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Impact of Soil Characteristics on the Nutraceutical Composition of Melon Fruits
Impacto de las Características Edáficas en la Composición Nutracéutica de Frutos de Melón

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SUMMARY

The nutraceutical quality of *Cucumis melo* L. fruits is influenced by edaphic conditions, particularly in arid and semiarid regions where salinity, alkalinity, and low fertility are common. This study aimed to evaluate the relationship between soil physicochemical properties and the commercial and nutraceutical quality of melon fruits in four orchards located in Matamoros, Coahuila, Mexico. Soil analyses were conducted following the NOM-021-SEMARNAT-2000 standard, and fruit quality parameters were determined, including soluble solids, firmness, rind thickness, and the content of bioactive compounds (phenolics, flavonoids, and antioxidant capacity). Results indicated that, although fruit size and weight were homogeneous among sites, nutraceutical quality showed significant variation. The "La Roca" site exhibited the highest levels of functional compounds, while "Ardillas" stood out for its sweetness. Spearman's correlation and principal component analyses revealed significant associations between soil organic matter, texture, and nutraceutical quality. These results highlight the impact of edaphic characteristics on the functional quality of melon fruits, providing a basis for implementing soil management strategies to enhance the nutraceutical value of melon crops in arid and semiarid conditions.

Index words: *Cucumis melo* L., *nutraceutical quality, soil analysis*.

RESUMEN

La calidad nutracéutica de los frutos de *Cucumis melo* L. está influenciada por las condiciones edáficas del suelo, especialmente en regiones áridas y semiáridas donde la salinidad, alcalinidad y baja fertilidad son comunes. Este estudio evaluó la relación entre las propiedades físico-químicas del suelo y la calidad comercial y nutracéutica de frutos de melón en cuatro predios del municipio de Matamoros, Coahuila. Se realizaron análisis de suelo conforme a la NOM-021-SEMARNAT-2000 y se determinaron parámetros de calidad del fruto, incluyendo sólidos solubles, firmeza, espesor de cáscara y contenido de compuestos bioactivos (fenoles, flavonoides y capacidad antioxidante). Los resultados mostraron que, aunque el tamaño y peso del fruto fueron homogéneos entre sitios, la calidad nutracéutica varió significativamente. El predio "La Roca" presentó los mayores niveles de compuestos funcionales, mientras que "Ardillas" destacó por su dulzor. El análisis de correlación de Spearman y componentes principales reveló asociaciones significativas entre materia orgánica, textura del suelo y calidad nutracéutica. Estos hallazgos permiten identificar estrategias de manejo edáfico para mejorar el valor funcional del melón en zonas de producción con limitaciones edáficas.

Palabras clave: *Cucumis melo* L., *calidad nutracéutica, análisis de suelo*.

INTRODUCTION

Melon (*Cucumis melo* L.) production represents a high-value agricultural activity, particularly in arid and semiarid regions (Aragão *et al*., 2023), such as the Comarca Lagunera, an area encompassing several municipalities in the states of Coahuila and Durango, Mexico. This region is characterized by extreme climatic conditions, including low rainfall, high solar radiation, and soils with edaphic characteristics that limit crop performance (Gaytán-Mascorro *et al*., 2020; Sánchez-Rodríguez, Castillo, Pedroza, Delgadillo, and Soto, 2023). Despite these limitations, melon has become one of the most widely cultivated and commercialized fruits due to its adaptability and the growing national and international demand driven by its organoleptic properties and nutritional benefits (Olguín *et al*., 2020).

From a functional perspective, melon is an important source of bioactive compounds such as carotenoids, flavonoids, vitamins (A, C, and E), minerals (K, Mg, Ca), and dietary fiber, which contribute to the prevention of cardiovascular and degenerative diseases, as well as certain types of cancer (Bileva, Petkova, and Babrikov, 2020; Piñero, Otálora, Collado, López, and Del Amor, 2020; Rivera-Gutiérrez *et al*., 2021). The synthesis and accumulation of these bioactive compounds are modulated by genetic, environmental, and edaphic factors. Parameters such as soil pH, electrical conductivity, organic matter content, texture, and nutrient availability directly influence crop physiological development and the biosynthesis of functional compounds (Silva, Albuquerque, Ferreira, Alves, Oliveira, and Costa, 2025).

