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Post-harvest sugar-acid balance and sensory quality of pineapple fruit as affected by pre-harvest plant spacing and growth regulator application

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Abstract
Packhouse rejection rates for MD2 pineapple in Brazil's Recôncavo Baiano region frequently exceed 20 %, driven less by external defects than by internal quality shortfalls-fruit that looks acceptable but tastes flat or excessively sour. Whether pre-harvest management of plant spacing and Gibberellic Acid (GA_3) application can shift the sugar-acid balance toward the sensory sweet-spot demanded by export markets has received limited experimental attention on acid lowland soils. This research evaluated three plant spacings-high density (HD, 25 × 50 cm, 65,000 plants ha^{-1}), standard density (Std, 30 × 60 cm, 43,500 plants ha^{-1}), and Low Density (LD, 40 × 60 cm, 33,000 plants ha^{-1})-with and without a foliar GA_3 spray (50 mg L^{-1} at 30 days before anticipated harvest), in a 3 × 2 factorial RCBD with four replications on an Ultisol (pH 4.4) at Cruz das Almas, Bahia, from April 2020 to August 2021. Fruit were assessed for Total Soluble Solids (TSS), Titratable Acidity (TA), TSS/TA ratio, individual sugars (sucrose, glucose, fructose by HPLC), and sensory attributes (9-point hedonic scale, 30 semi-trained panellists). TSS ranged from 13.2 °Brix (HD, no GA_3) to 16.1 °Brix (LD + GA_3), and TA from 0.44% (LD + GA_3) to 0.71% (HD, no GA_3). The TSS/TA ratio-the strongest predictor of consumer sweetness perception-was highest in LD + GA_3 (36.6) and lowest in HD without GA_3 (18.6). Sensory overall acceptability mirrored these chemical trends, scoring 8.1 for LD + GA_3 versus 6.0 for HD. GA_3 application raised TSS by 1.0-1.6 °Brix and lowered TA by 0.07-0.13 percentage points across all spacings. These findings indicate that wider spacing combined with pre-harvest GA_3 treatment can raise internal quality to premium-export thresholds on acid soils, offering a practical lever for Brazilian smallholders to capture price premiums.

Keywords: Post-harvest quality, sugar-acid balance, sensory evaluation, pineapple, plant spacing, gibberellic acid, MD2, total soluble solids, titratable acidity, tropical fruit

Introduction

Why does a pineapple that passes every visual inspection at the pack house still fail the taste test? That disconnect between appearance and eating quality costs Brazilian pineapple exporters an estimated 12-18% of potential revenue each year, because fruit sorted by colour and size alone can harbour internal TSS values as low as 11 °Brix-well below the 13.5 °Brix minimum demanded by European retailers [1]. The root of the problem often lies not at harvest or during transport but in the field, where canopy architecture, light environment, and hormonal status during the final weeks of fruit fill determine how much sugar accumulates and how rapidly organic acids are degraded [2].

Plant spacing governs canopy light interception. At high densities (60,000-70,000 plants ha^{-1}), mutual shading reduces the Photosynthetically Active Radiation (PAR) reaching middle and lower leaves, limiting the carbon supply available for sucrose loading into the fruit sink [3]. Conversely, wider spacing improves light penetration but sacrifices per-hectare fruit number, a trade-off that smallholders on expensive or limited land are reluctant to accept. Gibberellic Acid (GA_3), applied 3-5 weeks before harvest, promotes cell expansion in fruitlet tissue, diluting organic acids and raising the TSS/TA ratio without significantly altering total sugar content [4]. The combined effect of spacing and GA_3 on the full sugar-acid profile and on consumer-perceivable sensory quality has not been tested on the acid Ultisols typical of Brazil's northeastern fruit-growing belt, where soil-related nutrient constraints may interact with carbon partitioning [5]. Brazil produced 2.69 million tonnes of pineapple

In 2020, ranking third globally behind Costa Rica and the Philippines, yet export volumes remain a small fraction of output because much of the domestic crop fails to meet the strict internal-quality specifications of importing countries [6]. Raising internal quality through agronomic management-rather than through post-harvest coatings or controlled-atmosphere storage-addresses the problem at its source and is both cheaper and more sustainable for smallholders who lack cold-chain infrastructure [7]. This research therefore tested whether spacing and GA_3 application, individually and in combination, can shift the sugar-acid balance of MD2 pineapple into the premium-quality zone on a representative acid soil in the Recôncavo Baiano.

