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Edaphoclimatic variation and harvest seasonality as determining factors of multidimensional quality in avocado cv. hass grown in the tropics

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ABSTRACT

The increase in cultivated areas in tropical zones such as Colombia for avocado cv. Hass and the lack of knowledge on edaphoclimatic relationships with factors associated with quality led to the present research. The aim of this research was to establish the relationship of soil, climatic, spatial factors (plot location), and harvest seasonality (principal and transitory) with the multidimensional quality of avocado cv. Hass planted under tropical conditions. This research was carried out on eight farms located in three producing subregions. Soil, environmental and harvest data were recorded for three years (2015–2017) in each plot. Avocado fruit samples were used to determine the parameters of macronutrient, fatty acids, minerals, and vitamin E. Descriptive, inferential statistics, multivariate analysis, effect size, second-order exponential model, and causal relationships were used to determine variables associated with soil, climate, harvest seasonality, and spatial location, and to determine quality parameters. The results established a relationship between nutritional quality and the origin region. Similarly, it was possible to identify parameters associated with differential quality with a robust statistical methodology to propose origin as a differentiating factor for quality. This study provided useful information for the value chain that selected the best areas for avocado crops according to market expectations and nutritional quality criteria.

1. Introduction

The avocado cv. Hass (*Persea americana* Mill.) is one of the fruits that has shown an increase in demand in recent years. Between 2009 and 2018, the average growth rate was 14 %, with the United States and the European Union being the main buyers [1]. Additionally, Colombia has been reported to export 67,071 tons of fresh fruit in 2020, which is an increase of 50 % compared to the previous year. The country's total sales were $125.9 million, which is a 41 % increase over the previous year [2].

The high dynamism in the global demand for avocados is stimulated by changes in consumer trends. Avocado consumption seeks to

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obtain reported health benefits from the habitual consumption of this fruit, which has recently been associated with the concept of "healthy lifestyle habits" [3]. Healthy benefits have been associated with the high content of monounsaturated fatty acids, carotenoids, and vitamin E [4]. Furthermore, it is an important source of folic acid, fiber, and elements such as potassium, magnesium, vitamin A, vitamin C, vitamin K, and vitamin B6, among others [5,6]. This concept or global trend is associated with multiple health benefits from the regular consumption of unsaturated fatty acids in avocado fruits [5–7].

The quality of avocado fruit should be understood from multiple factors, along with changes that depend on the link in the value chain. This is how producers, packers, marketers, and consumers can present different concepts and perceptions of quality depending on economic, commercial, nutritional, and even aesthetic and emotional aspects [3]. These parameters can be objective and subjective, a unified definition of quality is highly complex and should consider multiple parameters within a value chain based on their importance based on intrinsic and extrinsic factors [3,8,9]. In this regard, the concept of multidimensional quality has been proposed as an integrative element that encompasses all aspects related to the quality of fruits and vegetables [3,9,10].

In general, intrinsic quality characteristics can be associated with the genetics of the cultivar, the agro-environmental conditions of crop development, and harvesting and post-harvest practices [3,9,11]. Extrinsic characteristics are influenced by socioeconomic and marketing factors that condition consumer perception [3,9,12]. Therefore, avocado production in recent years has focused on improving the quality parameters associated with physicochemical, nutraceutical, aesthetic, organoleptic and sanitary characteristics [9,13,14]. This trend is based on the concept of 'product of origin' [15] by selecting producing areas with particular edaphoclimatic characteristics that increase competitiveness in target markets by offering fruit with better quality attributes, based on genotype by environmental interaction, where certain parameters of fruits are expressed that are highly valued by consumers [8,15,16].

Recent studies have found that the concentration of fatty acids is highly influenced by the origin of fruits [13,17,18]. Despite the commercial importance of these quality parameters in the tropics, there are no studies that detail the edaphoclimatic variables and anthropic parameters of the production systems that influence nutritional concentration [15]. Under tropical conditions, avocado fruits grown between 1400 and 2600 m above sea level have been reported to have different concentrations of fatty acids and physicochemical characteristics [3,16]. This altitudinal profile presents a high source of climatic variability for tropical and subtropical zones and edaphic variation that generate ecological niches with differential responses in production and quality variables in cv. Hass avocados [19,20]. Under the highly variable conditions of the tropical region, the characteristics of the pedoclimatic and production systems are largely unknown, as is their role in determining quality.

The quality factors in avocado have focused primarily on the concentration and type of fatty acids and their associated factors. However, in our approach, the quality of avocado is considered multidimensional. In this regard, the concentration of macro- and micronutrients, as well as vitamin E, are also important parameters [5,21]. Unfortunately, very little is known about the factors associated with geographical, soil and climatic conditions that determine the relationships governing these quality parameters in cv. Hass avocado, especially under tropical conditions, one of the most dynamic areas worldwide for this fruit.

One of the main challenges in cultivating cv. Hass avocado in tropical conditions is understanding the concept of multidimensional quality throughout the value chain and try to identify the variation associated multiple edaphoclimatic characteristics and intrinsic factors of the production systems. Existing studies focus primarily on regional analyses, attributed variation to plots or geographical zones [14–17,22], overlooking the vast edaphoclimatic diversity where avocados are grown in tropical production zones. These areas exhibit significant altitudinal and microclimatic variations, along with diverse soil conditions [19]. Multidiverse environmental factors generate multiple responses in genotype-environment interactions, affecting various physiological processes of cv. Hass avocado [23]. Detailed local studies that elucidate the relationship between edaphoclimatic variations within batches and multifunctional quality parameters of cv. Hass avocados remain scarce. Such studies are crucial in improving the quality parameters of this fruit, informed by evidence-based decision criteria, to systematically improve the quality of avocados.

In addition, traditionally, analyses associated with the characterization of quality parameters and their relationship with soil climatic variables and specific aspects of avocado production systems have been carried out using multivariate approaches [15,24]. These methods allow for an initial approximation and management of the data, enabling the grouping of sources of variation and the determination of patterns regarding the quality parameters evaluated based on multiple associated variables. However, this type of analysis does not allow quantification of the type of relationship, effect size, and variation of the quality determining variable based on soil-climatic variables and characteristics of the production system as determinants of multidimensional quality.

Based on the information above, the objective of this study was to establish the relationship of edaphic, climatic, spatial factors (lot location) and harvest (principal and transitory) with multidimensional quality parameters associated with the concentration of nutritional compounds in three avocado cv. Hass producing regions in Antioquia, Colombia. This research was motivated by the need for clear and concise decision-making information on the selection of production areas and the pursuit of criteria to improve quality in Colombian Hass avocados. Furthermore, the objective was to apply the concept of "avocado of origin" to further refine quality standards based on the ability to quantify the impact and relationships between multidimensional quality parameters and edaphoclimatic and seasonal characteristics at the level of batches producing avocados under tropical conditions. The results provide a basis for strengthening the food industry for agricultural products with high added value for use in the cosmetic and natural product industries, along with providing elements so that entrepreneurs, agricultural, and investors can identify areas with potential biomarkers of origin.

2. Materials and methods

2.1. Description of the methodological approach

Given the knowledge gap associated with determining and understanding the impact of climatic, edaphic, seasonal and geographical variables (such as the location of avocado batches) on multidimensional quality parameters in avocados, specifically related to physicochemical criteria, macronutrients, mineral concentration, fatty acids and vitamin E, our approach involved selecting a set of eight batches within an altitudinal profile (1753–2448 m), as this variable represents a significant source of edaphoclimatic variation under tropical conditions (Supplementary information Table 1). In each batch, fruits were harvested during the two harvest seasons (main and secondary), which exhibit considerable variation not only in quantity but also in quality criteria such as size [23]. Subsequently, fruit ripening was induced under controlled conditions for multidimensional quality characterization. We then propose a multi-approach data analysis. First, multivariate analysis was used to understand the relationships between multiple interdependent variables (soil, climate, geographical location, and harvest seasonality). Next, since our goal is to identify the effect and impact of each source of variation, we propose four models based on the analysis of variance, complemented by determining the confidence interval and effect size. Finally, a polynomial model is proposed to determine the impact of predictor variables on multidimensional quality characteristics, such as an alternative to model multidimensional quality in avocado.

2.2. Location of farms and fruit harvest

The fruits used in the determination of multidimensional quality characteristics, such as macronutrients, fatty acids, minerals, and vitamin E (described in detail in the next paragraph), were collected from eight farms certified by the Instituto Colombiano Agropecuario (ICA) as export properties. These production systems were located in three subregions of the Department of Antioquia: four in the East ("LA" in the municipality of El Peñol, "EC" and "EG" in El Retiro and "LE" in Rionegro); two in the Southwest ("IM" in Amaga and "BV" in the Garden) and two in the North ("CS" and "EB" in San Pedro de Los Milagros), providing a good representation of the soil and environmental variability of the producing areas [19]. The specific location and the average climatic characteristics of the evaluated areas are shown in Supplementary Information Table 1. This study was developed between 2015 and 2017, obtaining two traditional crops each year ("principal" and "transitory"). In the plots evaluated and considering the climatic variation, particularly the days of degree of growth, the principal and transitory harvest occurs during the periods between November–February and June–September, respectively [22]. Production systems were selected within an altitudinal profile typical of tropical conditions, such as those found in Colombia (Supplementary information Table 1), within a range suitable for commercial cultivation of the species [19]. This altitudinal profile represents significant climatic variability with an impact on the physiological, phenological, productive, and quality behavior of avocado cv Hass under tropical conditions [16,19,23].

