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The climactic conditions limit fruit production and quality in gulupa (*Passiflora edulis* Sims f. edulis) under integrated fertilization

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ABSTRACT

The gulupa (*Passiflora edulis* Sims *f. edulis*) is one of the main fruit trees that are part of Colombia's export supply. The objective of this research was to determine the effect of chemical fertilizers alone (control) or together with integrated fertilization (humic acids or vermicompost; two separate treatments), on the yield and quality of gulupa fruit during two consecutive production cycles in the Colombian Amazon foothills. The climatic conditions were monitored and the phenological state of the plant was related to the average temperature, relative humidity, precipitation, solar radiation, and vapor pressure deficit. The integrated fertilization with vermicompost offered better values in productive parameters (fresh weight, number of fruits and equatorial diameter) irrespective of the cycle considered, but the fruit quality attributes were similar irrespective of the fertilization treatment tested. The fluctuations of the climatic variables of precipitation, relative humidity and solar radiation in both cycles (the second rainiest and affected by the ENSO phenomenon) reduced the quality of the fruit (whole fruit firmness by 19%, dry matter and pulp total titratable acidity by 24%, total soluble solids by 8%, individual sugars by 49%, organic acids by 63% and antioxidant capacity by 67%) as well as the productive parameters during the second cycle. These results demonstrate the high degree of influence exerted by the climate on productive and fruit quality attributes that are decisive in the production and marketing of the fruit.

1. Introduction

The gulupa (*Pasiflora edulis* Sims *f. edulis*), also known as purple passion fruit, is a species native to southern Brazil, Paraguay and northern Argentina (Ocampo and Morales, 2012). Its fruit has a high interest in the Colombian productive sector as a result of the increase in its exports to the European market in the last decade (ANALDEX, 2020). Consumer demand for gulupa fruit is due to its organoleptic and nutritional characteristics, in addition to potential medicinal benefits (Fonseca et al., 2022). This boom has motivated the expansion of this species to other areas of the country. However, not all locations are appropriate for the development of these crops, given the specific requirements that must be met to obtain the best yields and maximize the genetic potential of the species (Pérez and Melgarejo, 2015). The location of the crop is essential for the development of commercial crops in a region. In other species the metabolites of the fruits, and fruit quality in general, can be considerably affected by the climatic conditions of the site and the variability of these between seasons, in addition to the interaction between the genotype and the environment (Fischer and Orduz-Rodríguez, 2012; Zeng et al., 2020). In the case of gulupa, various studies have established the presence of native accessions well adapted in various areas of the Colombian Andes (Castillo et al., 2020), as is the case of the Sibundoy valley region, which is located in the foothills Amazon in southern Colombia. The ideal conditions for the development of gulupa are altitudes between 1800 and 2400 masl, average temperatures between 15 and 20 °C, average relative humidity of 80%, and well-distributed average annual rainfall of 900 to 1200 mm (Jiménez et al., 2012).

Climate change has become a determining factor within agricultural production systems, given that the behavior of variables such as precipitation, temperature, solar radiation and carbon dioxide content end up causing significant impacts on plant physiology in stages prior to harvest, affecting the yields, quality and potential use of edible plant products (Ali et al., 2020). The climatic phenomena affects fruit quality and physiological behavior, which in turn influences the

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presence of secondary metabolites and nutritional components (Ali et al., 2021; Srivastava, 2019). For example, radiation increase phytochemicals compounds in apple (Mignard et al., 2021) or polyphenols in Chinese plum (Liu et al., 2022), or determined whole fruit firmness according to the position in the canopy (Lobos et al., 2018). Also, radiation enhanced desirable attributes such as litchi color (Purbey et al., 2019). On the other hand, higher precipitation records increased the anthocyanin content and an improvement in currant or pomegranate fruit quality, respectively (Boussaa et al., 2020; Pott et al., 2023). In strawberry, excessive precipitation caused a drop in pH, acidity and TSS (Agehara and Nunes, 2021), and in apple it caused the proliferation of *Botrytis* sp (Tuyet et al., 2012). The increase in relative humidity also favored the development of plant diseases in mandarines (Nawaz et al., 2021).

An important part of the costs of this crop is associated with the consumption of fertilizers and other inputs necessary to obtain excellent quality fruit and avoid triggering plant nutritional disorders for export (Aular et al., 2014). In the case of Passifloras, it has been found that the macroelements with the highest extraction are nitrogen, followed by K, Ca, P, Mg and S. In terms of microelements, iron is found, followed by B, Mn, Zn, Cu. and Mo (Primavesi and Malavolta, 1980). The use of organic fertilizers is an alternative to develop amendment plans that guarantee an appropriate, sufficient, and timely supply of nutrients to the plant. Integrated fertilizer management involves the judicious use of chemical and organic fertilizers, as well as resilient germplasm, along with an understanding of the skills to employ such practices in local conditions, with the aim of increasing the efficiency of agronomic fertilizer use applied and improve crop yields (Vanlauwe et al., 2010). In general, an inadequate supply of nutrients reduced the yield and quality of gulupa fruit, as shown by preharvest studies using foliar applications of boron (Quiroga-Ramos et al., 2018) or application of micronutrients (Fe, Mn and Zn) (Cárdenas-Pira et al., 2021). Also, postharvest studies of fruits grown under controlled fertilization showed that deficiencies negatively affected metabolic processes in plants. (Flechas et al., 2020).