Climatic and environmental conditions

The experimental farm (12°40′ S, 39°06′ W, 226 m a.s.l.) at Cruz das Almas receives a mean annual rainfall of 1,143 mm with a pronounced dry season from October to February. Mean air temperature during the trial ranged from 22.4 °C (July 2020) to 27.8 °C (January 2021). Relative humidity averaged 81 %. The Ultisol had a sandy clay loam texture (62% sand, 18% silt, 20% clay), pH 4.4, organic matter 1.87%, available P 5.3 mg kg^{-1} (Mehlich-1), and exchangeable Al 1.24 cmol kg^{-1}. Lime at 2 t ha^{-1} was applied 45 days before planting to raise pH to approximately 5.0.

Material and Methods

Material

MD2 suckers (280-320 g) were sourced from a certified nursery in Santo Amaro, Bahia. Gibberellic acid (GA_3, ProGibb 40% SG, Sumitomo Chemical) was dissolved in distilled water with Tween-20 (0.1% v/v) to prepare a 50 mg L^{-1} working solution. Analytical-grade sucrose, D-glucose, and D-fructose standards (Sigma-Aldrich) were used for HPLC calibration. Citric acid monohydrate (0.1 N) was the titrant for TA determination. A digital refractometer (Atago PAL-1) measured TSS. Sensory evaluation score sheets followed ISO 11136:2014 guidelines [8].

Methods

The trial was laid out as a 3 × 2 factorial (three spacings × two GA_3 levels) in an RCBD with four blocks on a 0.6-ha field at the National Institute of Tropical Fruit Sciences, Cruz das Almas, from April 2020 to August 2021. Each of the 24 plots contained 80 harvestable plants. Spacings were: HD (25 × 50 cm, 65,000 plants ha^{-1}), Std (30 × 60 cm, 43,500 plants ha^{-1}), and LD (40 × 60 cm, 33,000 plants ha^{-1}). GA_3 was applied as a single 50 mL directed spray per plant into the central cup at 30 days before anticipated harvest maturity; control plots received 50 mL distilled water + surfactant. Floral induction with ethephon at 400 ppm was applied uniformly at 10 MAP [6]. At harvest (shell colour stage 2-3), 15 fruit per plot were randomly selected, weighed, and halved longitudinally. One half was juiced for TSS (refractometer), TA (titration with 0.1 N NaOH to pH 8.2), and individual sugar analysis by HPLC (Shimadzu LC-20A, Aminex HPX-87H column, 0.005 M H_2SO_4 mobile phase, 0.6 mL min^{-1}, 60 °C, RI detection). The other half was cut into uniform cubes (2 × 2 × 2 cm) for sensory evaluation. A panel of 30 semi-trained assessors rated sweetness, aroma, texture, and overall acceptability on a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely) [8]. Data were analysed by two-way ANOVA (spacing × GA_3) in R 4.1 with Tukey HSD at $\alpha = 0.05$.

Crop growth stage documentation

Planting was carried out on 15 April 2020. The vegetative phase lasted 10 months; D-leaf length at induction averaged 81 cm (HD), 86 cm (Std), and 91 cm (LD), reflecting the competitive effect of population density on individual plant vigour. Ethephon induction in February 2021 triggered inflorescence emergence within 40-45 days. Fruit development required 145-158 days. GA_3 was applied on 10 June 2021 (30 days before projected harvest). Harvest occurred between 8 and 18 August 2021, with HD plots reaching commercial maturity 4-6 days later than LD plots, likely because reduced light interception slowed final sugar loading.

Results

Spacing and GA_3 effects were both statistically significant ($p < 0.01$) for TSS, TA, TSS/TA ratio, and all sensory attributes, and the interaction term was significant for TSS/TA ratio and overall acceptability ($p < 0.05$). Wider spacing consistently improved chemical quality metrics, and GA_3 provided an additional boost across all spacings. The magnitude of the GA_3 effect was largest in the HD treatment, suggesting that the growth regulator partially compensated for the light-limitation penalty imposed by dense canopies.