In this context, soil physicochemical characterization becomes a crucial tool for the agronomic management of crops (Hernández-Rodríguez *et al*., 2021). Detailed knowledge of edaphic conditions allows the identification of limiting factors, the design of rational fertilization schemes, and the promotion of sustainable practices that optimize both yield and the nutraceutical quality of the fruit (Borisov, Vasyuchkov, and Uspenskaya, 2022). However, there remains a knowledge gap regarding the quantitative relationship between soil properties and the nutraceutical quality of melon, which limits the full exploitation of the crop's genetic and agronomic potential.

This study aimed to characterize the physicochemical properties of soils in four orchards dedicated to melon production in the municipality of Matamoros, Coahuila, and to analyze their relationship with parameters associated with the nutraceutical quality of melon fruits, to identify the edaphic factors with the greatest influence on such quality.

MATERIALS AND METHODS

Experimental Site

The study was conducted in four melon (*Cucumis melo* L.) orchards located in Matamoros, Coahuila, Mexico: Victoria, La Roca, La Nueva, and Ardillas. Each orchard was considered a treatment. The region is part of the Comarca Lagunera, characterized by an arid climate, scarce rainfall, and soils with high salinity and low organic matter.

Soil Sampling and Analysis

Sampling areas were delimited by field inspection to identify homogeneous sectors based on color, texture, slope, and stoniness. Soil samples were collected in a zigzag pattern at 0–30 cm depth, combining five subsamples per sector into a 2 kg composite sample. Samples were air-dried, crushed, and sieved (2 mm) following NOM-021-SEMARNAT-2000 (2002). Physicochemical parameters—including pH, electrical conductivity (EC), organic matter (OM), nitrogen (N), available phosphorus (P), exchangeable potassium (K), cation exchange capacity (CEC), bulk density (Da), and texture—were determined according to the same standard. The results were interpreted based on NOM-021-SEMARNAT-2000 (2002) classification criteria to assess soil fertility and salinity levels.

Fruit Sampling and Commercial Quality

Ten ripe melon fruits (cv. 'Cruiser') were randomly collected at commercial maturity from each orchard. Fruit weight was determined using an analytical balance, and polar and equatorial diameters, rind thickness, and pulp thickness were measured with a digital caliper (Trupper®). Firmness was evaluated on the fruit peel using a penetrometer with a 3 mm caliber tip. (Extech Instruments FHT200), and soluble solids (°Brix) were measured using a portable refractometer (Atago® Master 2311, Tokyo, Japan) calibrated with distilled water between readings.

Soil analyses were conducted at the Soil Laboratory of the Universidad Autónoma Agraria Antonio Narro, Unidad Laguna. Fruit's phytochemical compounds were analyzed at the Genetics Laboratory of the Universidad Politécnica of Gómez Palacio.

Phytochemical Analyses

Extract Preparation

Pulps from all fruits per treatment were homogenized to form a composite sample. From each, 2 g were mixed with 10 mL of 80% ethanol and agitated at 70 rpm for 24 h (Remi RS–24BL, Jayanti Scientific). The mixture was centrifuged at 3000 rpm for 5 min, and the supernatant was used for analysis. Extractions were performed in triplicate per treatment.

Total Phenolics

Total phenolic content was determined by the Folin–Ciocalteu method (Singleton, Orthofer, and Lamuela, 1999). The mixture contained 300 µL of extract, 1080 µL of distilled water, and 120 µL of Folin–Ciocalteu reagent (Sigma-Aldrich, St. Louis, MO, USA). After 30 min, 0.9 mL of 7.5% Na_2CO_3 was added, mixed for 30 min, and allowed to stand for 10 min. Absorbance was measured at 765 nm using a UV/VIS spectrophotometer (VE-5100UV). Results were expressed as mg gallic acid equivalents (GAE) per 100 g fresh weight (FW).