In gulupa, studies under consecutive productive cycles of gulupa crop subjected to organic fertilization are non-existent. Therefore, the objective of this work was to determine the effect of integrated fertilization schemes on the gulupa fruit's quality at harvest, comparing two consecutive productive cycles with notable climatic differences.

2. Materials and methods

2.1. Study location

The study was carried out on a farm in the municipality of Sibundoy (1°12′41.425″ N and 76°54′32.654″ W —altitude 2260 m), in the Amazon foothills, in southern Colombia. The soil at the site was classified as Andisol, according to the US Soil Taxonomy (USDA, 2014). The climate of the region is of Cfb type, according to the Köppen classification, with a humid temperate climate and cool summers (IDEAM, 2014). The region has an average annual temperature of 15.6 °C, an average annual rainfall of 1529 mm, and an average relative humidity of 81% (Corpoamazonia et al., 2010).

2.2. Plant material

The gulupa (*Passiflora edulis* Sims *f. edulis*) is a plant susceptible to attack by fungi present in the soil, so a cholupa (*Passiflora maliformis* L.) rootstock was used to reduce damage.

The farm is certified by the Colombian Institute of Agriculture (ICA) to export fresh fruit, so its phytosanitary management and other procedures for the adequate support of the crop are adjusted within the regulations required by said entity for such aspects (ICA, 2022).

2.3. Fertilization treatments

The fertilization treatments were established according to the soil analyzes carried out by Agrosavia (Bogotá, Colombia) and the crop requirements (Marín and Rengifo, 2018) at each phenological stage, setting N as the limiting element. The results reported a soil with a strongly acid reaction (pH 5,44), a high percentage of organic matter, indicating adequate availability of nitrogen; phosphorus and sulfur elements are found in low quantities, as well as the exchange bases calcium, magnesium and potassium. The concentration Boron native content was low, while other microelements (iron, manganese and zinc) were not included in the fertilization plan because values were mean to high (Table S1). In treatment 1 (control) commercial chemical synthesis fertilizers (FSQ) described by (Jiménez et al., 2012) were used (Table 1). In treatment 2, a liquid fertilizer with humic and fulvic acids of 15.5% (w/v) each one (Chemie, 2019) was used in conjunction with FSQ. Treatment 3 included the use of vermicompost (Los Andes, 2020) together with FSQ. The proportion of organic fertilizers in the treatments was set according to how its composition allowed to integrate it with the FSQ to meet the needs of the crop. Later its application was divided into two portions, one at the beginning of growth and the other during the emergence of the inflorescence in each productive cycle (Table 2). The inputs were applied in a crescent above the plant considering the slope of the land, and efforts were made to bury them to reduce losses due to volatilization.

The experimental blocks (six block per crop productive cycle) comprised twelve plants, arranged with a spacing of 3.5 m between rows and 4.0 m between plants for a density of 714 plants per ha^{-2}. Plants (*Salvia corrugata*) were placed in the perimeter of the crop, as a living barrier and attractant of pollinators. The crop was established under a simple double-wire trellis system with semi-roof which is described by (Fischer and Miranda, 2021) as offering good results to reduce the impact of rain on the plants, especially on the flowers and the incidence of diseases. A drip irrigation system (a dripper of 4 L h-1 per plant) located 40 cm from the stem of the plant was used to guarantee the water supply according to the daily assessment of the water content in the soil (Rocha L, 2004). The seedlings were 3 months old at the time of transplantation, which was carried out in February 2020 and in July 2021 a renewal pruning was carried out, accepting recommendations from (Jiménez et al., 2012) to distinguish the second productive cycle. The plants were located on beds raised 20 cm to protect the stem and considering the slope of the land, bank terraces were arranged in order to reduce erosion processes of runoff.

2.4. Meteorological data

The meteorological data were measured through a METER brand meteorological station (Coltein, Bogotá) installed on the farm. Relative humidity (%), temperature (°C), precipitation (mm), solar radiation (μmol * m-^{2}s $^{-1}$) and vapor pressure deficit (VPD, in kPa) were recorded. The recording interval was 15 min. Full bloom was observed in the third week of September 2020 for the first cycle and the second week of November 2021 for the second cycle. The fruits were collected in the last week of April 2020 for the first cycle, and the first week of June 2022 for the second cycle. The records were established according to the phenological stages of the crop (Flórez et al., 2012b). From the above measurements, mean data on precipitation, relative humidity, photosynthetically active radiation, temperature (minimum and maximum), and mean vapor pressure deficit were calculated.

2.5. Fruit sampling

The first harvest of the fruit was made the year after transplant. The gulupa fruits were harvested at maturity stage four (Orjuela-Baquero et al., 2011), which corresponds to purple fruits between 70% and 80%

Table 1
Fertilization monthly plans according to phenological stages of the gulupa crop (Dose per plant kg ha^{-1}).