The production systems evaluated utilize clonal canopies of the 'Hass' cultivar, which significantly reduce variability and, as rootstocks, a seed-origin material called "Antillano" is employed. Furthermore, the plots were divided into two homologous zones based on productivity, phenology, and vigor variability, to minimize variation. Based on the factors mentioned above, in each farm, during both harvests (principal and transitory) two trees (one for each homologous zone), without the visible presence of pests or diseases were selected. In each tree, 25 fruits were harvested in each harvest (principal and transitory) that had a caliber between 18 and 20 (i.e. between 184 and 243 g), which have a higher demand in the international market [3]. These fruits were harvested manual with a dry matter content of 23.5 % on average according to the official analysis method to guarantee a suitable ripening process [25]. The selection of fruits per tree was carried out according to the criteria of each farm. Subsequently, the fruits were stored in plastic crates and promptly transported to the postharvest warehouse of each production unit. The harvested fruits were labeled in a paper bag and delivered to the Postharvest Laboratory at the La Selva de Agrosavia Research Center in Rionegro, Antioquia, in 24 h.

2.3. Determination of edaphoclimatic variables

2.3.1. Climatic variables

An automated WatchDog 2000 ET (Spectrum, IL) automated weather station was installed and operated on each farm, located in accordance with the World Meteorological Organization (WMO) guidelines for the installation of standard weather stations [26]. Each station was equipped with sensors to determine ambient temperature (°C), relative humidity (%), soil temperature (°C), soil moisture (%), solar radiation (W m^{-2}), photosynthetically active radiation - PAR (μmol of photons m^2 s^{-1}) and precipitation (mm). The data was recorded at an interval of 15 min.

2.3.2. Physical and chemical soil variables

In the flowering phenological phase (90 ± 20 days), depending on the degree days, they accumulate based on elevation [23] and each harvest (principal and transitory), two soil analyzes were carried out per year to determine the nutrient content based on the specific recommendation of each productive unit. Samples were taken at two depths (0–30 cm and 31–60 cm) and sent to the soil laboratory of the Agrosavia Research Center "Tibaitata". The following variables were determined: pH in solution 1:1 (VC-R-004 version 2), organic matter content (OM, %) (Walkey & Black), P with the Bray II method (mg kg^{-1}), S determined with the monocalcium phosphate method (mg kg^{-1}), exchangeable acidity (Al + H) using the reagent KCl 1 M (cmol (+) kg^{-1}); Ca, Mg, K and Na exchangeable with the ammonium acetate method in Colombian Technical Standard (NTC 5349, 2008) (cmol (+) kg^{-1}), Cation exchange capacity (CICE) determined as the sum of bases and exchangeable acidity (cmol (+) kg^{-1}); available Fe, Mn, Cu and Zn (mg kg^{-1}) using the Olsen method (NTC 5526, 2007) and available B using the monobasic calcium phosphate method (mg kg^{-1}). Each specific analysis for each element is part of the internal protocol validated by the Colombian technical standard of the Agrosavia-Tibaitata soil analysis laboratory (https://repository.agrosavia.co/bitstream/handle/20.500.12324/11556/Ver_documento_11556.pdf?sequence=2&isAllowed=y).

2.4. Physicochemical evaluation of fruits and sample preparation for the determination of quality variables

In the laboratory, the fruits were washed and dried according to the disinfection protocol used for the avocados intended for export [3]. Subsequently, a simulated journey was conducted to the consumer, which includes refrigeration and ripening under ambient conditions. For the ripening process, the fruits were stored under refrigerated conditions for two weeks in a cooler (5 ± 2 °C and 80 ± 2 % relative humidity (HR) (Supernordic., Colombia ™). Subsequently, they were placed in a climatic chamber (Memer, Germany ™) with a temperature of 20 ± 1 °C and a HR of 90 ± 2 %, until they reached the maturity of consumption (State of maturity 5) [27], in which fruits receive pressure not greater than 2 mm in the peduncle area without permanently contracting. Once consumption was reached, the random fruits were selected by each plot and harvest (principal and transitory), from which the mesocarp was extracted for a composite sample to determine macronutrients and minerals. Subsequently, a subsample was taken to be ultra-frozen at −40 °C and stored in an ultra-freezer at −80 °C, followed by analytical determination of vitamin E and fatty acids.

2.4.1. Analysis of macronutrient content in Hass avocado fruits

From these samples, the determination of quality parameters associated with macronutrients was carried out using analytical methods developed at the " Laboratorio de Nutrición Animal de Agrosavia," which is certified and follows the AOAC, 2005 standard. Specifically, the following protocols were followed: Humidity (ISO 6496 of 2011- NTC4888 of 2000), ash (AOAC 942.05 of 2012), ethereal extract (AOAC 2003.06 of 2012), protein (AOAC 960.52 of 2012), and crude fiber (ISO 6865 of 2012-NTC 5122 of 2002).

2.4.2. Analysis of mineral and micronutrient content in Hass avocado fruits

The determination of multiple minerals was also carried out. In this regard, the concentration of minerals phosphorus (P), potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) was determined by acid digestion using a microwave oven, followed by reading with Bila plasma emission spectrometry [28]. The concentration of iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn) was determined by acid digestion using a microwave oven with a subsequent reading with atomic absorption spectrometry [29]. Nitrogen concentration (N) was determined with Method 351.3 from Ref. [30]. Finally, the boron concentration (B) was determined using the methodology proposed by NTC 5404. These analyzes were carried out at the Laboratorio de Suelos of Agrosavia-Tibaitata.

2.4.3. Analysis of the content of fatty acids and vitamin E in Hass avocado fruits

The determination of the concentration of the fatty acids: palmitic, arachidonic, stearic, palmitoleic, oleic, linoleic and linolenic was carried out by gas chromatography with a split/split injector and a flame ionization detector [29]. Fatty acid profiles were analyzed using an Agilent 7890 gas chromatograph with a 5975C mass spectrometer detector (Wilmington, USA) and HP-5MS column (30 m × 0.25 mm x 0.25 μm), located at the Laboratorio de Sustancias Bioactivas, Universidad de Antioquia. The system was operated in split mode with helium as the carrier gas at a flow rate of 1 ml min^{-1}. The GC oven temperature was initially held at 45 °C for 4 min, increased to 160 °C at 15 °C min^{-1}, held for 1 min, then ramped to 240 °C at 4 °C min^{-1} and held again for 1 min, and finally raised to 310 °C at 10 °C min^{-1} for a final hold of 1 min. Both the ionization source and quadrupole were maintained at 230 °C and 150 °C, respectively. Electron impact ionization was conducted at 70 eV, with mass spectra recorded in SCAN mode across an *m/z* range of 45–500. Compound identification utilized retention times and mass spectra comparisons against the NIST 17.0 library. Quantification was based on external standards using a 37-component FAME mix from Supelco (Sigma-Aldrich), with solutions prepared in dichloromethane and serially diluted to cover six concentration levels. Fatty acid content was reported as mg per 100 g of sample [29].

In the case of vitamin E concentration was quantified using high-performance liquid chromatography (HPLC) (Shimadzu®, Kyoto, Japan), equipped with an SPD-M20A diode array detector and a SIL-20A HT autosampler. Chromatographic separation was achieved at a controlled temperature of 30 °C using an Eclipse Plus C18 reverse-phase column (4.6 mm × 250 mm x 5 μm). The mobile phase consisted of 53 % methanol, 45 % acetonitrile, and 2 % water, with a flow rate of 0.8 ml min^{-1}. Detection was conducted at a wavelength of 285 nm using the UV/Vis detector. Quantification of Vitamin E was performed by calibrating against a standard of Dl-α-tocopherol acetate (Sigma-Aldrich®) [31]. This test was carried out at the Laboratorio de Trazabilidad y Residualidad at the Corporación Universitaria Lasallista, Colombia.

2.5. Data gestion and statistical analysis

Based on the foregoing, our approach relied on the use of data analysis tools and a multi-approach of statistical methods that allow us to identify patterns, clusters, significance, effect size, sources of variation, and the relationship of each of the variables and parameters determining multidimensional quality criteria.

Phase 1. In this initial phase, our analysis objective was to determine the significance and size of the macro variables evaluated (harvest year and geographical location of the lots) in the multidimensional quality variables. Additionally, we assessed the variation of each of the quality criteria based on these macrovariables. In this data analysis stage, a descriptive and exploratory analysis of the relationships between the type of harvest (principal and transitory) and the analysis region (North, East, and Southwest) was performed with respect to the quality determinants according to the macronutrients parameters, mineral concentration, vitamin E and fatty acids in the ripe fruit.

Later, a analysis of variance was done for these variables by adjusting to four extra models (I, II, III, IV) using functions from the *emmeans* library run into the free R software. The best model was selected based on the Akaike Information Criterion (AIC). Subsequently, if there was statistical significance ($p<\alpha = 0.05$), a comparison of means with the Tukey test was carried out to verify which had differences. In addition to the significance value, two elements were incorporated: (i) confidence interval and (ii) effect size of each factor using Eta^2 and Cohen's index [32] using the *effect size* library in the free software R. This analysis quantifies and interprets the variation and avoids errors when obtaining a significant effect that is only due to chance [33].

I) $yij = \alpha j+\epsilon ijyij = \alpha j+\epsilon ij$
II) $yij = \beta j+\epsilon ijyij = \beta j+\epsilon ij$
III) $yijk = \alpha j+\beta k+\epsilon ijkyijk = \alpha j+\beta k+\epsilon ijk$
IV) $ijk = \alpha j+\beta k+(\alpha\beta)jk+\epsilon ijk$

where: **yy:** response variable. Represents each variable of bromatological quality, mineral concentration, vitamin E, and fatty acids; **αα:** effect of harvest (principal and transitory); **ββ:** effect of region (North, East, and Southwest); **(αβ):** harvest and interaction effect of the region.

Phase 2. In the initial stage of data analysis in this phase, various multivariate methods are proposed to reduce dimensionality and identify patterns associated with multidimensional quality (macronutrients, mineral contents, vitamins E and fatty acids) criteria based on macro characteristics of production systems (harvest and geographic region). In this regard, Principal Component Analysis (PCA) was initially employed to address the complexity of the associated numerical variables. Before the analysis, the variables were standardized to ensure a mean of zero and a variance of one, with the aim of uncovering inherent patterns and clusters without the influence of varying scales. PCA is a dimensionality reduction technique, known for its unsupervised nature, which highlighted the intrinsic variability of the data, enabling effective visualization and analysis of the underlying relationships among samples [34].

