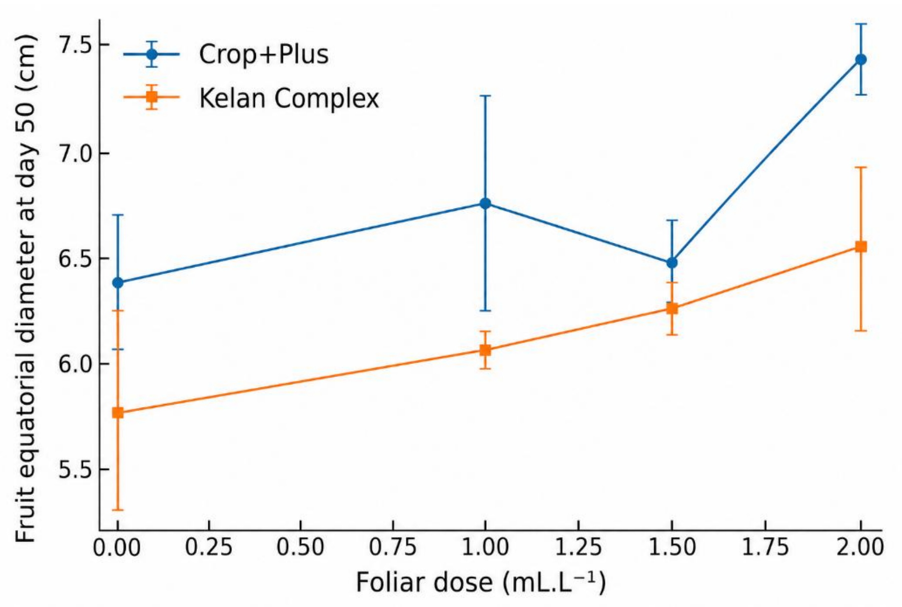

Figure 4. Effects of foliar application of Crop+Plus and Kelan Complex on the equatorial diameter of sweet granadilla fruit measured at day 50 according to foliar dose. Values represent means ± standard errors.

At day 50, the overall effect of biostimulant formulation was significant ($F_{1,2}$=41.66, P=0.023), whereas the dose effect ($F_{3,12}$=3.23, P=0.061) and the biostimulant × dose interaction was not significant ($F_{3,12}$=0.47, P=0.711), indicating that the pattern of response to increasing dose did not differ sufficiently between the two formulations, even though Crop+Plus consistently produced larger numerical values.

Again, the reduction observed with Crop+Plus at 1.5 mL·L^{-1} prevents the response from being described as strictly linear. By contrast, the gradual increase obtained with Kelan Complex suggests a more regular concentration-related response, although the absolute fruit diameter remained below that observed with Crop+Plus.

Effects on sweet granadilla fruit quality, weight, and estimated yield

Total soluble solids were significantly affected by both biostimulant formulation ($F_{1,16}$=19.38, P<0.001) and application dose ($F_{3,16}$=25.46, P<0.001), but no biostimulant × dose interaction was detected ($F_{3,16}$=3.03, P=0.060) (Table 1), indicating that the magnitude of the dose response tended to differ between formulations, although this pattern was not sufficiently strong to confirm distinct response curves.

Table 1. Effects of foliar biostimulant formulation and application dose on total soluble solids, fruit weight, and estimated yield of sweet granadilla (*Passiflora ligularis* Juss.)

Biostimulant	**Dose (mL·L⁻¹)**	**Total soluble solids (°Brix)**	**Fruit weight (g)**	**Estimated yield (kg·ha⁻¹)**
Crop+Plus	0.0	17.20 ± 1.001 bc	65.00 ± 5.000 bc	3640.0 bc
	1.0	17.60 ± 0.351 bc	74.30 ± 6.027 abc	4160.8 abc
	1.5	20.40 ± 0.815 a	103.30 ± 36.171 ab	5784.8 ab
	2.0	20.90 ± 0.569 a	120.00 ± 26.458 a	6720.0 a
Kelan Complex	0.0	16.40 ± 0.404 c	53.30 ± 2.556 c	2984.8 c
	1.0	17.50 ± 0.643 bc	70.00 ± 5.000 bc	3920.0 bc
	1.5	18.10 ± 0.436 bc	80.00 ± 8.660 abc	4480.0 abc
	2.0	19.00 ± 1.071 ab	101.67 ± 17.559 abc	5693.52 abc

Means followed by the same letter in a column did not differ according to Tukey's HSD test at P<0.05. Estimated yield was derived from mean fruit weight.