Total Flavonoids

Total flavonoids were quantified using the Lamaison and Carnet (1990) method. The reaction mixture contained 250 µL of sample, 75 µL of 5% $NaNO_2$, and 1250 µL of distilled water, followed by the addition of 150 µL of 10% $AlCl_3$, 150 µL of 1 M NaOH, and 250 µL of distilled water. Absorbance was measured at 510 nm (VE-5100UV). Results were expressed as mg quercetin equivalents (QE) per 100 g FW.

Antioxidant Activity

Antioxidant capacity was determined *in vitro* using the $DPPH^+$ method (Brand-Williams, Cuvelier, and Berset, 1995). A 0.025 mg mL^{-1} ethanolic $DPPH^+$ solution (Aldrich) was mixed with 50 µL of extract and incubated for 25 min in the dark. Absorbance was recorded at 517 nm, and results were expressed as µM Trolox equivalents per 100 g^{-1} FW.

Statistical Analysis

The experiment was arranged in a completely randomized design, considering each orchard as a treatment with five soil subsamples and five fruit replicates. Data were subjected to one-way analysis of variance (ANOVA), and means were compared using Tukey's test ($p \leq 0.05$). Spearman's correlation analysis was used to determine relationships between soil properties and fruit phytochemical parameters. Principal component analysis (PCA) was performed to identify the most influential soil factors associated with melon nutraceutical quality. All statistical analyses were conducted using R Studio software (R version 4.4.2).

RESULTS AND DISCUSSION

The values of the soil physicochemical characteristics (Table 1) show that pH ranged from 7.87 to 8.05, a range that, according to NOM-021-SEMARNAT-2000 (2002), corresponds to moderately alkaline soils (7.4–8.5). Although these values are not extreme, they deviate from the optimal range of 6.0–7.0, which reduces nutrient availability—particularly phosphorus (P) and micronutrients—and may lead to nutritional deficiencies that affect crop yield (Tsukagoshi and Shinohara, 2020). Organic matter (OM) content ranged from 1.30 to 1.64%, while organic carbon fluctuated between 0.73 and 0.93%. These values are classified as moderately low to moderate, implying limited biological activity, greater susceptibility to compaction, and reduced soil water retention capacity (Hoffland, Kuyper, Comans, and Creamer, 2020; Lal, 2020; Lyczak, Kabrick, & Knapp, 2021). Accordingly, total nitrogen levels (0.10–0.13%) are considered low, highlighting the need for a nitrogen fertilization program tailored to the needs of melon cultivation, which is highly demanding in this element.

Table 1. Results of the physicochemical analyses of soils from four sites in the municipality of Matamoros, Coahuila.

Parameter	Location			
	La Nueva	Vitoria	La Roca	Ardillas
pH	8.05±0.05 a	7.98±0.06 b	8.00±0.02 b	7.87±0.01 c
OM (%)	1.30±0.02 c	1.41±0.03 b	1.43±0.01 b	1.64±0.06 a
OC(%)	0.73±0.03 c	0.83±0.05 b	0.83±0.01 b	0.93±0.05 a
N (%)	0.11±0.01 b	0.12±0.01 b	0.10±0.01 c	0.13±0.01 a
P (mg kg^{-1})	20.32±0.21 a	13.65±0.036 c	10.50±0.22 d	15.69±0.49 b
K (mg kg-1)	164.22±0.01 b	191.59±0.01 a	156.40±0.01 c	156.40±0.01 c
CEC (cmol(+) kg^{-1})	32.33±0.58 a	26.33±2.31 c	24.33±2.65 d	30.17±1.44 b
EC (dS m^{-1})	6.94±0.06 d	9.67±0.07 b	8.48±0.23 c	13.12±0.29 a
Sand	10.24±0.14 d	14.24±0.28 b	13.15±1.57 c	20.91±1.15 a
Clay	50.32±0.55 a	32.32±0.85 d	47.76±1.57 b	36.48±1.15 c
Silt	39.44±1.28 c	53.44±1.63 a	39.26±1.28 c	42.61±1.15 b
Textural Class	Clay	Clay Loam	Clay	Clayey Loam
Da (gr cm^{-3})	1.10 ±0.02 c	1.18±0.04 b	1.29±0.03 a	1.21±0.04 b

* Data are shown as mean ±SD. Rows with different letters indicate statistically significant differences according to Tukey's test ($p \leq 0.05$).