Later, with the aim of identifying sources of discrimination of multidimensional quality characteristics, a partial least squares discriminant analysis (PLS-DA) was applied to refine the understanding of the differences between predefined groups, in this case, using "Harvest" and "Region" as classification factors. This supervised approach focused on maximizing the variability attributable to differences between these categories, facilitating a clear and substantiated distinction between regions or analyzed experimental conditions [35]. Thus, the PLS-DA approach, considering all variables simultaneously [35], allows for a more refined interpretation of the relative contributions of each macronutrient, highlighting the complexity associated with evaluating the quality and nutritional diversity of avocados. To quantify the influence of each variable on the discrimination achieved by the PLS-DA model, the Variable Importance in Projection (VIP Score) was calculated. This process entailed a detailed assessment of how the variance explained by the model is distributed among the variables, assigning VIP scores that highlight those with the greatest impact on the model's discrimination capacity. Variables with the highest VIP scores were identified as critical to differentiating between regions, thus providing an objective basis for selecting potential biomarkers and deep understanding the distinctive characteristics underlying each analyzed group [36].

Phase 3. In this final phase, our objective in the analysis was to determine the existing relationship and quantify the effect between the multidimensional quality parameters and the sources of variation at the microlevel (lot), such as the soil and climatic variables. To achieve this, a factorial model is proposed. First, to determine all sources of variation, an analysis of variance was carried out to establish statistical differences between the evaluation years and the sample depths of the soil variables using functions from the *emmeans* library run in the free R software. An analysis of the residuals was carried out to evaluate compliance with the assumptions of normality, independence, and heteroscedasticity,

Later, the average values of each soil variable for the three years of evaluation (time soil sample was not significance $P > 0.05$) and the values for each depth (concentration in the depth sample was significative $P < 0.05$) were selected given the results obtained in the fist step (Supplementary information 2). Furthermore, the climate variables included were monthly accumulated precipitation, average solar radiation, average even radiation, average relative humidity, average, minimum and maximum temperature, and standard deviation of temperature. Based on the above variables and to determine the influence of the edaphoclimatic variables on each of the aspects of multidimensional quality of avocado fruits, a linear polynomial model was proposed (equation IV), where each response variable (ϕ) was assumed to be a nutritional aspect of interest in the fruits sampled (bromatological, micronutrients, and fatty acids). On the other hand, the edaphoclimatic variables were taken as fixed-effect covariates. The data were subjected to a Cochrane-Orcutt optimization process, where the least-squares procedure was modified to allow autocorrelation between successive residues. In this case, both the autocorrelation standard (ρ) and model parameters (β_k) were interactively determined, for which between 20 and 25 interactions were used until the change in the value derived from each parameter compared to the previous step was less than 0.01 [37]. This method is recommended to treat situations in which the residues of the model are not independent, as in this case.

IV $\phi = \beta_0 (1-\rho)+\beta_1 x_1 +\beta_2 x_2 + \dots \beta_k x_k$

Where: k: number of independent variables; ϕ: factor to predict; β_k: parameters associated with the cause-effect relationship; ρ: Autocorrelation standard.

3. Results

3.1. Macronutrients content of cv. Hass through geographical location and types of harvest

The ANOVA of the macronutrients variables (Table 1) showed the performance of the models tested. In model 1 (harvest factor) the % of humidity presented significant differences with a long effect size. Model 2 (region factor) was the best for the ethereal extract, with a short effect size. Model 3 (Harvest factors + region) had better fiber and carbohydrate content performance with no significant differences between harvests, but did between regions. The carbohydrate content was higher in the Southwest than in the other two regions; while the fiber content was in decreasing order: Southwest > East > North. The size of the effect was long for crops and regions for fiber content and long and medium for carbohydrate content, respectively (Table 1). Finally, model 4 (Crop × region interaction) was the best performer for ash and protein content, with an effect size of medium for regions, short for harvests and long for interaction. In particular, we found that the protein content was higher in the north, followed by the southwest under transitory harvest. The rest of the values did not differ from each other (Table 1). The values of Eta^2 and Cohen I. were long in all cases for this variable.

Transitory harvests in the three regions had a higher value for the content of carbohydrates and protein; in contrast, the moisture and fiber content were higher in the principal harvest than in the transitory one. The content of ash and ethereal extract was higher in transitory harvest in the North region and lower in the Southwest. In the East, the ash content was higher and the ethereal extract was similar (Fig. 1).

3.1.1. Fatty acid content of cv. Hass through geographical location and types of harvest

The ANOVA for fatty acids is shown in Table 2 and Fig. 2, show the behavior of the variance analyzes that described the influence of harvest and region on the lipid profile. Model 1 (harvest factor) represented the variability of arachidonic acid content, with a short effect size. However, model 2 (region factor) was the best model for stearic acid, with differences from the southwest subregion, where the concentration was higher and with a large effect size. Regarding the model 3 (harvest + region) was the best model for linoleic acid with a significant difference by region and harvests. The effect size was long for region and harvest. This model also explain linolenic acid, with a long effect size for harvest and regions (Table 2). Furthermore, model 4 (harvest factor + region and crops x regions) was the best model for palmitoleic acid, and the highest concentration was found in the southwest with significant differences from the

Table 1
Analysis of bromatological quality variance of variables of Hass avocado fruits with respect to principal harvests (PH) and transitory (TH) and regions in the Department of Antioquia.

Model	Variable (%)	Source of varitión	Median	Confidence Interval		α< 0.05 %	Effect size	
				Lower limit	Upper limit		Eta2[a]	Cohen I[a]
Model 1	**Humidity (%)**	**PH**	3.1	2.58	3.61	a	0.29 L	0.64 L
		TH	1.84	1.33	2.35	b		
Model 2	**Etherel extract (%)**	**Nortt**	66.0	63.5	68.5	a	0.11C	0.35 M
		East	63.5	61.8	65.3	a		
		Southwest	63.0	60.5	65.5	a		
Model 3	**Fiber of the ripe fruit**	**Nortt**	13.2	12.0	14.3	a	0.53 L	1.07 L
		East	15.0	14.2	15.8	b		
		Southwest	17.6	16.4	18.7	c		
		PH	22.4	21.6	23.3	a	0.96 L	4.93 L
		TH	8.0	7.2	88	b		
	Carbohydrate es from the ripe fruit	**Nortt**	3.9	1.36	6.4	b	0.25 L	0.57 L
		East	5.9	4.1	7.7	b		
		Southwest	9.1	6.6	11.7	a		
		PH	5.4	3.6	7.3	a	0.07 M	0.27 M
		TH	7.2	5.4	9.0	a		
Model 4	**Ash of the tipe fruit**	**PH-Nortt**	10.9	8.2	13.6	a	0.15 L	041 L
		TH-Nortt	12.7	10.0	15.4	a		
		PH-East	10.8	8.9	12.7	a		
		TH-East	12.8	11.0	14.8	a		
		PH-Southwest	11.1	8.5	13.8	a		
		TH-Southwest	8.7	6.0	11.4	a		
	Ripe fruit protein	**PH-Nortt**	5.6	3.7	7.6	c	0.21 L	0.51 L
		TH-Nortt	11.2	9.3	13.1	a		
		PH-East	5.3	3.9	6.6	c		
		TH-East	6.6	5.2	7.9	c		
		PH-Southwest	5.0	3.0	6.9	c		
		TH-Southwest	8.3	6.3	10.2	b		

**TH: Transitory Harvest and PH: Principal Harvest. Note: In the comparison region and harvest the n was: The eastern region n = 48, the north region n = 24, and the southwest region n = 24. In the case of the interaction between regions and harvest for the north n: 12, southwest n: 12 and for the east n: 24.

[a] Effect Size: C: Short. M: Medium. L: Long and ML = Very long.

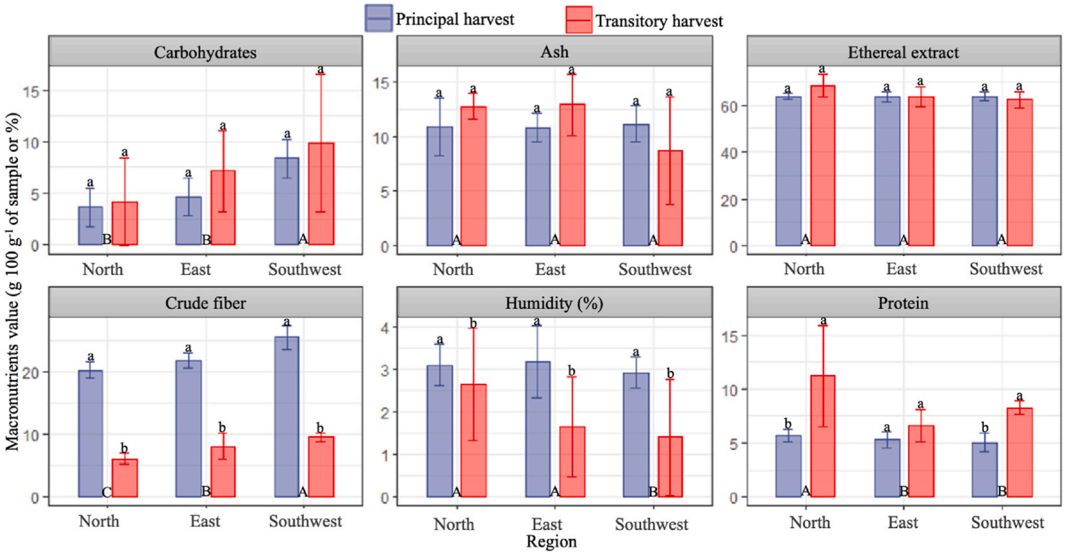

Fig. 1. Results of the bromatological quality interaction in Hass avocado fruits from primary and transitory harvests in the north, east, and southwest regions of the Antioquia Department. The bars represent the confidence interval of the validated mean with a significance level of a $\alpha < 0.05$. Letters that are the same indicate no significant differences were found; lowercase letters denote the effect of the harvest, while uppercase letters denote the effect of the region.

north and east. Regarding harvests, there were no significant differences. For the interaction between crops and regions, the highest concentration was in the Southwest and transitory harvest. Meanwhile, the size of the effect was long for the regions and the interaction between harvest and regions, and medium for the harvests (Fig. 2 and Table 2).