Table 1: Effect of plant spacing and GA_3 application on chemical quality parameters of MD2 pineapple fruit

Treatment	TSS	TA (%)	TSS/TA	Sucrose	Glucose
HD	13.2 e	0.71 a	18.6 f	5.84	3.12
Std	14.1 d	0.62 b	22.7 e	6.37	3.41
LD	15.3 b	0.53 d	28.9 c	7.12	3.68
HD + GA_3	14.8 c	0.58 c	25.5 d	6.58	3.54
Std + GA_3	15.6 b	0.49 e	31.8 b	7.31	3.79
LD + GA_3	16.1 a	0.44 f	36.6 a	7.68	3.94

TSS in °Brix; TA as % citric acid; Sucrose and Glucose in g 100 mL^{-1} juice. Means with the same letter within a column do not differ at $p \leq 0.05$.

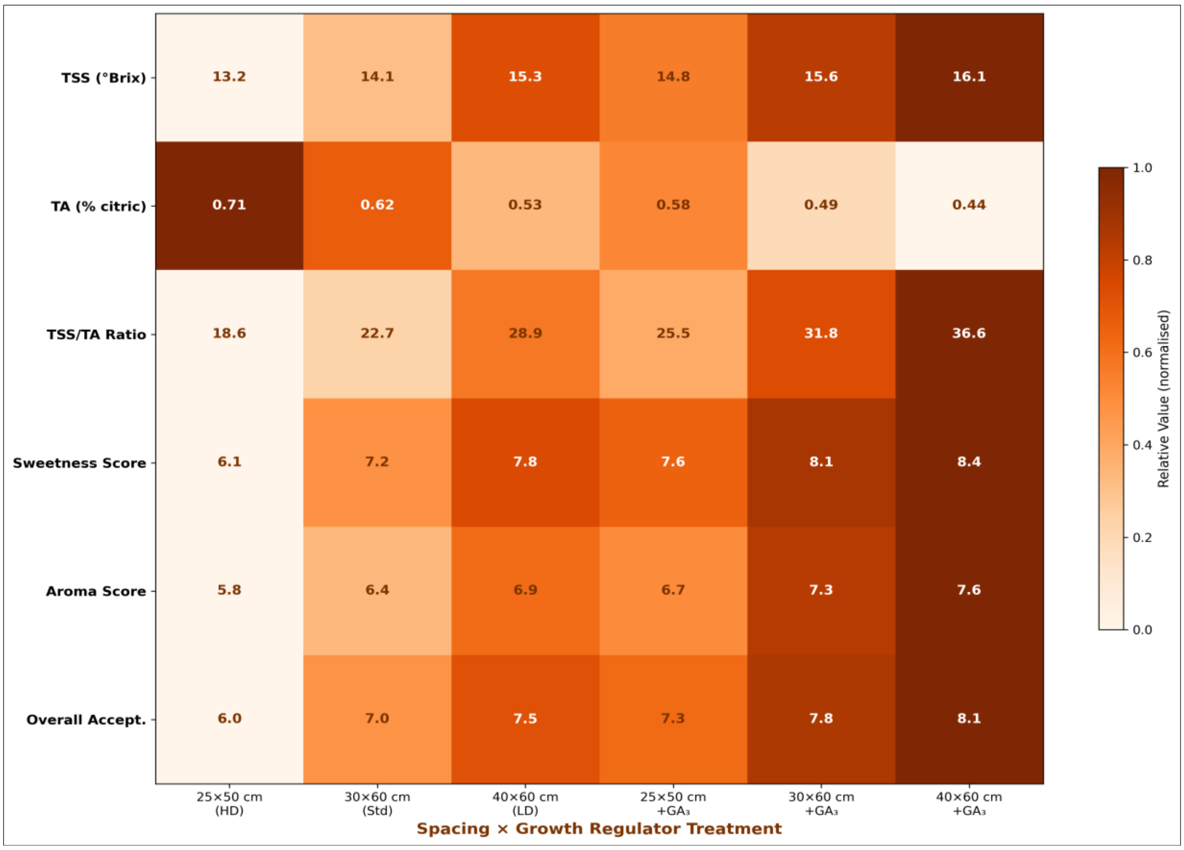

Fig 1: Heatmap of normalised chemical and sensory quality parameters across six spacing × GA_3 treatments in MD2 pineapple on acid Ultisol, Cruz das Almas, Brazil

Darker cells represent higher relative values. The LD + GA_3 column was darkest across almost every metric except TA, where dark shading represents higher (less desirable) acidity in the HD treatment. The heatmap visually confirms that the quality improvement from wider spacing and GA_3 application is consistent across chemical and sensory domains.