Time (month)	Phenological stage	Treatment 1		Treatment 2		Treatment 3	
		Product	Dose	Product	Dose	Product	Dose
0	Shoot formation	10 20 20	37.5 kg	Vermicompost[z]	350 kg	Humus[x]	3.5 L
						10 20 20	37.5 kg
		Bórax	3 kg	Urea	22 kg	Bórax	3 kg
1	Longitudinal stem growth	10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5,7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum[y]	7,1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7,1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
2	Vegetative development	10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
3		10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
4		10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
5		10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
6	Flower bud emergence	10 20 20	11.4 kg	Vermicompost	350 kg	Humus	3.5 L
		Urea	5 kg				
		KCl	5.7 kg			10 20 20	37.5 kg
		Gypsum	7.1 kg				
		Mg Sulphate	7.1 kg	Urea	22 kg	Bórax	3 kg
7	Bloom	10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
8	Fruit development	10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
9	Maturation	10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg
10	Senescence (Harvest)	10 20 20	11.4 kg	10 20 20	11.4 kg	10 20 20	11.4 kg
		Urea	5 kg	Urea	5 kg	Urea	5 kg
		KCl	5.7 kg	KCl	5.7 kg	KCl	5.7 kg
		Gypsum	7.1 kg	Gypsum	7.1 kg	Gypsum	7.1 kg
		Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg	Mg Sulphate	7.1 kg

[z] Vermicompost. Product of composting using various worms to create a heterogeneous mixture of decomposing vegetable or food waste, bedding materials, and vermicast.

[y] Gypsum. Is a natural hydrated calcium sulfate ($CaSO_4$ $2H_2O$), used to treat sodic soils. Symptoms of sodic soils are waterlogging, increased runoff, poor water storage, surface crusting, and problems with cultivation and erosion. Sodium causes swelling and dispersion of clay. The clay particles may then move through the soil, clogging pores and reducing infiltration and drainage. The calcium from gypsum displaces the sodium which can then be leached deeper into the soil.

[x] Humus. It is a liquid organic amendment that provides a high concentration of humic acids and fulvic acids.

of their surface. The fruits were selected according to their appearance and physical characteristics (homogeneous color, size, without bruises and wrinkles). The harvest was carried out during the production peaks of each cycle (April-2021 and June-2022), collecting 12 fruits per plant within each block or repetition. The fruits were collected from three central plants seeking to avoid the edge effect.

At the time of harvest, the equatorial and longitudinal diameter of the fruit (mm) was recorded along with the weight of the fresh fruit (g). The number of fruits was recorded only for the plants that were selected, keeping the record during the two production periods. After harvest, the fruit was individually protected with Kraft paper to be stored in styrofoam refrigerators at a temperature of 12 °C, and then sent by airplane to the Science and Food Technology Institute

Table 2
Categorization of the phenological stages (PS) of the gulupa (*Passiflora edulis* Sims f. edulis) crop.

PS4	PS5	PS6	PS7	PS8	PS9
Vegetative development	Floral button	Flowering and anthesis	Fruit development	Fruit Ripening	Senescence (harvest)

Postharvest Laboratory, ICTA at National University (Bogota), where they were stored in refrigeration at 8 ± 2 °C until processing (approximately 48 h), a situation that could affect the identification of the respiration rate peaks.

For the dry matter analysis, three fruits were used per replicate (n = 3) following the procedure of the literature (Hernández et al., 2007). For juice analysis, six fruits per replicate were cut in half to obtain the pulp with seeds using a sterile spoon according to the procedure described by the Colombian technical standard (NTC 5468: 2012) (ICONTEC, 2012). The juice was extracted from the pulp using a spoon and the seeds were separated from the juice using a manual strainer. The average juice yield was 42% (w/w). Two tubes of 15 mL of juice were stored at −80 °C for analysis of composition in sugars, organic acids, and antioxidant activity. The rest of the juice was used for the measurement of total titratable acidity or total soluble solids.

2.6. Quality attributes and respiration rate

For the determination of the quality attributes, three fruits were used per replicate (n = 3). Whole fruit firmness was evaluated in Newton (N) using a texture analyzer (CT3 Brookfield) with a 2 mm tip and a speed of 1 mm.s^{-1} (Osorio et al., 2011), making 2 opposite measurements of the equatorial zone of the fruit. Fruit color was determined with a Chroma Meter CR-400 Konica Minolta® colorimeter with illuminant D65 and a viewing angle of 0° in the CIE L*, a* and b* color space. The measurements were always taken at two opposite points of the equatorial zone of the fruits. Subsequently, the values of C* (chroma) and h° (hue angle or tone) were calculated (Hernández et al., 2007).

On the juice extracted from the pulp, the TSS content in the juice (°Brix) was determined using a portable digital refractometer (HI 96,801 Hanna Instruments) with temperature adjustment. The total titratable acidity -TTA- (mg of citric acid per 100 mL) and the pH of the juice were measured using a mini titrator HI 84,532–01 (Hanna Instruments) (Hernández et al., 2007).

Fruit juice obtained from the pulp was analyzed for organic acids (mg/100 g) and sugars (mg/100 g), according to (Hernández et al., 2007); carotenoids (mg / 100 g), according to (Biswas et al., 2011); and antioxidant capacity (μmol Trolox-Equivalent / 100 g juice), by the DPPH method according to (Grande-Tovar et al., 2019) and ABTS according to (Villa-Rodríguez et al., 2011).