For monounsaturated fatty acids, the northern region had the highest concentration (70.8 %), followed by the east (68.9 %) and the southwest (63.5 %) (Fig. 2 and Table 2). For the interaction between crops and regions, the highest concentration was in the principal harvest in the north and with differences from the main harvest in the southwest. The effect size was medium for the harvests and long for the regions and interaction (Fig. 2 and Table 2). In the case of the highest concentration of polyunsaturated fatty acids was presented in the Southwest with short size for crops and regions and a long size for interaction between regions (Fig. 2 and Table 2). On the other hand, for the relationship of saturated/unsaturated fatty acids and palmitic acid concentration, a significant difference was found between the north and east regions and the southwest, with a greater relationship in the southwest. The interaction had a difference between crops and regions, which was greater in the Southwest, followed by the East and finally the North. For the saturated/unsaturated fatty acid ratio, the effect size was large for the regions and the harvest × region interaction and short for the crops. For palmitic acid, the size was large for all parameters (Fig. 2 and Table 2).

In the case of oleic acid, the North region had the highest concentration (64.7 %), followed by the East (61.3 %) and finally the Southwest (51.8 %). The harvest x-region interaction had the highest concentration in the main harvest in the north, and there was a difference from the principal and transitory harvests in the southwest. The size of the effect was medium for the regions and the interaction and long for the harvests (Fig. 2 and Table 2).

Furthermore, there was an interaction between regions and crops for the contents of stearic acid, palmitic acid, oleic acid, the sum of monounsaturated and saturated acids, and the saturated/unsaturated acid ratio in the southwest (Table 2 and Fig. 2). The content of palmitoleic acid and the sum of polyunsaturated acids in the east also had an interaction, while the north did not have any interaction (Table 2 and Fig. 2). The highest concentration of fatty acids was in the transitory harvest of arachidonic, linoleic, stearic and linolenic acids for all regions. Transitory harvest in the north had a higher concentration of arachidonic acid, stearic, linoleic, linolenic, palmitic, palmitoleic, saturated unsaturated ratio, the sum of polyunsaturated acids and the sum of saturated fatty acids (Table 2 and Fig. 2). In addition, arachidonic acid, stearic acid, palmitic acid, palmitoleic acid, the sum of polyunsaturated fatty acids and saturated fatty acids had the highest concentrations in the southwest region. The sum of monounsaturated fatty acids and oleic acid had the highest content in the north region, which was very close to the concentration in the east. For the harvest, a higher concentration of fatty acids was found in the transitory harvest for linoleic acid, the ratio of saturated/unsaturated acids, the sum of polyunsaturated and the sum of saturated fatty acids. For polyunsaturated fatty acids, sum of monounsaturated fatty acids, oleic acid content, and palmitic acid, the highest concentration was in the main harvest (Table 2 and Fig. 2).

3.1.2. Mineral and vitamin E content of cv. Hass through geographical location and types of harvest

In Table 3 we show that model 1 (harvest factor) was the best model to explain the variation in the concentration of S and Na with an effect size of short for sulfur, and medium for Na. Furthermore, model 2 (region factor) was the best model for the concentration of Mn, Cu, N, Fe, Zn and P in the fruit. The contents of Mn, Cu, Zn, and P were significantly higher in the north region compared to the east and southwest. No significant differences were detected for Fe or N between regions. The effect size was long for Mn, Cu, Zn, and P, and

Table 2
Analysis of variance of the fatty acid profiles of Hass avocado fruits and their relationship with type of harvest and regions of the Department of Antioquia.

Model	Variable (%)	Source of Variation	Median	Confidence Interval		α< 0.05 %	Effect size	
				Lower limit	Upper limit		Eta2[a]	Cohen I[a]
Model 1	**Arachidonic acid percentage**	**PH**	0.72	0.64	0.79	a	0.03C	0.17C
		TH	0.76	0.69	0.84	a		
Model 2	**Sorric acid**	**North**	0115	0.092	0.138	a	0.65 L	1.37 L
		East	0.119	0.103	0.135	a		
		Soutwest	0.213	0.19	0.236	b		
Model 3	**Linoleic acid**	**North**	4.65	4.15	5.14	a	0.51 L	1.03 L
		East	4.65	4.22	4.91	a		
		Soutwest	6.10	5.61	6.59	b		
		PP	4.51	4.15	4.86	a	0.47 L	0.93 L
		TH	5.70	5.34	6.06	b		
	Linolenic acid	**North**	0.72	0.62	0.83	A	0.03C	0.30 M
		East	0.71	0.63	0.78	A		
		Soutwest	0.81	0.707	0.78	A		
		PH	0.72	0.64	0.80	A	0.08 M	0.18C
		TH	0.77	0.69	0.854	a		
Model 4	**Oleic acid**	**PH-North**	68.7	63.1	74.3	a	0.12 M	0.38 M
		TH-North	60.7	55.1	66.3	b		
		PH-East	63.2	59.3	67.2	b		
		TH-East	59.3	55.4	63.2	b		
		PH Soutwest	50.7	45.1	56.2	c		
		TH-Suroeste	53	47.4	58.5	c		
	Palmitic acid	**PH-North**	13.2	10.2	16.2	a	0.15 L	0.42 L
		HT-North	17.5	14.5	20.5	b		
		PH-East	16.2	14	18.3	b		
		HT-East	18.9	16.8	21	b		
		PH-Soutwest	21.7	18.8	24.7	c		
		TH-Soutwest	20.2	17.2	23.2	C		
	Sum af saturated fatty acids	**PH-North**	13.3	10.3	16.3	a	0.15 L	0.42 L
		TH-North	17.7	14.7	20.7	b		
		PH-East	16.3	14.2	18.4	b		
		TH-East	19.1	17.0	21.2	b		
		PH-Soutwest	22	19.0	24.9	c		
		TH-Soutwest	20.4	17.4	23.4	c		
	Unsaturated Saturated Ratio	**PH-North**	0.15	0.17	0.201	a	0.14 L	0.4 L
		TH-North	0.21	0.16	0.262	b		
		PH-East	0.19	0.16	0.23	b		
		TH-East	0.23	0.20	0.27	b		
		PH-Soutwest	0.28	0.23	0.331	c		
		TH-Soutwest	0.25	0.21	0.305	c		
	Sum of saturated fatty acids	**PH-North**	13.3	10.3	16.3	a	0.15 L	0.42 L
		TH-North	17.7	14.7	20.7	b		
		PH-East	16.3	14.2	18.4	b		
		TH East	19.1	17	21.2	b		
		PH-Soutwest	22	19	24.9	c		
		PH-Soutwest	20.4	17.4	23.4	c		
	Unsaturated saturated ratio	**PH-North**	0.15	0.17	0.20	a	0.14 L	0.4 L
		TH-North	0.21	0.16	0.26	b		
		PH-East	0.19	0.16	0.23	b		
		TH-East	0.23	0.20	0.27	b		
		PH-Soutwest	0.28	0.23	0.33	c		
		TH-Soutwest	0.25	0.21	0.30	c		

**TH: Transitory Harvest and PH: Principal Harvest. Note: In the comparison region and harvest the n was: The eastern region n = 48, the north region n = 24, and the southwest region n = 24. In the case of the interaction between regions and harvest for the north n: 12, southwest n: 12 and for the east n: 24.

[a] Effect size: C: Short. M: Medium. L: Long and ML: Very long.

medium for Fe and N. Model 3 (region + harvest) was the best model to explain the contents of Ca, Mg, and K in fruits, with a significantly higher value for Ca and K in the north region compared to the east and southwest. In addition, harvest had a significant difference in concentration in all minerals except Mg and K. The effect size for Ca and K was long between regions and harvest and for Mg it was long between regions and medium for harvest (Fig. 3 and Table 3). However, model 4 was the best model for the content of B in the fruits, without significant differences for the harvest but with differences for the north, east, and southwest. There were significant differences in the interaction with the following decreasing order: CP North > CT North > CT Southwest > CT East, CP East > CP Southwest. The size of the effect was short for both crop metrics and long for the regions and the harvest × region interaction (Fig. 3 and Table 3). Regarding to the vitamin E content was not adjusted to any of the four models, with a short effect size (Fig. 3 and Table 3).

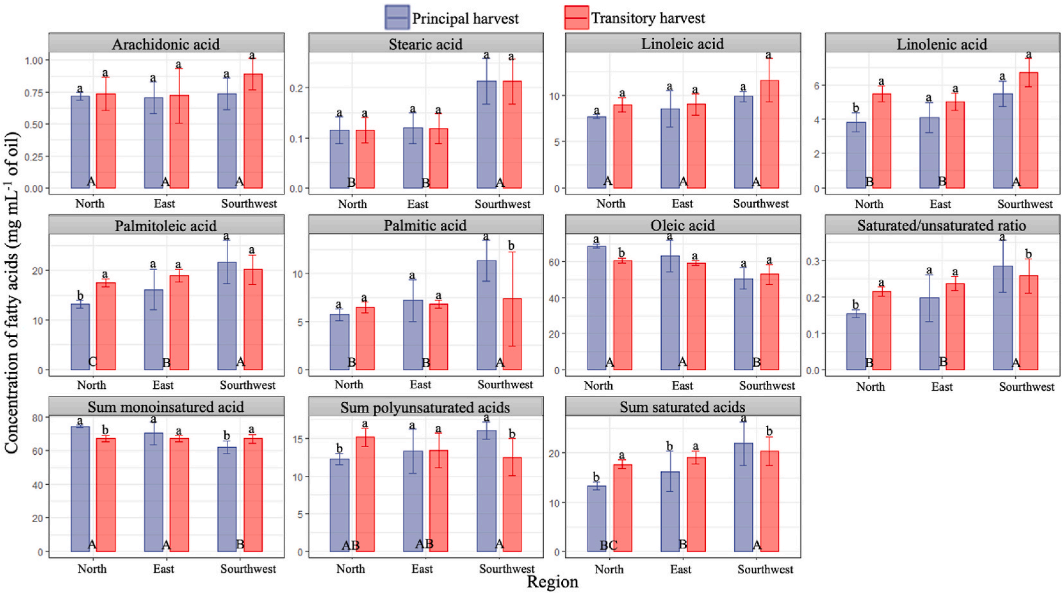

Fig. 2. Results of the interaction of the main fatty acids in avocado fruits from principal and transitory harvests in the north, east, and southwest regions of the Antioquia Department. The bars represent the confidence interval of the validated mean with a significance level of a $\alpha < 0.05$. Letters that are the same indicate no significant differences were found; lowercase letters denote the effect of the harvest, while uppercase letters denote the effect of the region.