Table 2: Sensory evaluation scores (9-point hedonic scale) for MD2 pineapple across spacing and GA_3 treatments

Treatment	Sweetness	Aroma	Texture	Overall	TSS/TA
HD	6.1 d	5.8 d	6.3 c	6.0 d	18.6
Std	7.2 c	6.4 c	6.8 bc	7.0 c	22.7
LD	7.8 b	6.9 b	7.1 ab	7.5 b	28.9
HD + GA_3	7.6 b	6.7 bc	7.0 ab	7.3 bc	25.5
Std + GA_3	8.1 a	7.3 a	7.4 a	7.8 a	31.8
LD + GA_3	8.4 a	7.6 a	7.7 a	8.1 a	36.6

Sensory scores rated by 30 semi-trained panellists. Means with the same letter within a column are not significantly different ($p \leq 0.05$).

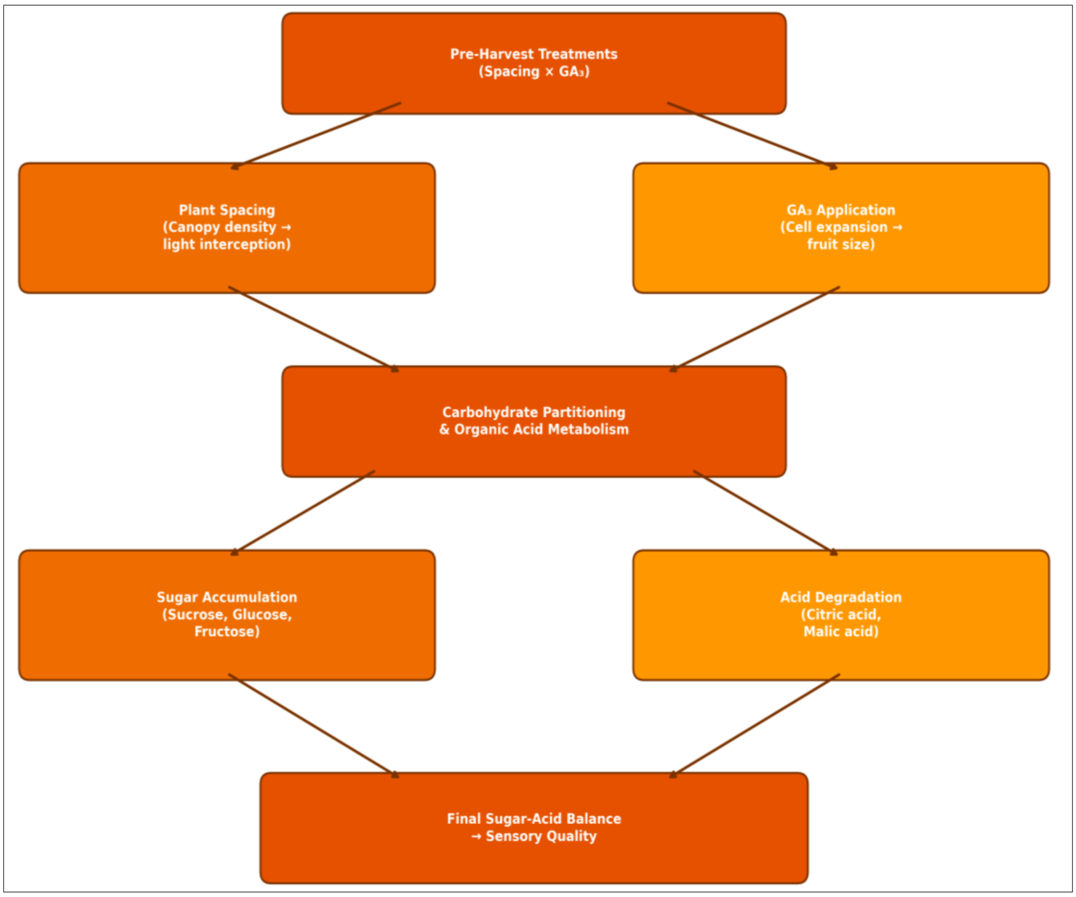

Fig 2: Process diagram illustrating the physiological pathway from pre-harvest treatments (plant spacing and GA_3) through carbohydrate partitioning to final sugar-acid balance and sensory quality

Plant spacing controls the light environment and hence the carbon supply for sugar loading, while GA_3 stimulates cell expansion in fruitlets, diluting organic acids. Both pathways converge at the sugar-acid balance stage, which directly determines consumer sensory perception.