To know the physiological behavior of the fruits subjected to integrated fertilization, their respiration rate was evaluated after harvest. Three fruits with similar maturity and weight were taken per replicate. Fruits were placed in a 2 L airtight chamber for 20 min at 14 °C. Carbon dioxide production was measured in triplicate using infrared CO_2 sensors (Vernier, Beaverton, OR, USA) coupled to a data capture system (Labquest,Vernier Software and Technology, Beaverton, OR, USA). The fruits weight was recorded daily to finally express the respiration rate in mL kg^{-1} h^{-1} of CO_2 (Balaguera-López et al., 2017). The average density of the fruit was determined (594 kg / m^3 following the method of (Pinzón et al., 2007), in order to calculate the headspace volume on which the CO_2 accumulated.

2.7. Statistical analysis

The physicochemical, biochemical and physiological variables of the fruit measured at harvest were subjected to the Kolmogorov-Smirnov and Levene tests to verify the assumptions of normality and homoscedasticity of the variances, respectively. A randomized block design with six repetitions was established. The linear model used for the randomized block design with bifactorial arrangement was as follows:

$$Y_{ijk(l)} = \mu + \alpha_i + \gamma_{\mathrm{j}} + (\alpha.\gamma)_{\mathrm{ij}} + \beta_{\mathrm{k}} + \varepsilon_{\mathrm{ijk(l)}}$$

In which $\mathrm{Y}_{\mathrm{ijk(l)}}$, represents the ʟ-ave sample of one dependent variable; μ, is the overall mean; α_{i}, is the treatment effect (i = 3); γ_{j}, is the cycle effect (j = 2); $\alpha.\gamma_{\mathrm{ij}}$ = is the interaction between treatment and cycle; B_{k}, is the effect of blocks and $\varepsilon_{\mathrm{ijk}}$ is the random error associated with the i-treatment, j-cycle, and k-block. The effect of the treatments together with the production cycles was evaluated by analysis of variance (ANOVA). A Tukey comparison test of means at 5% was applied to those variables that presented statistically significant differences. When the block was not significant, the ANOVA was performed again only with the main factors and interactions to increase the power of the analysis due to the increased number of replicates per significant factor. Comparison of respiration rate data between crop productive cycles in one integrated fertilization treatment was also made by univariate ANOVA. All analyzes were performed using the Statgraphics Centurion XVIII statistical software (Maryland, USA). Data are presented as mean values ± standard error (n = 6).

3. Results

3.1. Meteorological parameters

During the study period, a typical climatic variation was recorded, mainly represented by the increase in rainfall during the development of the second productive cycle (Fig. 1). All this could influence the development of the plant and the quality of the fruit, for which each parameter was studied in relation to the phenological stage of the plant (Table 2).

In the second cycle, precipitation increased significantly during the stages of flower bud, flowering and the first month of fruit development (Fig 1A). However, this variable had a valley effect for the same period of the first cycle. During later phenological stages, precipitation increased in both cycles.

The differences in relative humidity between cycles were noticeable in the flower bud, flowering and fruit development stages (PS5, PS6 and PS7), because RH was higher during the second cycle and only diminished during flowering in the first cycle (Fig 1B).

Solar radiation presented higher values during the first productive cycle (Fig. 1D), and an example of this was the peak that was recorded in that cycle between the flowering stage (PS6) and the first month of fruit development (PS7). There was also a decrease from PS7 in its third month to PS9 for the two cycles, observing a greater radiation received by the plant during this period in the first cycle.

The minimum temperature values fluctuated between 6 and 10 °C (at night and until sunrise) (Fig 1E). The maximum temperature values ranged between 23 and 30 °C (between 10:00 am and 3:00 pm) (Fig 1F). The records of the minimum temperatures followed a similar pattern for the two cycles. On the other hand, the highest records of maximum temperatures were attained in the first cycle, and particularly in the stages of flower bud, flowering and the first month of fruit development.

On the other hand, it was not possible to distinguish any influence of the vapor pressure deficit on any of the phenological stages analyzed during the two cycles (Fig 1C).