Fig. 3 shows the interactions of the elements of the ripe fruit with the regions and crops, with a relationship between the regions and the crops for B, Cu, Fe, Mn, Na, P, S, and Zn in at least one of the regions. The region with the highest concentrations of K, Mg, P, N, and S was the north in the transitory harvest, along with B and Cu in the main harvest. The concentration of Ca in the fruit was higher in the east in both crops. However, vitamin E had a higher concentration in the southwest in both crops, followed by the east and the north.

3.2. Multivariate analysis approach

Our multivariate analysis is based on the search for patterns and relationships using the PLS-DA method, following the reduction of dimensionality using PCA. The results presented are based on determining the clustering of multidimensional quality determinants based on macro sources of variation (harvest and geographical location of the lots) according to the VIP score metric. In Fig. 4, the consolidated Principal Component Analysis (PCA) illustrates the relationships among macronutrients, micronutrients, and the fatty acid profiles in avocado fruits from three subregions of Antioquia, Colombia.

The first principal component (PC1) predominantly captures variations in micronutrients and specific fatty acids, whereas the second component (PC2) delineates differences related to other fatty acids and structural components such as fiber. This analysis distinctly visualizes these variables and their correlations with the evaluated subregions: West, North, and Southwest, reflecting the diversity in nutritional profiles shaped by differences in cultivation practices and local edaphic and climatic conditions. Variables such as zinc (Zn_f), phosphorus (P_f), and potassium (K_f) exhibit a strong positive correlation with samples from the North and Southwest regions. In contrast, fatty acids like oleic and linoleic predominantly associate with the West region, while polyunsaturated and linoleic acids are primarily linked to the Southwest region, suggesting disparities in soil composition or crop management practices. Meanwhile, magnesium and iron, with vectors pointing towards the North region, likely indicate fertilization practices or soil characteristics optimized for enhancing the absorption of these minerals. Additionally, proteins and carbohydrates are dispersed across all regions, showing a slight bias towards the Southwest region for proteins (Fig. 4 A).

The data consolidated for the Partial Least Squares Discriminant Analysis (PLS-DA) and the Variable Importance in Projection (VIP) scores provide an assessment of how various nutrients and fatty acids discriminate between the avocado growing regions in Antioquia. Initially, the sample dispersion on the PLS-DA plot validates the variations between the West, North, and Southwest regions identified by the PCA, affirming that the nutritional profile can effectively differentiate the samples based on their geographical origins. The samples from the North and Southwest form well-defined clusters in contrast to those from the West, highlighting significant differences in the chemical and nutritional characteristics of the fruits. Furthermore, VIP scores detail the most influential variables in regional discrimination. Nutrients such as phosphorus (P_f) and boron (B_f) achieve the highest scores, underscoring their critical role in regional differentiation. This may relate to the availability of these nutrients in the soil or their targeted management in various locales. Minerals like zinc (Zn_f) and copper (Cu_f), along with nitrogen (N_f) and magnesium (Mg_f), also score highly, emphasizing their significance in the nutritional makeup that characterizes each region. This analysis suggests that profiles of micronutrients and fatty acids not only reflect the nutritional quality of Hass avocados but also serve as markers of the geographical and agronomic specifics of cultivation (Fig. 4 B and C).

Table 3
Analysis of variance of quality variables associated with vitamin E and minerals of Hass avocado fruits with respect to crops and regions in the Department of Antioquia.

Model	Variable (%)	Souce of variation	Median	Coefidence intervalo		α< 0.05 %%	Effect size	
				Lower limit	Upper Limit		Eta2[a]	Cohen I[a]
Model 1	**Sulfur in ripe fruit**	**PH**	0.12	0.109	0.136	a	0.00C	0.05C
		TH	0.13	0.111	0.139	a		
	Sodium in ripe fruit	**PH**	0.025	0.004	0.055	a	0.03C	0.16 M
		TH	0.007	0.023	0.037	a		
Model 2	**Manganese**	**North**	10.91	7.93	13.89	a	0.31 L	0.67 L
		East	4.47	2.37	6.58	b		
		Southwest	6.95	3.97	9.93	b		
	Copper in ripe fruit	**North**	6.75	2.38	8.13	a	0.24 L	0.56 L
		East	4.32	3.34	5.29	b		
		Southwest	4.64	3.27	6.02	b		
	Nitrogen in ripe fruit	**North**	0.92	0.834	1.006	a	0.1 M	0.33 M
		East	0.84	0.78	0.902	a		
		Southwest	0.83	0.739	0.911	a		
	Iron in ripe fruit	**North**	24	18.7	29.3	a	0.12 M	0.37
		East	21.2	17.5	25	a		
		Southwest	16.8	11.5	22	A		
	Zinc in ripe fruit	**North**	23.8	20.4	27.2	a	0.30 L	0.66 L
		East	16.7	14.3	19.1	b		
		Southwest	17.7	14.3	21.1	b		
	Phosphorus in ripe fruit	**North**	0.176	0.154	0.198	a	0.47 L	0.94 L
		East	0.112	0.096	0.127	b		
		Southwest	0.119	0.097	0.141	b		
Model 3	**Calcium in ripe fruit**	**North**	0.043	0.027	0.06	a	0.22 L	0.53 L
		East	0.067	0.056	0.079	b		
		Southwest	0.047	0.031	0.063	b	0.2 L	0.49 L
		PH	0.421	0.03	0.054	a		
		TH	0.06	0.051	0.075	b		
	Magnesium in ripe fruit	**North**	0.1	0.085	0.115	a	0.16 L	0.44 L
		East	0.104	0.09	0.115	a		
		Southwest	0.084	0.07	0.098	a		
		PH	0.091	0.08	0.102	a	0.06 M	0.26 M
		TH	0.101	0.09	0.112	a		
	Potassium in ripe fruit	**North**	1.78	1.61	1.95	a	0.24 L	0.56 L
		East	1.55	1.43	1.67	b		
		Southwest	1.44	1.27	1.61	b		
		PH	1.47	1.35	1.59	a	0.23 L	0.55 L
		TH	1.71	1.59	1.83	a		
Model 4	**Boron in ripe fruit**	**PH-North**	63.2	49.48	76.8	a	0.31 L	0.66 L
		TH-North	38.5	24.87	52.2	b		
		PH-East	18.5	8.81	28.1	d		
		TH-East	21.5	11.86	31.2	d		
		PH-Southwest	12.2	1.48	25.9	e		
		TH-Southwest	31.8	18.16	45.5	c		
Model 5. Heterosedastic	**Vitamin E**	**PH**	0.118	0.101	0.134	a	0.000C	0.1C
		TH	0.118	0.105	0.131	a		

**TH: Transitory Harvest and PH: Principal Harvest. Note: In the comparison region and harvest the n was: The eastern region n = 48, the north region n = 24, and the southwest region n = 24. In the case of the interaction between regions and harvest for the north n: 12 Southwest n: 12 and for the east n: 24.

[a] Effect size: C: short. M: Medium. L: Long and VL: Very long.

In the case of macronutrients, the PCA revealed a distinctive nutritional discrimination between the two groups of avocado samples associated with harvest (’PH and ’TH). The first PC1 highlighted a significant contribution from proteins and carbohydrates, suggesting that these macromolecules are key differentiators in the nutritional profile between the harvested examined. On the contrary, the clustering of PH near the vectors of crude fiber and related moisture in PC2 highlights a distinctive composition that could influence the water content of the fruit (Fig. 5 A).

The low interspecific variability within the PH group indicates proximal homogeneity, while the larger dispersion in TH suggests slightly broader variability, possibly due to physiological differences in cultivation for each harvest and their metabolic and energetic wear (Fig. 5 A). Furthermore, in line with the PCA results, PLS-DA corroborated the importance of fiber and proteins as key discriminatory variables regarding the type of harvest, as reflected in their high VIP scores (Fig. 5 A, B and C). This finding indicates its notable role in nutritional separation between harvests (PH and TH), providing a quantitative basis for determining macronutrient nutritional differences for each harvest type based on their nutritional value promises.