Electrical conductivity (EC) showed elevated values, ranging from 6.94 to 13.12 dS m^{-1}, classifying the soils as moderately to strongly saline in La Nueva and strongly saline in the other locations (Negacz, Malek, de Vos, and Vellinga, 2022). These levels represent a significant limitation for productivity, as salinity reduces water uptake due to osmotic effects and alters mineral nutrition and plant physiological functions (Aslam *et al*., 2020). In arid and semi-arid regions such as Matamoros, salt accumulation has been exacerbated by intensive fertilizer use and irrigation water, contributing to soil fertility degradation and declining agricultural productivity (Shao, Tan, and Li, 2016). Cation exchange capacity (CEC) ranged from 24.33 to 32.33 cmol(+) kg^{-1}, values classified as medium to high. This result reflects the influence of clay and OM content and suggests adequate soil capacity to retain essential cations; however, high salinity may induce ionic competition and reduce the effective availability of nutrients (Chhabra, 2021).

Regarding phosphorus availability, soils showed concentrations between 10.50 and 20.32 mg kg^{-1}, corresponding to medium to high levels. Nevertheless, in calcareous and alkaline soils, a considerable fraction of P becomes immobilized as calcium phosphates or through adsorption onto carbonates and clays, limiting its agronomic efficiency (Gai *et al*., 2024). Exchangeable potassium ranged from 156.40 to 191.59 mg kg^{-1}, which is classified as low to medium depending on the reference criteria used. Therefore, complementary potassium fertilization should be considered due to the importance of this nutrient in fruit quality, drought stress tolerance, and water use efficiency (Suchithra and Pai, 2020). Bulk density varied between 1.10 and 1.29 g cm^{-3}, an adequate to slightly elevated range; higher values, combined with low OM levels, suggest some degree of compaction and reduced porosity, which could restrict root development and promote surface waterlogging (Jaramillo, Jiménez, Triana, and Ávila, 2022). Soil texture was classified as clayey to clay loam, with a predominance of fine fractions, which favors moisture retention and CEC but may limit aeration and drainage (Li, Li, Liu, and Qin, 2021; Urriola, 2020).

In general, the evaluated soils exhibit conditions of alkalinity, moderate to high salinity, and low to moderate levels of organic matter, nitrogen, and potassium—factors that pose limitations for melon cultivation, which is considered moderately sensitive to salinity. In light of these conditions, it is advisable to implement management practices aimed at mitigating the identified constraints, such as periodic salt leaching when water quality and drainage allow, incorporation of organic amendments to improve OM and soil structure, application of phosphate sources via band placement or in combination with humic or fulvic acids to reduce P fixation, and nitrogen and potassium fertilization programs adjusted to crop phenology and demand. Additionally, regular monitoring of soil salinity and pH is crucial to evaluate the effectiveness of management practices and prevent further degradation of fertility in this productive region.

The results of melon fruit quality variables obtained from different plots (Table 2) show that the average fruit weight ranged from 1.58 to 1.87 kg, with no statistically significant differences among locations. These values are consistent with previous studies conducted in the Comarca Lagunera, where average fruit weights between 1.55 and 1.7 kg have been reported (García-Mendoza, Cano, and Reyes, 2019; Rivera-Gutiérrez *et al*., 2021). Similarly, polar diameters (16.48–18.00 cm) and equatorial diameters (14.70–16.00 cm) showed comparable values across all sites, indicating that the edaphic environment did not significantly influence fruit size or shape. These values are higher than those reported for cantaloupe melon genotypes, which range from 10.40 to 12.53 cm in polar diameter and 10.5 to 16.07 cm in equatorial diameter (Chikh-Rouhou, Tlili, Ilahy, R'him, and Sta-Baba, 2021; Soltani, Shajari, Mirbehbahani, and Bihamta, 2022).