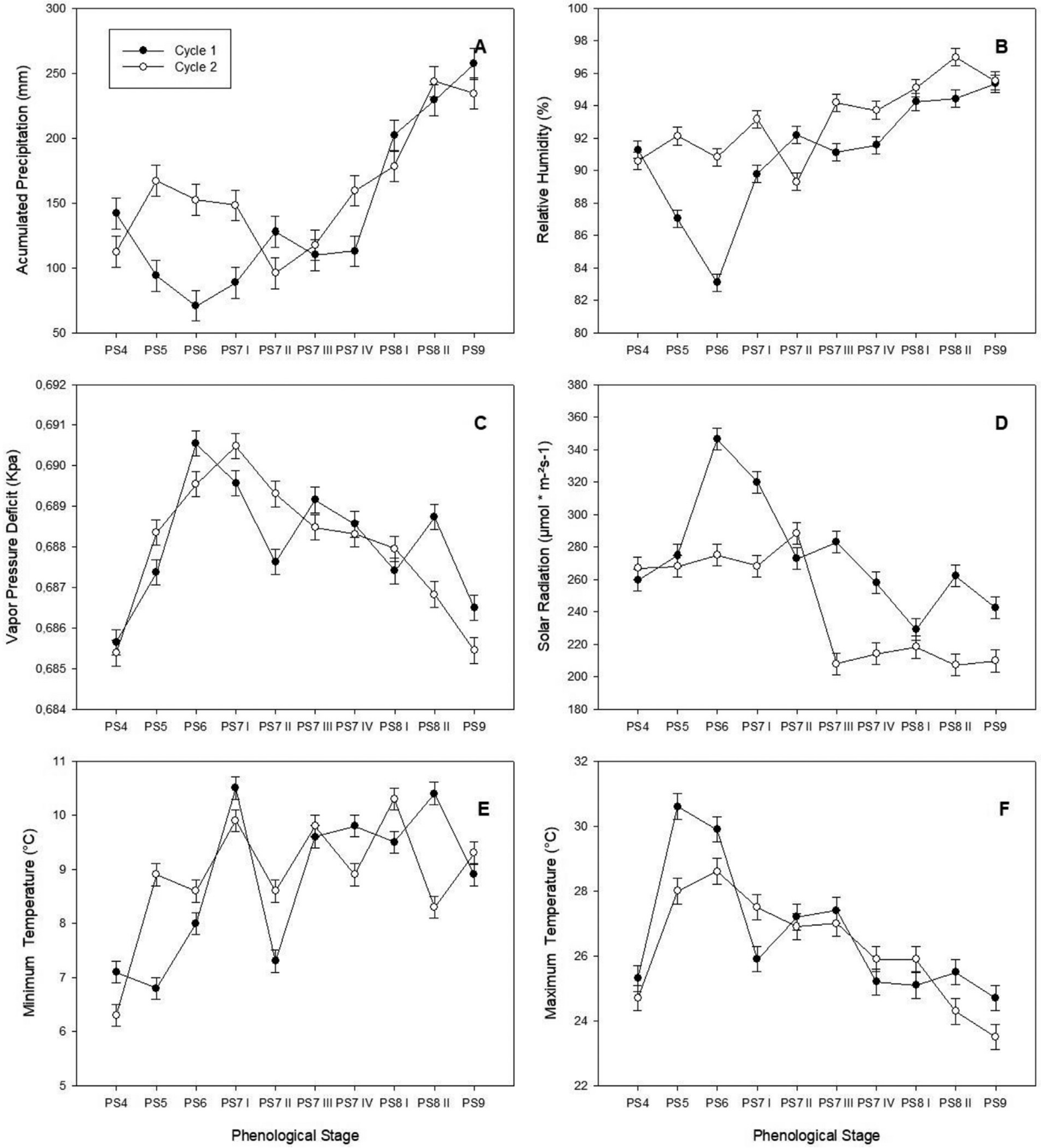

Fig. 1. Behavior of the climatic variables in relation to the phenological stages according to Table 2 of the gulupa crop during the two consecutive productive cycles: A) accumulated precipitation, B) relative humidity, C) vapor pressure deficit, D) solar radiation E) minimum temperature, F) maximum temperature (mean of the period ± SE).

3.2. Physical and production parameters of the fruit at harvest

The plants that developed during the first cycle obtained higher production, and fruits of greater weight and size, than those obtained during the second cycle. The crop cycle effect on these parameters was notably higher than that of fertilization and with significant differences (higher values in cycle 1, Table 3), with absence of cycle x fertilization interaction or block effect (Table S2; data not shown). Regarding the fertilization treatments, their effect could only be noticed in the parameters of fresh weight (FW), number of fruits (NF) and equatorial diameter (ED), obtaining the highest values with the use of vermicompost (Table 3). In fact, they were the main differences among the fertilization treatments of this experience.

3.3. Quality attributes at harvest

The first productive cycle presented fruits with higher levels of whole fruit firmness, total soluble solids, total titratable acidity and dry matter in relation to the second crop cycle. However, no differences were obtained in these quality attributes of the gulupa associated with the block, fertilization, or the interaction between fertilization and the crop cycle (Tables 4 and S2; data not shown).

Regarding the pH assessment, there were no significant differences among fertilization treatments and neither between cycles, with a mean value at harvest of 2.969 units (Tables 4 and S2).

The colorimetric coordinates L*C*h did not show significant differences among the fertilization treatments evaluated. However, the color was affected by productive cycles (Tables 5 and S2). Lower

Table 3
Average values of fresh weight, fruits per plant, equatorial and longitudinal diameter in gulupa for the main significant factors of the experiment: Fertilization[z] (three treatments) and crop productive cycle (1, 2).

Factors	Fresh weight (g)	Fruits per plant	Fruit equatorial diameter (mm)	Fruit longitudinal diameter (mm)
Treatment				
Treatment 1	43.57 ± 0.48 a[y]	104.42 ± 1.57 a	46.46 ± 0.52 a	53.10 ± 0.59 a
Treatment 2	44.42 ± 0.49 a	105.83 ± 1.18 ab	46.95 ± 0.53 ab	53.61 ± 0.61 a
Treatment 3	45.97 ± 0.51 b	106.66 ± 1.19 b	47.39 ± 0.53 b	53.84 ± 0.61 a
Crop cycle				
Cycle 1	48.55 ± 0.54 A	106.91 ± 1.21 A	51.51 ± 0.57 A	58.71 ± 0.65 A
Cycle 2	40.47 ± 0.45 B	104.20 ± 1.16 B	42.26 ± 0.47 B	48.34 ± 0.54 B

[z] Fertilization treatments were: 1, chemical fertilizers; 2, humic acids plus chemical fertilizers; 3, vermicompost plus chemical fertilizers. More information is provided in Table 1. [y] Values are mean±SE (standard error) from triplicate replications; Mean followed by different letters within the same factor in one column were significantly different according to Tukey's test ($p = 0.05$).