The biplot shown in the PCA graph illustrates the variability of fatty acid profiles between three avocado-growing regions: west, north, and southwest (Fig. 6 A). In PC1, a clear division is observed between the West region, which shows a strong association with

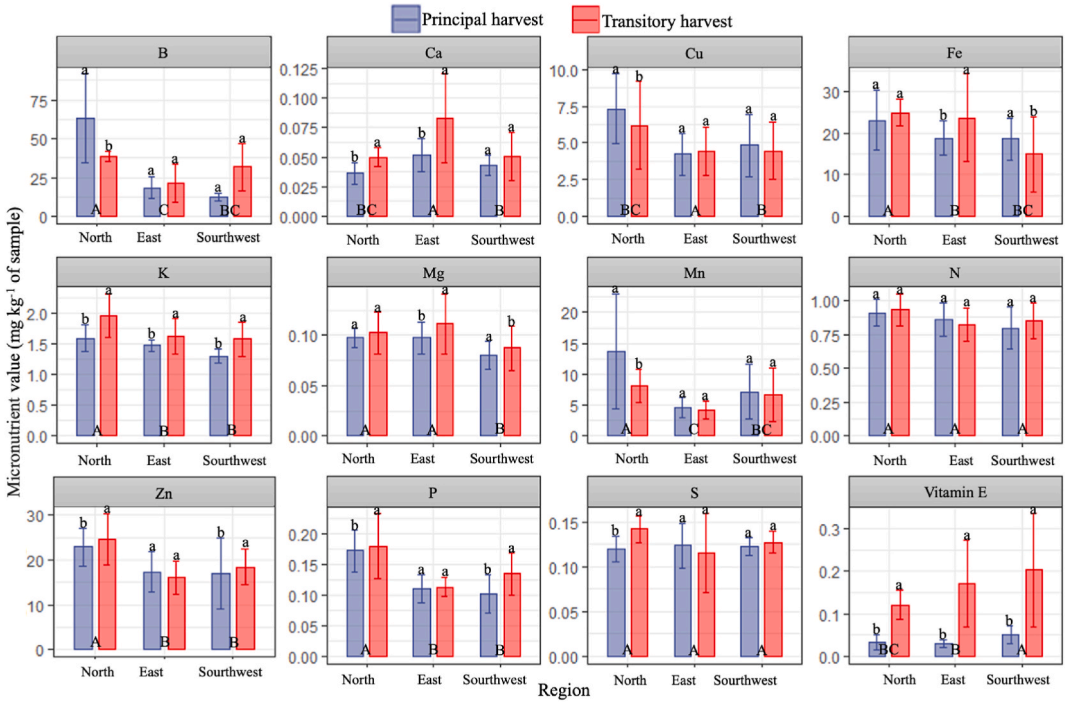

Fig. 3. Results of the interaction of elements and vitamin E in avocado fruits of the principal and transitory harvests of the north, east, and southwest regions of the Antioquia Department. The bars represent the confidence interval of the validated mean with a significance level of a $\alpha < 0.05$. Letters that are the same indicate no significant differences were found; lowercase letters denote the effect of the harvest, while uppercase letters denote the effect of the region. B: boron, Ca: calcium, Cu: copper, Fe: iron, K: potassium, Mg: magnesium, Mn: Manganese, N: nitrogenous, Zn: Zinc, P: phosphorus, S; sulfur.

high levels of polyunsaturated fatty acids, and the North and South regions, which exhibit an affinity for saturated fatty acids (Fig. 6 A). This orientation suggests a differentiated composition in the lipid profile, which could reflect edaphoclimatic variants, which in this analysis overlapped with the differences shown between different types of harvest. On the other hand, PC2 does not appear to capture additional variability associated with other factors not identified by PC1 (Fig. 6 A).

The integration of PLS-DA with VIP scores provides deeper insights into the influence of each fatty acid on regional discrimination, confirming the trend observed in PCA, with a clear distinction of regions in the latent component space (Fig. 6 B and C). VIP scores highlight the preponderance of linoleic and palmitic fatty acids as the most relevant for differentiating regions, followed by the content of saturated fatty acids and the ratio of saturated to unsaturated fatty acids. These results emphasize the value of specific fatty acids not only from a nutritional perspective, but also as possible quality biomarkers at the regional level or under the environmental conditions of avocado cultivation for the Antioquia department in Colombia.

The PCA for avocado micronutrients showed a clearer discrimination at the regional level, where a geographical distribution is manifested based on the nutritional profile (Fig. 6 A). The dispersion of samples along PC1 indicates moderate interspecific variability, primarily influenced by levels of phosphorus (P_f), boron (B_f), and zinc (Zn_f), while PC2 seems to be associated with elements such as sodium (Na_f) and vitamin E (VitaE), implying that secondary variability in samples may be related to these second nutrients. The differentiated clustering of samples, especially notable between the West and Southwest regions, could suggest significant differences in soil composition or fertilization practices that influence avocado nutrient absorption (Fig. 7 A).

PLS-DA, complemented by VIP scores, shows a clear separation of samples in the PLS space, confirming that the differences in nutritional profiles are not random, but possibly related to regional soil climatic conditions together with some unmeasured influence related to agricultural practices (Fig. 7 B and C). VIP scores amplify this distinction, with phosphorus (P_f), manganese (Mn_f), and zinc (Zn_f) emerging as the most influential variables in regional discrimination.

3.3. *Relationship and quantification of sources of variation at the microlevel (soil and climatic variables) associated with multidimensional quality in cv. Hass avocado fruits*

There were several soil factors (at both depths) that were more determinant of macronutrients parameters in the Hass avocado fruits (Fig. 8). The protein content was positively affected by the level of Mg in P1 and the pH in P2. On the contrary, it was adversely affected by exchangeable Al in P1 and by the level of K and Na in P2. Similarly, the crude fiber content tended to be higher with an increase in CICE and B in P1 and with Na and Ca in P2, and lower with the increase in Mg in P1 and K and pH in P2. On the other hand, the ash content (minerals) in the fruit was favored by the increase of Mg in both P1 and P2, and decreased with the exchangeable Na in

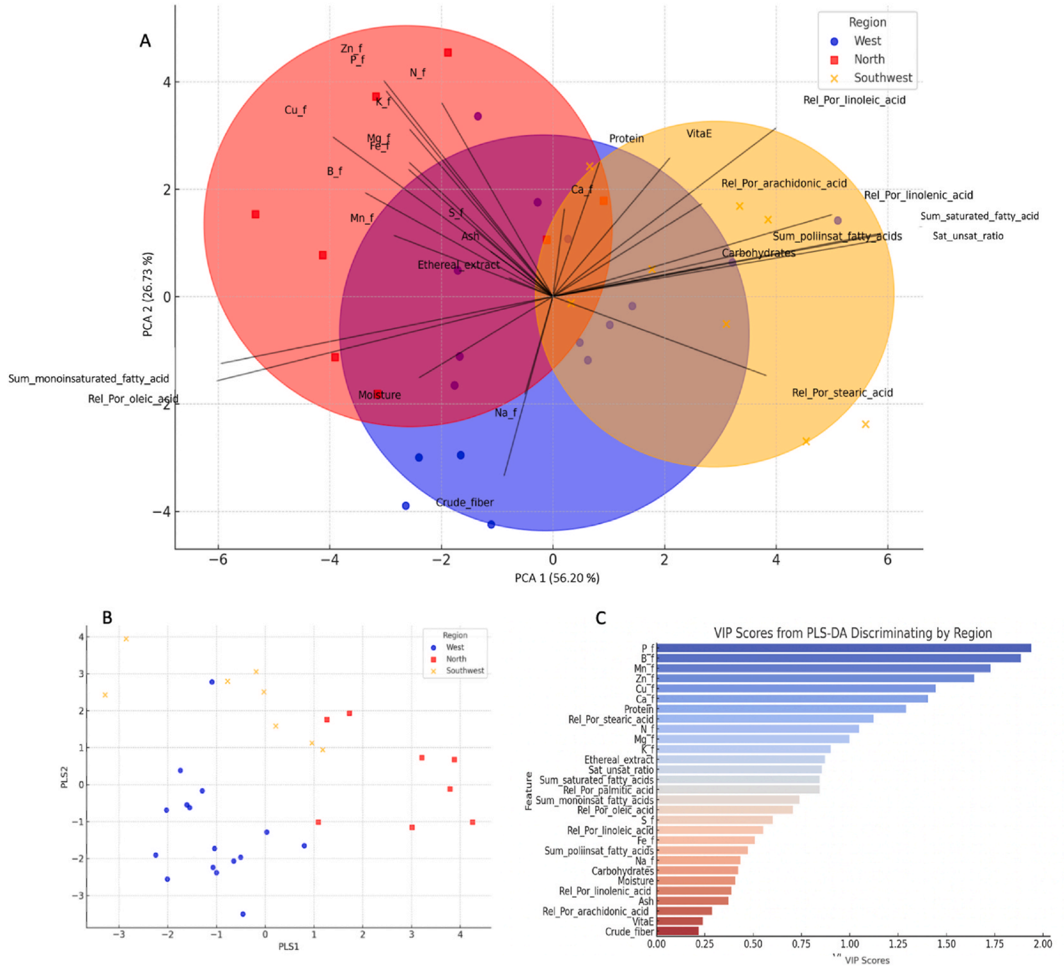

Fig. 4. Consolidated multivariate analysis of multidimensional quality variables in Hass avocado fruits from main crops (PH) and transitional crops (TH) under tropical conditions. A: principal component analysis. B and C: partial least squares discriminant analysis. The letter "f" for each element (e.g., Zn_f: Zinc in fruit) signifies that the concentration value of the nutrient was determined in the fruit.

P2, and to a lesser extent with CICE and B in P1. The carbohydrate content was positively affected by exchangeable Mg in P1 and much more by exchangeable Na in P2. The negative effect was detected with exchangeable K and Al in P1 and surprisingly with exchangeable Mg and K in P2. The moisture content of the fruits was positively affected by exchangeable Mg at both depths and negatively affected by CICE in P1 and Na in P2.

The lipid profile showed that several soil factors (at both depths) were more determinant of the fatty acid content in the Hass avocado fruits (Fig. 8). For example, the oleic acid content was positively affected by CICE in P1 and by K and Na in P2; in contrast, it was negatively affected by exchangeable Mg in both P1 and P2. Similarly, the stearic acid content tended to be higher with increased K in P1 and Mg in P2 and lower with increased Na in P2. However, arachidonic acid content was favored by the increase in K in P1 and Mg in P2 and decreased with the pH in P1 and the exchangeable Na in P2. Palmitoleic acid content was positively affected by exchangeable Mg in P1 and exchangeable Na in P2. The negative effect was detected with K at both depths and exchangeable Al in P1. The linoleic acid content was positively affected by exchangeable Mg at both depths and negatively affected by CICE at P1 and Na at P2. The sum of monounsaturated fatty acids was positively correlated with B and CICE in P1 and K and Na in P2, and negatively correlated with Mg in P1 and P2. The sum of polyunsaturated fatty acids was positively correlated with Mg at both depths and negatively correlated with Na at P2.