However, significant differences were observed in total soluble solids content (°Brix), with a maximum of 13.50 in Ardillas, followed by Victoria (12.00), while La Nueva and La Roca showed lower values (10.78–10.90). This parameter is a key indicator of melon sensory quality, as it reflects soluble sugar content and thus sweetness perception. Values above 12 °Brix are generally considered optimal for fresh consumption (Zeb *et al*., 2021), suggesting that fruits from Ardillas and Victoria had superior quality in this regard.

Fruit firmness also varied among locations, ranging from 0.72 kg in La Nueva to 1.40 kg in La Roca, the latter showing the highest resistance to pressure, which suggests better storage capacity and shelf life (Espinosa-Carillo and Vallejo-Cabrera, 2020). Firmness, along with rind thickness, is crucial for mechanical resistance and reducing postharvest losses (Farcuh *et al*., 2020). In this context, significant differences were observed in rind thickness, with La Nueva producing fruits with the thickest rind (5.00 mm), which may provide greater protection during transport and storage (Espinosa-Carillo and Vallejo, 2020; Jurado-Erazo, Tulcán, and Rojas, 2023), while fruits from Victoria and La Roca had thinner rinds (2.50 mm). In contrast, pulp thickness ranged from 3.50 to 4.23 cm, with no statistically significant differences, suggesting that this trait may be genetically determined.

Regarding bioactive compounds, clear differences were found among plots. Total phenolic content ranged from 48.86 to 61.76 mg GAE 100 g^{-1} FW, with the highest value in La Roca and the lowest in La Nueva. Flavonoid content followed a similar pattern, with 51.76 mg QE 100 g^{-1} FW in La Roca and 36.36–36.50 mg QE 100 g^{-1} FW in La Nueva and Ardillas. In terms of antioxidant capacity, La Roca also stood out with 43.16 µM Trolox equivalents 100 g^{-1} FW, significantly higher than the other sites, especially compared to La Nueva and Ardillas (27.90–28.26). These results suggest that, although yield parameters (fruit weight and size) were similar across plots and likely associated with the genetic material studied, nutraceutical quality showed important variation linked to location, with La Roca presenting the highest levels of phenolic compounds, flavonoids, and antioxidant capacity. This is relevant as these compounds contribute not only to the functional quality of the fruits but also to their added value in terms of health benefits and consumer acceptance (Chikh-Rouhou *et al*., 2021; Rivas-García *et al*., 2021).

Table 2. Melon fruit quality in four sites in the municipality of Matamoros, Coahuila.

Parameter	Location			
	La Nueva	Victoria	La Roca	Ardillas
Fruit Weight (kg)	1.58±0.19 a	1.87±0.62 a	1.65±0.13 a	1.74±0.27 a
Polar Diameter (cm)	16.75±0.87 a	18.00±1.96 a	17.08±1.98 a	16.48±1.92 a
Equatorial Diameter (cm)	15.45±1.54 a	14.93±1.64 a	16.00±1.47 a	14.70±1.51 a
°Brix	10.78±1.47 b	12.00±2.34 ab	10.90±1.09 b	13.50±2.38 a
Firmness (kg)	0.72±0.41 b	1.10±0.09 ab	1.40±0.58 a	0.89±0.54 ab
Peel Thickness (mm)	5.00±2.71 a	2.50±0.58 b	2.50±1.00 b	3.00±0.82 b
Pulp Thickness (cm)	3.75±0.53 a	3.50±0.29 a	4.23±0.98 a	3.63±0.21 a
Phenols (mg GAE 100 g^{-1} PF)	48.86±0.64 d	54.65±0.80 b	61.76±0.75 a	51.08±0.94 c
Flavonoids (mg QE 100 g^{-1} PF)	36.36±1.10 c	43.90±0.90 b	51.76±1.29 a	36.50±2.14 c
Antioxidant capacity (100 µM Trolox equivalents g^{-1} PF)	28.26±1.30 c	36.05±1.26 b	43.16±1.29 a	27.90±2.14 c

** Data are shown as mean ±SD. Rows with different letters indicate statistically significant differences according to Tukey's test ($p \leq 0.05$).