Table 4
Average values of whole fruit firmness, total soluble solids, total titratable acidity and dry matter in the gulupa fruit at harvest for the crop productive cycle factor significant.

Crop cycle	Whole fruit firmness (N)	TSS (°Brix)	TTA (% Citric Acid)	Dry matter (%w/w)
Cycle 1	13.34 ± 0.15 a[z]	12.38 ± 0.14 a	3.87 ± 0.04 a	27.90% ± 0.31 a
Cycle 2	10.86 ± 0.12 b	11.39 ± 0.13 b	2.93 ± 0.03 b	21.20% ± 0.24 b

[z] Values are mean±SE (standard error) from triplicate replications;
Mean followed by different letters within the same column were significant different, according to a Tukey's test ($p = 0.05$).

Table 5
Average values of the skin color indices variables L, C* and h° in the gulupa fruit at harvest for the crop productive cycle factor significant.

Crop cycle	L* (Lightness)	C* (Chroma)	h° (Hue angle)
Cycle 1	28.13 ± 0.31 b[z]	6.39 ± 0.07 b	48.27 ± 0.54 b
Cycle 2	26.40 ± 0.29 a	5.21 ± 0.06 a	38.62 ± 0.43 a

[z] Values are mean±SE (standard error) from triplicate replications; Mean followed by different letters within the same column were significantly different, according to a Tukey's test ($p = 0.05$).

Table 6
Average values of the content of individual sugar compounds (mg/100 g FW) content in the juice of the gulupa fruit at harvest for the crop productive cycle factor significant.

Crop cycle	Sucrose	Fructose	Glucose	Glycerol	Raffinose
Cycle 1	2324 ± 26a[z]	2198 ± 24a	1646 ± 18a	117 ± 1.3 a	228 ± 2.55 a
Cycle 2	1259 ± 14b	1093 ± 12b	1030 ± 11b	32 ± 0.3 b	134 ± 1.51 b

[z] Values are mean±SE (standard error) from triplicate replications; Mean followed by different letters within the same column were significantly different, according to a Tukey's test ($p = 0.05$).

Table 8
Antioxidant capacity (μmol Trolox-Equivalent/100 g of juice;) evaluated by two methods in the juice of the gulupa fruit at harvest for the crop productive cycle factor significant.

Crop cycle	DPPH	ABTS
Cycle 1	141.523 ± 1.58 a[z]	78.31 ± 0.87 a
Cycle 2	60.414 ± 0.67 b	17.75 ± 0.21 b

[z] Values are mean±SE (standard error) from triplicate replications;
Mean followed by different letters within the same column were significantly different, according to a Tukey's test ($p = 0.05$).

concentrations were also obtained for the second cycle in soluble sugars (Table 6), organic acids (Table 7) and antioxidant activity evaluated by two different methods (Table 8), again without significant effect of fertilization treatments or the interaction fertilization treatment x productive cycle (Table S2)

Sucrose was the predominant sugar in the juice of the gulupa, followed by fructose and glucose. In parallel, the same reduction in sugars behavior was observed in cycle 2 versus cycle 1 determined in the titration of acids, although not as pronounced. The reduction of the second cycle versus the first one in sucrose, fructose, glucose, glycerol and raffinose was 46%, 50%, 37%, 72% and 41%, respectively.

Citric acid was the main organic acid in gulupa, although the citric content decreased by one sixth in cycle 2 versus cycle 1. A similar trend was observed in malic, succinic, and ascorbic acids (reduction by 75%, 65%, and 28%, respectively, for the second cycle).

The antioxidant activity values of the DPPH method were higher than those obtained with the ABTS method. The levels of total antioxidant activity diminished in cycle 2 compared with cycle 1 and, this decrease was more pronounced in ABTS than in DPPH (Table 8).

The content of total carotenoids in the juice of the fruit at harvest was 3081 mg/100 g FW, with no differences observed in the factors analyzed (Table S2).

Table 7
Average values of citric, malic, succinic and ascorbic acid content in the juice of the gulupa fruit at harvest for the crop productive cycle factor significant.

Crop cycle	Citric Acid (mg/100 g FW)	Malic Acid (mg/100 g FW)	Succinic Acid (mg/100 g FW)	Ascorbic Acid (mg/100 g FW)
Cycle 1	3064.27 ± 34.31 a[z]	424.61 ± 4.75 a	213.72 ± 2.39 a	53.32 ± 0.61 a
Cycle 2	518.72 ± 5.81 b	106.05 ± 1.18 b	76.46 ± 0.85 b	38.53 ± 0.43 b

[z] Values are mean±SE (standard error) from triplicate replications. Mean followed by different letters within the same column were significantly different, according to a Tukey's test ($p = 0.05$).