Crop+Plus at 1.5 and 2.0 mL·L⁻¹ produced the highest total soluble-solids concentrations, reaching 20.40 and 20.90 °Brix, respectively, indicating that increasing the Crop+Plus concentration from 1.5 to 2.0 mL·L⁻¹ did not result in a further statistically detectable increase in soluble solids. Relative to the untreated control, Crop+Plus increased total soluble solids by 18.6 % at 1.5 mL·L⁻¹ and by 21.5 % at 2.0 mL·L⁻¹, suggesting that the response became evident once the application concentration exceeded 1.0 mL·L⁻¹. Kelan Complex produced a more gradual numerical increase, from 16.40 °Brix in the untreated treatment to 19.00 °Brix at 2.0 mL·L⁻¹. The highest dose increased soluble solids by 15.9 % relative to its control and differed significantly from the untreated Kelan Complex treatment. However, it did not differ from the 1.0 or 1.5 mL·L⁻¹ doses. Besides, Crop+Plus applied at 1.5 mL·L⁻¹ produced significantly higher soluble solids than Kelan Complex, with values of 20.40 and 18.10 °Brix, respectively. The marginal interaction term (P=0.060) is consistent with the sharper increase observed for Crop+Plus between 1.0 and 1.5 mL·L⁻¹, compared with the more progressive response of Kelan Complex.

The increase in total soluble solids is agronomically relevant because this trait is closely associated with sweetness and consumer acceptance of fresh granadilla. Notably, the increases in °Brix occurred alongside increases in fruit weight, particularly at the higher Crop+Plus doses. This suggests that fruit enlargement was not accompanied by dilution of soluble constituents and may instead reflect enhanced import and accumulation of photoassimilates in the developing fruit.

In regard to effects on fruit weight, it was strongly affected by application dose ($F_{3,16}$=9.89, P<0.001), whereas the overall effect of biostimulant formulation ($F_{1,16}$=4.01, P=0.062) and the biostimulant × dose interaction was not significant ($F_{3,16}$=0.33, P=0.805), indicating that the dose-related increase in fruit weight followed a statistically similar pattern for both formulations.

Crop+Plus at 2.0 mL·L^{-1} produced the greatest mean fruit weight, reaching 120.00 g, significantly exceeding the Crop+Plus control in 84.6 %, the untreated Kelan Complex treatment and Kelan Complex at 1.0 mL·L^{-1}. Kelan Complex also showed a marked dose-related increase, from 53.30 g in the untreated treatment to 101.67 g at 2.0 mL·L^{-1} which represented an increase of 90.8 % relative to its control. Thus, although Crop+Plus produced the highest absolute fruit weight, both formulations were associated with substantially heavier fruits at the highest concentration. Despite these large numerical increases, Crop+Plus at 2.0 mL·L^{-1} did not differ significantly from Crop+Plus at 1.0 or 1.5 mL·L^{-1}, Kelan Complex at 1.5 mL·L^{-1} or Kelan Complex at 2.0 mL·L^{-1}.

The increase in fruit weight was consistent with the simultaneous enlargement of polar and equatorial diameters observed during fruit development, suggesting that heavier fruits resulted from general fruit expansion rather than growth restricted to a single dimension. Physiologically, this response may be associated with enhanced cell division, cell expansion, nutrient assimilation or assimilate allocation to reproductive sinks. However, further studies considering dry matter, pulp proportion, peel thickness and fruit water content should be carried out to determine whether the increase in fresh weight is associated to structural biomass accumulation, juice accumulation or changes in water status.

Finally, estimated weight-based yield showed increases from 3,640.0 to 6,720.0 kg·ha^{-1} under Crop+Plus and from 2,984.8 to 5,693.52 kg·ha^{-1} under Kelan Complex, with the highest numerical value obtained with Crop+Plus at 2.0 mL·L^{-1}, representing an increase of 84.6 % relative to its control, whereas Kelan Complex at the same dose produced a 90.8 % increase relative to its corresponding control. The current results demonstrated that increasing biostimulant dose was associated with heavier individual fruits and, consequently, with higher extrapolated production under a fixed fruit-density assumption.

Discussion

The present findings indicate that foliar biostimulant performance in sweet granadilla was strongly formulation-dependent. Crop+Plus produced a more sustained enhancement of fruit expansion than Kelan Complex, suggesting that differences in the composition and bioavailability of their active constituents influenced the magnitude of the plant response. From a physiological view, this sustained fruit expansion may reflect formulation-specific stimulation of nutrient uptake and assimilation, hormone-like signalling, cell division and expansion, and source-sink carbon allocation towards developing fruits [20], [21], [22]. Consistent with this interpretation, similar responses have been reported in kiwifruit, where post-fruit-set application of seaweed extract increased fruit length, diameter and fresh weight, indicating enhanced support for growth during the active expansion phase [23]. Moreover, biostimulant treatments in passion-fruit plants have been associated with the regulation of auxin-responsive and gibberellin-related pathways [17]. Nevertheless, because these physiological and molecular processes were not directly measured in the present study, they should be regarded as plausible explanations rather than demonstrated mechanisms. More broadly, commercial biostimulants may influence nutrient assimilation, photosynthetic performance, hormonal regulation and assimilate partitioning, although the magnitude and direction of these effects remain dependent on both formulation and crop species [17], [24].