On the other hand, Fig. 8 shows that the palmitic acid content of the ripe fruits had a positive causal relationship in P1 with Mg and B and a negative relationship with K and pH. In P2, the correlation was positive for CICE and negative for K. Linoleic acid was positively related to Mg and acidity and negatively related to CICE and B in P1. At depth two, the relationship was positive for K and negative for Na. The sum of saturated fatty acids in P1 had a positive behavior for B, Mg and the maximum ambient temperature and a negative one for K and pH. In P2, the correlation was positive for CICE and negative for K. The saturated/unsaturated fatty acid ratio was positive for B and maximum ambient temperature and negative for K and pH at P1. In P2, it was positive for CICE and negative for K.

The contents of N, K, Na, S, and Zn in avocado fruits were positively associated with the level of exchangeable Mg in P1 and, in some

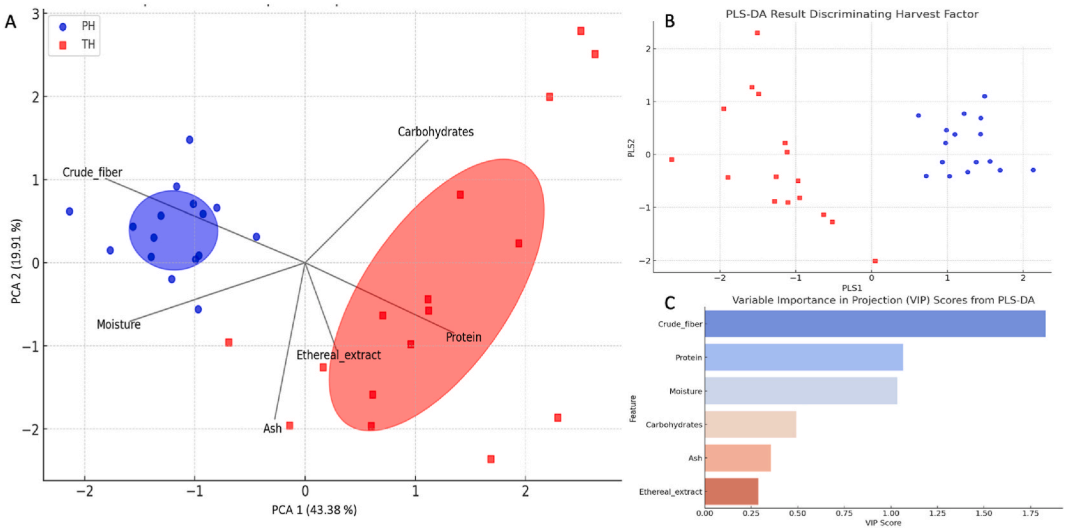

Fig. 5. Multivariate analysis associated with macronutrient quality in Hass avocado fruits from principal (PH) and transitory (TH) harvests under tropical conditions. A: principal components analysis. B and C: partial least squares discriminant analysis.

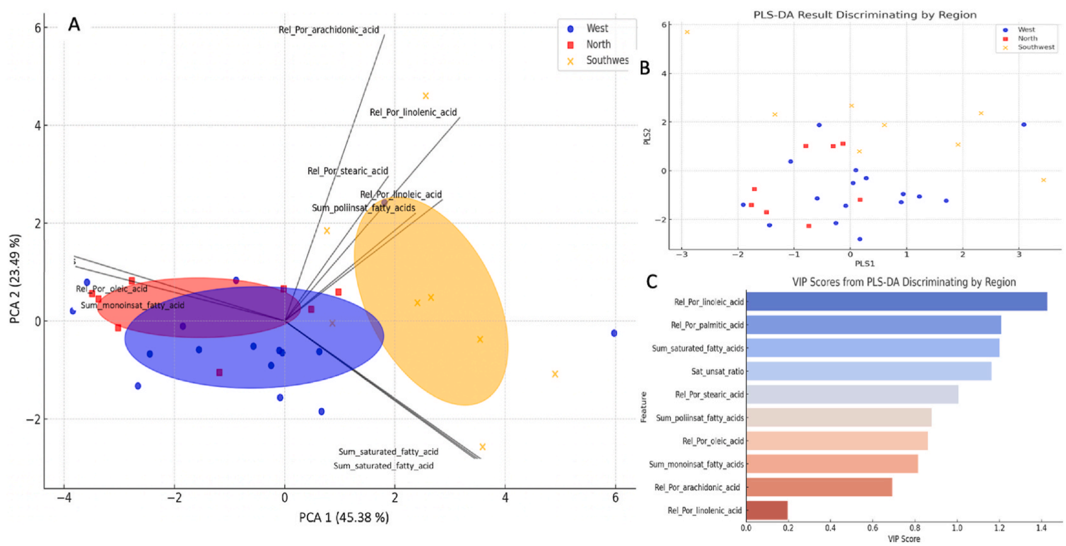

Fig. 6. Multivariate analysis associated with fatty acid quality in Hass avocado fruits of principal different geographical locations (west, east, and southwest) under tropical conditions. A: principal components analysis. B and C: partial least squares discriminant analysis.

cases, with K and Na in P2. B was positively associated with the level of B in the soil, which was also positively associated with the content of P, Mg, Cu and Mn in the fruits. However, there was a positive association of the Ca, Mn and vitamin E fruit content with the CICE in the soil (Fig. 8).

On the contrary, there was a negative association of CICE in P1 with N, K, Na, and S. Additionally, B in the soil in P1 was negatively associated with the fruit contents of N, K, Na, and Zn, and in P2, with Cu, Mn, and B in the fruits. There was a negative relationship between exchangeable Mg in P1 with P, Ca, Mg, Cu, Mn and vitamin E in fruits and exchangeable Mg in P2 with K, Ca, Mg and Cu in fruits. Similarly, exchangeable K in P2 was negatively associated with N, S, Fe, and Zn in fruits (Fig. 8).

4. Discussion

Our multifaceted approach, integrating traditional analysis methods such as ANOVA and multivariate methods like PCA, was combined with new analysis strategies under a modern framework including effect size, confidence intervals, PLS-DA, and models for determining and quantifying relationships like polynomial models. This allowed for an approach to understanding the determinants of multidimensional quality of avocados under tropical conditions. Not only did it provide insight into general patterns associated with

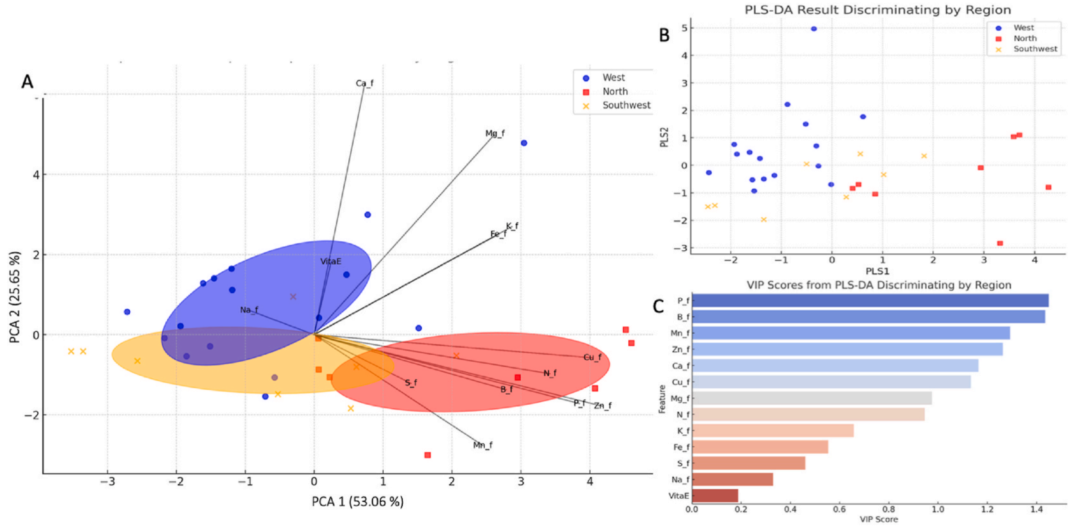

Fig. 7. Multivariate analysis associated with micronutrient quality in Hass avocado fruits from different principal geographical locations (west, east, and southwest) under tropical conditions. A: principal components analysis. B and C: partial least squares discriminant analysis. The letter "f" for each element (e.g., Ca_f: calcium in fruit) signifies that the concentration value of the nutrient was determined in the fruit. The letter "f" for each element (e.g., Zn_f: Zinc in fruit) signifies that the concentration value of the nutrient was determined in the fruit.

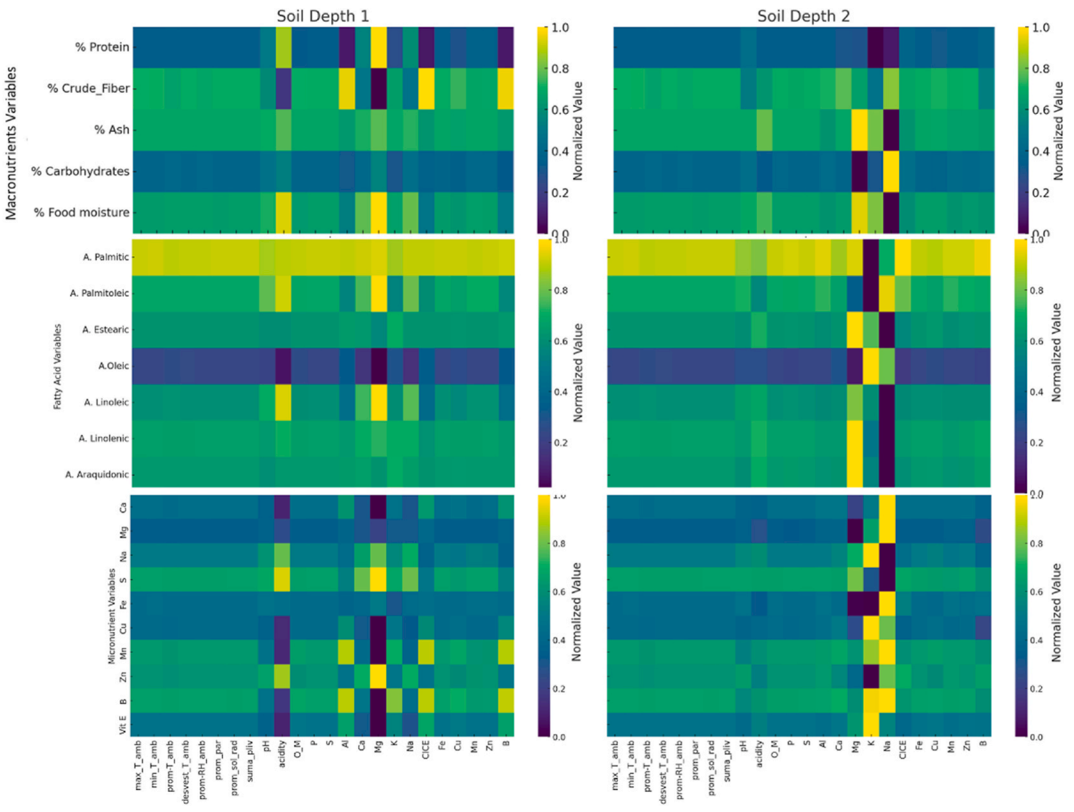

Fig. 8. Polynomial analysis of edaphoclimatic variables and their relationship with the macronutrient quality parameters, fatty acid and mineral content of Hass avocado fruits under tropical conditions.