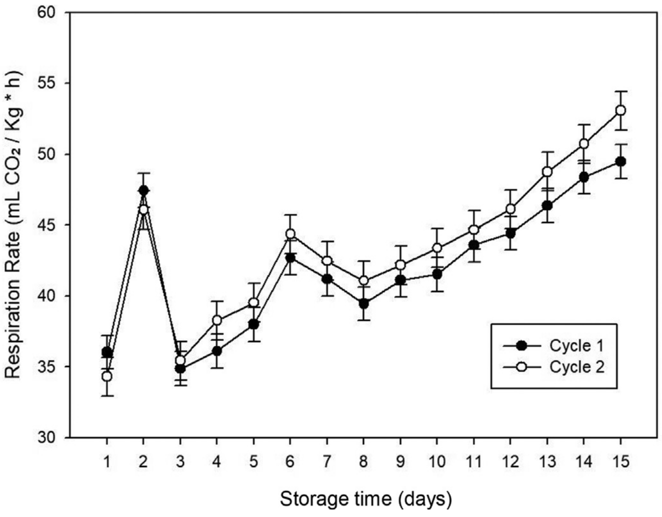

Fig. 2. Postharvest respiration rate at 14 °C of gulupa fruits harvested in two consecutive productive cycles that were previously cultivated under integrated fertilization (mean ± SE, $n = 6$).

Postharvest respiration rate

Regarding the respiration rate during postharvest, it was preliminarily established that there were no significant differences between the three fertilization treatments tested in the experimentation (data not shown). A respiratory peak in fruit grown under integrated fertilization was found on day 2 (4 days after harvest). After this event, another less pronounced peak appears again towards the sixth day of evaluation, to continue an upward behavior for the two productive cycles. The mean inter-cycle difference in mean respiration rate from day 6 was 1.3 mL kg^{-1} ·h^{-1} of CO_2 higher in the second cycle versus the first cycle (Fig. 2).

4. Discussion

Putting together our results revealed that most of the significant changes in gulupa were due to the productive cycles because of important differential climactic conditions, followed by the fertilization treatments, which generated changes only on the productive variables. The effect of meteorological conditions (temperature, solar radiation, altitude, rain, wind, and atmospheric composition) on fruit growth and maturity at harvest and in postharvest has also been outlined by several authors in other tropical and subtropical fruits (Fischer and Melgarejo, 2020; Restrepo-Diaz et al., 2020; Yahia et al., 2019). Here, we determined that this effect was particularly noticeable in certain phenological stages of the gulupa.

The precipitation showed a great variation during the development of our gulupa experiment (Fig. 1A).This behavior was a typical effect of the ENSO phenomenon (El Niño Southern Oscillation) that began from the second half of 2020 and is expected to last until the end of 2022, becoming the first triple episode of this phenomenon recorded in this century according to the World Meteorological Organization (WMO) (ONU, 2022). In tropical conditions, the temperature and the photoperiod are relatively uniform throughout the year and the climatological variable that has the greatest impact on growth, development and production is rainfall (Ramírez et al., 2021). Its bimodal distribution in the Andean region defines the volume, quantity and quality of fruits, as well as the times of flowering and harvest (Cleves-Leguizamo et al., 2021). Therefore, it could be deduced that the precipitation peaks recorded during the second cycle could be one of the main climatic causes of the alterations suffered by the fruits in that period. In particular, the color of the fruit would have been affected by the lower interception of light due to greater periods of precipitation and overcast skies, which possibly limited the full development of these qualities in the fruit (Figure S1). In this regard, (Azari et al., 2010) demonstrated in tomato fruits that light is an important component that affects the expression of genes related to pigment synthesis and also regulates their accumulation by controlling the light signaling apparatus. On the other hand, the dry matter and the texture could be seen diminished as a result of extensive periods of rain, resulting in an increase in the humidity of the fruit. According to (Fischer and Melgarejo, 2021), the excess of rains during the development of Andean fruits makes them more watery, softer and with reduced sugar content, a pattern that matches our results in gulupa.

In the same sense, a fluctuation in relative humidity was evident (Fig. 1B), which was directly related to rainfall and has a marked impact on aspects such as the activity of pollinators, air temperature, the presence of winds, fog and drizzle, plant physiology, pathogen distribution, fruit quality and crop productivity (Cleves-Leguízamo and Jarma Orozco, 2009; Miranda et al., 2009). This condition would have influenced the increase in the respiration rate of the fruits during the second cycle. A similar behavior occurred in mango where the respiration rate, ethylene production and fruit quality were related to the water balance of the plant (Nordey et al., 2016). In fact, it is well known that high relative humidity hinders adequate transpiration of the fruit tree, causing poor absorption of the nutrients that are taken by mass flow (Miranda et al., 2009).