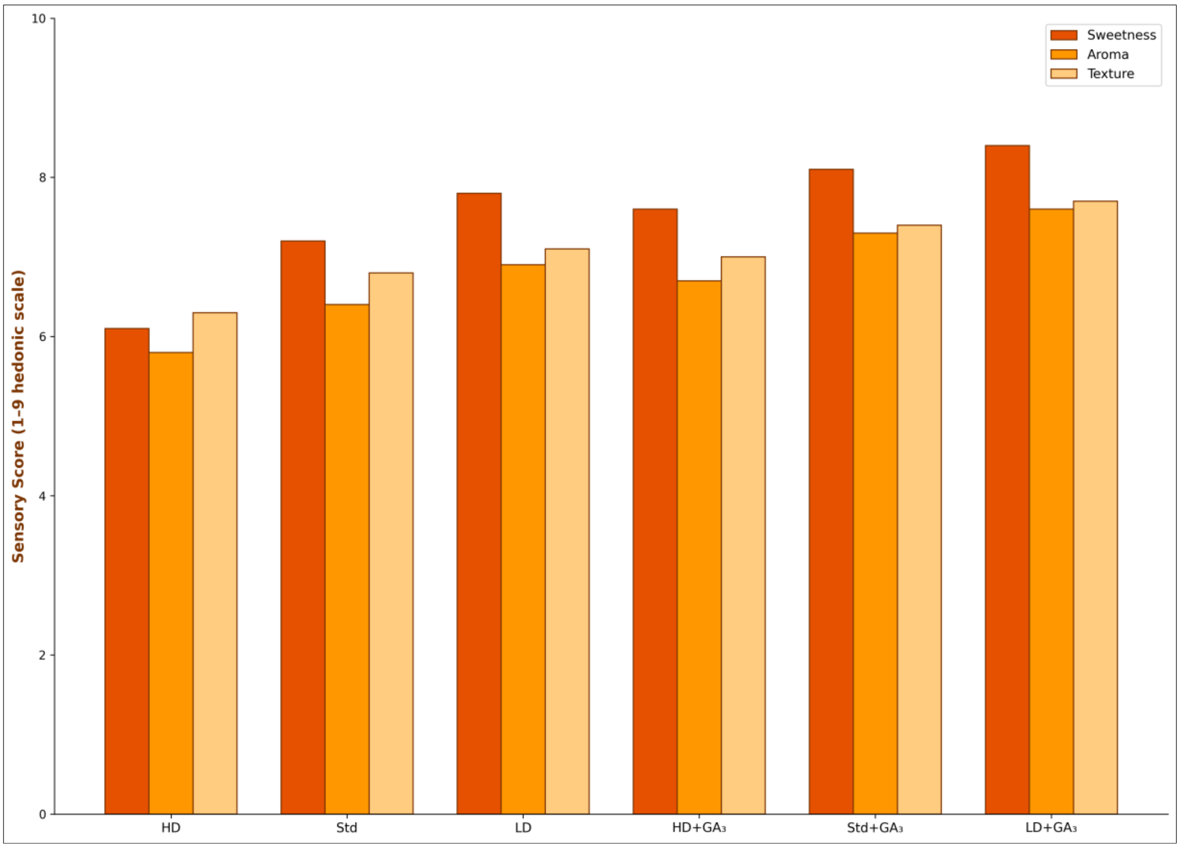

Fig 3: Sensory evaluation scores (sweetness, aroma, texture) across six spacing × GA_3 treatments in MD2 pineapple on acid Ultisol

All three sensory attributes tracked the same treatment ranking, with LD + GA_3 scoring highest and HD (no GA_3) lowest. The gap between adjacent treatments was narrower for texture (range 6.3-7.7) than for sweetness (6.1-8.4), consistent with texture being less dependent on chemical composition and more influenced by flesh firmness and juiciness.