The progressive differences between formulations during fruit development suggests that the treatment effects were cumulative. The simultaneous increases in polar and equatorial diameters, together with the higher fresh weight recorded at harvest, are consistent with coordinated whole-fruit enlargement rather than growth restricted to a single axis. Comparable responses have been reported in apricot and greenhouse tomato, in which biostimulant treatments simultaneously enhanced fruit dimensions, volume and fresh weight [25], [26]. In sweet granadilla, fruit dimensions are closely associated with commercial calibre and other morphological quality traits; however, these characteristics are also influenced by genotype, crop load and environmental conditions [3].

Although the highest concentration generally produced the most favourable response, the intermediate doses did not follow a consistently linear pattern. In particular, the reduction observed at the intermediate Crop+Plus dose should not be interpreted as physiological inhibition due to it may reflect spatial field heterogeneity, variation among sampled fruits or a genuinely non-linear dose response. Such variability is common in biostimulant trials because product efficacy depends on formulation composition, application concentration, crop developmental and phenological stage, treatment timing, and prevailing edaphoclimatic conditions [19]. Consistent with this interpretation, a global meta-analysis demonstrated substantial heterogeneity in field responses and showed that increasing the application dose does not necessarily lead to proportional agronomic benefits [16]. Accordingly, 2.0 $mL \cdot L^{-1}$ should be regarded as the most effective concentration within the tested range rather than as a confirmed optimum.

Moreover, as observed for polar diameter, the formulation-dependent response may reflect differences in the concentration, bioavailability, or interaction of the bioactive constituents present in the two commercial products. Evidence from Passiflora and other horticultural crops indicates that biostimulant responses are highly formulation-specific and may involve changes in nutrient acquisition, phytohormone regulation, photosynthetic performance, and source-sink relationships [17].

The concurrent increase in total soluble solids and fruit fresh weight is agronomically relevant because it suggests that fruit enlargement was not accompanied by dilution of the soluble fraction. Consistent with this interpretation, comparable responses have been reported in grapevine and woodland strawberry, where biostimulant treatments increased fruit mass together with total soluble solids, dry matter, or total sugar concentration [27], [28]. Such a combined response may reflect greater assimilate availability and modified carbohydrate partitioning towards developing fruits. Supporting this possibility, protein-hydrolysate biostimulants in tomato altered both total soluble solids and the expression of genes involved in sugar metabolism, indicating a potential role in regulating fruit carbohydrate accumulation [29].

Nevertheless, °Brix represents an estimate of the soluble fraction rather than a direct measurement of individual carbohydrates. Indeed, although foliar biostimulants applied to field-grown strawberry increased fruit weight and total soluble solids, no increases in glucose, fructose, or sucrose were observed, demonstrating that °Brix and sugar profiles are not necessarily associated [30]. The response of sweet granadilla contrasts with that reported for Passiflora edulis, in which biostimulant application increased productivity without significantly altering soluble solids or juice quality [19]. This fact confirms that biostimulant responses cannot be extrapolated across species or formulations and underscores the need for crop-specific validation under defined production conditions.

Conclusions

Foliar biostimulants influenced sweet granadilla fruit development and quality under Andean field conditions. Crop+Plus promoted greater polar and equatorial expansion than Kelan Complex, while higher doses increased total soluble solids and fruit weight. Crop+Plus at 2.0 $mL \cdot L^{-1}$ produced the largest fruits, greatest weight, and highest soluble-solids concentration, making it the most promising treatment evaluated. However, dimensional responses were not strictly monotonic, and yield was estimated from fruit weight using a fixed fruit-density assumption. Multi-season trials with direct marketable-yield measurements, physiological assessments, and economic analysis are needed before establishing an optimum dose or recommending commercial adoption.

Author contributions

AC-R: conceptualisation, preparation of the original manuscript, and data processing. **JM**: statistical analysis of the results, manuscript review, and final editorial review. **G.M-A.**: data processing and manuscript review.

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Ethics statement

The authors declare that this study was conducted in accordance with the ethical principles of scientific research integrity. The study did not involve experimentation with humans or animals, thereby ensuring compliance with data-protection and intellectual-property regulations.

Use of Artificial Intelligence

The authors declare that no generative artificial intelligence tools or AI-assisted technologies were used in the preparation or writing of this manuscript. All content, including the writing, analysis, and presentation of the results, was produced independently by the authors.

Data availability

The data used in this study are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declare that they have no financial, personal, or professional conflicts of interest.

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