macro parameters (lot location and harvest type), but it also allowed for specific identification of the type (positive-negative) and size (effect size) of these relationships both at the macro level and specifically in relation to local sources of variation (plot) such as soil and climatic characteristics.

We confirm the results obtained by different authors and new evidence associated with the quality parameters of the cv was generated. Hass avocados and especially the concentration of fatty acids are largely determined by the edaphoclimatic characteristics of the region of origin [8,13]. Specifically, in our case we found that for most fatty acids, the variables associated with location or region have a higher probability of explaining the behavior of palmitic acid, stearic acid, the sum of saturated fatty acids and the relationship between unsaturated and saturated fatty acids. This is partly due to the relationship between altitude and the maximum, average, and minimum temperature and precipitation variables, characteristics that played a role in the productive units evaluated in all regions [19,23].

Concerning the concentration of fatty acids and their association with the specific location. This phenomenon could be attributed to the metabolism of saturated, monounsaturated and unsaturated fatty acids that are affected by environmental variables where the plots are planted and during harvest and after harvest ripening management [14,16,38,39]. In the specific case of our study, the highest concentration of established fatty acids occurred in the north, followed by the east and then the southwest, confirmed that avocados from the Northern subregion of Antioquia Colombia have a better nutritional composition [3,15,16].

The environmental variable that most positively affected avocado quality associated with the concentration of fatty acids was altitude, which presented a direct proportional relationship with the increase in oleic acid and the sum of monounsaturated fatty acids, as well as a lower ratio of saturated/unsaturated fatty acids. It is important to understand that in the tropical zone, elevation partly governs the behavior of the temperature, where at higher elevation, a lower temperature occurs, causing longer phenological phases in avocado [24], giving place to greater accumulation of nutrients in fruits, which considerably improves the biofunctional quality [3,18]. Furthermore, low-altitude plots increased saturated fatty acids and linolenic acid concentration, as reported for tropical and subtropical conditions [14,16].

However, the concentration of fatty acids was affected by variations in the soil, mainly by the concentrations of exchangeable ions such as Mg and K. Furthermore, the macroregion has an impact on fatty acids, especially good fatty acids (mono and polyunsaturated), where the north and east regions as the the coolest zones presented the highest concentration. The results obtained in another species showed that soil-exchangeable Mg and K can control at some level the concentration of fatty acids, as they play an important role in the synthesis of these compounds [40]. It should be clarified that the concentration of fatty acids in avocado was not only determined by soil factors that can be partially controlled with fertilization management, but there was a set of variables that are not subject to control. Therefore, they must be considered when choosing the location of crops.

Furthermore, the influence of the type of harvest (principal and transitory) and region showed that the fatty acids were affected by harvest rather than by the interaction between region and harvest, which was more evident in the main harvest than in the transitory harvest. Similar results were reported in Mexico, where differences between regions and harvests were found in evaluations carried out in Jalisco, Nayarit and Michoacán [41].

As an important result of our work, fatty acids from Colombian avocados were found to be found to be higher than those reported worldwide [13,22,42]. Furthermore, we confirm that the acid found in higher concentrations in Hass avocados is oleic acid (53 %), followed in decreasing order by palmitic (20 %), linoleic (14 %), palmitoleic (7 %) and linolenic acid (4 %). Here, the average content of oleic acid was 59.76 %, and palmitic acid 17.84 %, creating a lower ratio between saturated and unsaturated fatty acids. Colombian avocados have the highest concentrations of mono and polyunsaturated fatty acids and the lowest saturated-unsaturated ratio, providing the best fatty acid profile. Colombian avocado producers could use this to access niche markets that are willing to pay a better price for these characteristics.

On the other hand, the macronutrient composition was strongly influenced by the origin of the plot, where the concentration in the southwest region for carbohydrate and protein content was significantly higher than in the north region. As one of the possible reasons for this variation, we found that the Mg-exchangeable soil positively affected the concentration of protein, ash, moisture content and crude fiber, with the help of exchangeable sodium, and negatively affected the concentration of protein, ash, and moisture content. Similar results have been reported where exchangeable soil Mg influenced the carbohydrate content, which together with Mn acted as important cofactors of enzymes that act in the maturation and hydrolysis of carbohydrates and lipids [14,15].

Regarding the mineral concentrations, avocado fruits are affected by intrinsic factors, such as metabolic reactions that occur at the cellular and genetic levels, and by extrinsic factors such as agronomic practices of the crop of the crop and environmental factors of the environmental factors of the environmental factors of the soil and climate, as evidenced by differences in concentrations between study varieties [43,44]. The minerals in fruits are synthesized by plants during the development phase, and their balance in the fruits must remain constant during the physiological ripening process and after harvest [45]. However, the overall balance of minerals in avocados is affected by external factors such as harvest times, climatic conditions, soil quality, and cultural practices, among others [21,44,46].

Previous research has related the mineral content of the soil to the yield and the concentration of fruits in terms of the severity of postharvest diseases and the quality of the fruits [14,43,47], but not for the nutrient content of fruits with the mineral content of the soil and its relationship with spatial and seasonal differences. On the basis of our result, notably, the content of B in the soil mainly affects the concentration of minor nutrients (Cu, Zn, Fe and Mn) and major nutrients (N and S) in fruits. Therefore, there is an opportunity to provide application recommendations to monitor these elements, especially with edaphic or foliar applications of B, which are very common in the preflowering and flowering stages of avocado [48]. This could suggest that it is possible for other micronutrients to be applied in a chelated form in addition to B to maintain nutritional balances in trees.

Our result confirmed the complex nature of causality analyses, where an effect is not associated with a particular cause, but with a sum of causes that have a complex perspective on the importance of a consortium of variables on aspects of interest. Finally, the results indicated that both soil and environmental variables can have a considerable impact on the nutritional quality of Hass avocado fruits. Therefore, it is recommended that a detailed review of historical climatic data is carried out when choosing a cultivation area, and once established, farmers should carry out rigorous soil and foliar analyzes not only for potential effects on soil dynamics, but also because of potential relationships with the nutritional quality of avocado fruits.

The edaphic and environmental characteristics impart special characteristics in terms of nutritional composition, allowing Colombian avocados to be denoted by origin as proposed [3,13,15,16], which is associated with the edaphoclimatic characteristics of altitude, minimum, average and maximum temperature and precipitation, solar radiation, and the composition of exchangeable bases such as Ca, Mg, and K, along with the relationship between them.

As we consider future perspectives on the identification of optimal avocado production areas in tropical conditions and emphasize the maximization of the biofunctional characteristics of the fruit, a compelling avenue to advance agricultural practices. Exploring the potential of avocado cultivation in various tropical regions requires a holistic approach that integrates climatic, soil and agroecological factors to define environments conducive to biofunctional excellence.

Moving forward, the next step in future endeavors extends beyond the identification of optimal cultivation zones. It involves using this knowledge to characterize avocados with exceptional biofunctional quality, a crucial aspect in aligning avocados with distinct and high-value market niches. An understanding of the intricate interplay between environmental conditions and biofunctional attributes equips us with tools to tailor cultivation practices and, consequently, the biofunctional profile of avocados to meet the specific demands of discerning consumers and industries. Additionally, this wealth of information can be instrumental in establishing quality standards, ensuring consistency, and ultimately elevating avocados to meet the stringent requirements of high-value market segments.

It is important to note that the results of our study made a concerted effort to ensure the validity of the findings given the high climatic and edaphic variability in tropical regions. However, achieving a greater characterization of multidimensional quality parameters in other study regions is necessary, which could increase the capture of possible greater variability. Furthermore, we suggest in future studies to include detailed information on key agronomic practices affecting quality, such as integrated fertilization management programs, sanitary issues, pruning techniques, harvest criteria, etc., as well as the genetic characteristics of the rootstock and canopy, which are highly determinant of avocado quality.

5. Conclusions

The results confirmed the hypothesis that the quality of Hass avocado is affected by soil and climatic factors, along with changes in spatial aspects (lot location) and seasonality of the harvest (principal and transitory). These factors influence the concentration of macro and micronutrients, as well as the proportion of fatty acids and bromatological compounds.

Data availability statement

Data included in article/supplementary material/referenced in article.

CRediT authorship contribution statement

Jaime Horacio López-Hoyos: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan Camilo Henao-Rojas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Nelson Walter Osorio-Vega:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Joaquín Guillermo Ramírez-Gil:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Joaquin Guillermo Ramirez Gil reports was provided by National University of Colombia. Joaquin Guillermo Ramirez Gil reports a relationship with National University of Colombia that includes: board membership. If there are other authors, they 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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Appendix A. Supplementary data

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