The reduction in radiation received by the plant during the second cycle (Fig. 1D), was another cause of significant devaluation in its quality properties. Indeed, solar radiation is a fundamental source of energy for the photosynthetic activity of plants (Koyama et al., 2012), its role being fundamental for the production of biomass and finally the yield of fruit crops (Fischer et al., 2016). On the other hand, the light exposure of the plant foliar area of is directly related to the quality of the fruit (Amaya, 2009) and particularly to one of its parameters: the concentration of soluble solids (Arias et al., 2016). In the present study, the SST were diminished during the second cycle due to these climatic conditions, which corresponds to what was found in other Andean fruit trees, where the radiation and precipitation conditions did not favor a greater development of this characteristic (Fischer et al., 2019; Fischer and Melgarejo, 2021; Martínez-Vega et al., 2008). This is related to attributes such as soluble sugars, given that their concentration is the result of the complex contribution of several stages that range from photoassimilated synthesis in the leaves to the accumulation of sugar in the fruit, including photosynthesis, the synthesis of translocation sugars, translocation sugar loading, translocation, unloading, membrane transport, and metabolic conversion among others (Yamaki, 2010). Studies on different fruits demonstrate the increasing trends in the accumulation of sugars in fruits that develop with adequate solar radiation (Choi et al., 2014; Mikulic-Petkovsek et al., 2015; Sim et al., 2017). This would explain the differences between cycle one and two, since the latter showed the lowest values. Another concatenated effect is the reduction of organic acids, total titratable acidity and antioxidant capacity during the second period (Tables 4, 7 and 8) and, particularly the relationship of the first with the remaining two. In fact, reducing the amount of acids would lead to a decrease in total titratable acidity and in ascorbic acid at the same time, which given its antioxidant properties, would cause the affectation of the antioxidant capacity of the fruit. In a different crop (strawberry) a positive correlation between global radiation and hours of sunlight on the total acid content was found (Davik et al., 2006). The fluctuations observed in the temperature records (Figs. 1E and 1F), mainly in the maximum values, would reinforce the findings that have been discussed so far on each of the production and quality parameters.

The results for pH and carotenoid content are stable between the two cycles, which contrasts with the differences in organic acid content. As expressed by (Menéndez Aguirre et al., 2006) for yellow passion fruit, this means there is a self-regulation system, which could be the result of a buffering effect of citric acid, which tends to become the corresponding salt, so this attribute tends to remain constant. Another explanation is that biotic and/or abiotic stress could have happened in the second cycle due to climactic conditions, increasing its need of sugar and acid substrates for plant homeostatic and fruit respiration rate (as observed in postharvest; Fig. 2).

Currently, many of the alternatives that seek to increase soil fertility and crop productivity, coupled with reducing the negative environmental impacts of traditional agriculture, are focused on the use of renewable resources. These include composted organic materials, as well as rational use of inputs that achieve the harmonization of available resources through new systems such as integrated fertilization management (Darjee et al., 2022), the one used to carry out this work.

Regarding the positive results obtained by the integration of vermicompost on fertilization treatments, it would constitute an option to improve the efficiency of the crop and potentially to reduce the use of synthetic chemical fertilizers (more expensive), given the reduction that partial substitution implies. There are environmental advantages as well since it makes use of renewable resources and reduces the polluting effects on the environment (volatilization and leaching, and their pernicious effects of deteriorating water quality and potential eutrophication of riverbeds and associated lakes or reservoirs) (Rashmi et al., 2022). Similar results to ours were found in strawberry, where the use of vermicompost increased characteristics such as leaf area, number of flowers, fruits per plant and consequently produced fruits with greater weight and size (Changotra et al., 2017). Other studies have shown that vermicompost amendment can directly increase plant production by increasing plant-available nutrients and indirectly promote soil quality by improving soil structure and stimulating microbial activities, relative to conventional chemical fertilization (Kashem et al., 2015; Song et al., 2016).

Taking into account the performance of the harvest periods in terms of productive attributes, it is found that the fruits obtained during the first cycle would be classified as caliber 2, while the fruits of the second cycle would be caliber 4 according to the Proposal for a Colombian Technical Standard for fresh fruits (Orjuela-Baquero et al., 2011) based on fresh weight and equatorial diameter. Such classification allows us to calculate the degree of influence that climatic conditions play in gulupa fruit productivity and quality.

Regarding fruit quality, in general the quantitative results found in this study during the first cycle agree with those reported by other authors (Bermeo Escobar, 2021; Diaz et al., 2012; Flórez et al., 2012; Osorio et al., 2011), although not with those of the second cycle, due to climatic variables' fluctuations reducing the quality of the fruit (whole fruit firmness by 19%, dry matter and total titratable acidity of the pulp by 24%, total soluble solids by 8%, individual sugars by 49%, organic acids 63% and antioxidant capacity by 67%) and production parameters. However, the differences found in some results could be attributed to the diversity of the genetic material used, the agronomic management practices, the technological facilities available, and the edaphoclimatic conditions that prevailed in the locations of the experiments the latter being the determining factor for this work. In this regard, (Fonseca et al., 2022) has identified the lack of existing taxonomic consensus in some studies on gulupa, which may contribute to inaccurate estimates on properties of different existing varieties of this species or perhaps intraspecies due to lack of clonal propagation of plant material.

These results may be useful for producers when choosing the production scheme that best suits them, but above all, it might help to identify contingency measures in the event of adverse weather conditions that may limit the productive and nutraceutical potential of the fruit.

5. Conclusions

The productive cycle of gulupa had a great influence on key production parameters for producers such as size and weight (and commercial category) as well as other quality parameters at harvest (whole fruit firmness, total soluble solids, dry matter, total titratable acidity, organic acids or sugars). This was due to climatological differences between both cycles, especially in the higher rainfall, relative humidity and solar radiation in the early stages of flower and fruit formation in cycle 2 (subjected to ENSO phenomenon) compared to cycle 1. Integrated fertilization with vermicompost is recommended as a viable and sustainable production scheme for the cultivation of gulupa. However, in general, the influence of fertilization on the production and quality of the fruit was less noticeable than the productive cycle.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.sajb.2022.11.043.

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