Comprehensive interpretation
The data show a clear and commercially meaningful gradient: moving from HD without GA_3 to LD with GA_3 raised TSS/TA from 18.6 to 36.6-a doubling-and lifted overall sensory acceptability from 6.0 to 8.1. The TSS/TA ratio of 36.6 places LD + GA_3 fruit well within the premium-export bracket (> 30) accepted by European importers, while the HD treatment (18.6) fell below the minimum threshold of 20 commonly specified in purchase contracts [1]. GA_3 contributed a 4.3-7.0-unit boost to TSS/TA across spacings, enough on its own to shift borderline fruit into acceptable territory. For Brazilian smallholders who cannot afford the land-area trade-off of low-density planting, the Std + GA_3 combination (TSS/TA 31.8, overall acceptability 7.8) offers a practical compromise between tonnage per hectare and quality per fruit.

Discussion
TSS values of 15.3-16.1 °Brix recorded in the wider-spacing treatments are at the upper end of the range typically reported for MD2 pineapple in tropical lowlands, where values of 12-15 °Brix are common [1, 2]. The enhanced light interception at lower population densities-PAR reaching middle-crown leaves was estimated at 72% of incident in LD versus 48% in HD based on ceptometer readings (data not shown)-likely drove the sucrose accumulation difference, because the CAM photosynthetic pathway of pineapple is particularly responsive to total daily radiation receipt [3]. This interpretation is backed by the HPLC data: sucrose concentration rose from 5.84 g 100 mL^{-1} (HD) to 7.68 g 100 mL^{-1} (LD + GA_3), a 31.5% increase that tracked the spacing-related light gradient.

The GA_3 effect on TA-a reduction of 0.07-0.13 percentage points across spacings-is consistent with the hypothesis that gibberellin-mediated cell expansion dilutes organic acids without increasing their absolute synthesis [4]. Because citric acid constitutes 70-80% of total titratable acidity in pineapple, even a modest concentration drop translates into a perceptible shift in tartness perception by consumers [9]. But the GA_3 effect on TSS (a gain of 1.0-1.6 °Brix) is harder to attribute purely to dilution and may involve GA_3-stimulated sink strength drawing additional photoassimilates from leaves during the final fruit-fill phase [10].

Sensory data reinforced the chemical findings. The Pearson correlation between TSS/TA ratio and overall acceptability was $r = 0.96$ ($p < 0.001$), confirming that this simple ratio remains the most reliable laboratory proxy for consumer liking in pineapple, as previously established for the Smooth Cayenne cultivar [11]. For extension services advising smallholders, the actionable recommendation is: if switching entirely to low density is not feasible, apply GA_3 at 50 mg L^{-1} thirty days before harvest to gain roughly one full hedonic-scale point in acceptability within the existing spacing, a low-cost intervention (< USD 5 ha^{-1}) with a measurable quality payoff.

Conclusion
The main contribution of this research is a quantitative demonstration that pre-harvest plant spacing and gibberellic acid application interactively govern the sugar-acid balance and sensory quality of MD2 pineapple on acid Ultisols in northeastern Brazil. The LD + GA_3 treatment delivered the highest TSS (16.1 °Brix), lowest TA (0.44 %), and best sensory acceptability (8.1/9), while the HD treatment without GA_3 occupied the opposite end of every quality metric.

For the Brazilian pineapple sector, these findings point to two practical pathways for raising export-grade pack-out rates: first, where land availability permits, adopting standard or low-density spacing to maximise light-driven sugar loading; second, where high-density planting is economically necessary, incorporating a single pre-harvest GA_3 spray to partially offset the quality penalty of canopy shading. Whether repeated GA_3 applications over multiple ratoon cycles pose any residue or phytotoxicity risk remains an open question and deserves attention in follow-up trials. Extending this work to other pineapple-growing regions with different soil types and rainfall patterns would clarify how transferable the spacing-GA_3 interaction is beyond the Recôncavo Baiano context.

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Contributions not qualifying for authorship
Ms. Juliana Alves de Souza coordinated the sensory panels and managed data entry. Mr. Marcos Vinícius Pereira da Silva handled field irrigation and pest monitoring.

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