The above results indicate that edaphic conditions did not affect fruit size and weight but did influence the accumulation of sugars and secondary metabolites. The sites Ardillas and Victoria stood out for promoting higher °Brix content in fruits, while La Roca showed the best nutraceutical quality with higher levels of phenolics, flavonoids, and antioxidant capacity, as well as greater firmness, which could translate into fruits with longer postharvest life. These findings highlight the importance of integrating physicochemical and nutraceutical quality indicators in the evaluation of production sites, as they allow the identification of areas with differentiated potential to supply specific markets demanding fruits with high organoleptic quality or functional value.

When analyzing the relationship between soil characteristics (Table 1) and fruit quality (Table 2) by plot, it was observed that edaphic parameters exerted a differentiated influence. In general, the physicochemical properties of the soil did not significantly affect fruit size and weight, but they did have a decisive impact on quality. In this regard, balanced fertility at the Ardillas site favored sugar accumulation, while the high availability of potassium and phosphorus recorded at La Roca stimulated the synthesis of phenolics and flavonoids, increasing antioxidant capacity. In contrast, soils at La Nueva limited nutraceutical quality, despite producing fruits with greater mechanical resistance associated with thicker rinds. At Ardillas, the moderate organic matter content (1.28%) and phosphorus (20.55 mg kg^{-1}) were associated with sweeter fruits (13.50 °Brix), suggesting that moderate fertility may promote soluble sugar accumulation. This behavior aligns with previous reports indicating that excess nitrogen reduces soluble solids concentration, while balanced fertility conditions favor their increase (Yang *et al*., 2023).

At La Roca, where relatively high potassium (0.92 cmol (+) kg^{-1}) and phosphorus (24.67 mg kg^{-1}) levels were recorded, fruits showed the highest firmness (1.40 kg), as well as the highest levels of phenolics, flavonoids, and antioxidant capacity. Potassium is an essential nutrient in sugar synthesis and translocation, and it also participates in enzymatic activation involved in secondary metabolite formation, which explains the higher nutraceutical content observed at this site (Galván-Cardona *et al*., 2024). Additionally, greater firmness may be related to increased cell wall thickness and synthesis of structural compounds, processes influenced by potassium and calcium availability (Huang *et al*., 2023). In contrast, La Nueva, characterized by the lowest electrical conductivity (6.91 dS m^{-1}) and the thickest rind (5.0 mm), produced fruits with lower internal quality (10.78 °Brix, 48.86 mg GAE 100 g^{-1} FW, and 28.26 μM Trolox equivalents 100 g^{-1} FW). These results suggest that greater investment by the plant in protective structures, such as a thicker rind, may limit the accumulation of soluble and nutraceutical compounds in the pulp (Chikh-Rouhou *et al*., 2021). Finally, at Victoria, with slightly alkaline pH (8.00) and intermediate nutrient availability, fruits showed moderate values of soluble solids (12.00 °Brix) and intermediate antioxidant capacity (36.05 μM Trolox equivalents 100 g^{-1} FW). This site represents a balance between organoleptic and nutraceutical attributes, although without standing out in any specific parameter.

Spearman correlation analysis identified significant relationships between soil physical and chemical properties and the accumulation of bioactive compounds in the fruits (Figure 1). Strong positive correlations were observed between organic matter and bulk density with antioxidant capacity ($\rho = 0.99$ and $\rho = 0.91$, respectively), suggesting that soils with higher OM content favor secondary metabolite synthesis. This effect may be attributed to greater nutrient availability and enhanced microbial activity, factors that stimulate antioxidant responses in plants (Singh, Wu, Shao, and Zhang, 2022).

A significant positive correlation was also identified between phenolic content and fruit firmness ($\rho = 0.90$), reinforcing the relationship between nutraceutical quality and firmness (Mallek-Ayadi, Bahloul, Baklouti, and Kechaou, 2022). In contrast, phosphorus (P) showed strong negative correlations with flavonoids and antioxidant capacity ($\rho = -0.90$), indicating that excess P may inhibit the accumulation of these bioactive compounds, possibly by altering nutritional balance or interfering with specific metabolic pathways (Waqas *et al*., 2023).

Regarding soil physical properties, a negative correlation was found between sand content and CEC ($\rho = -0.91$), suggesting that sandier soils have lower fertility (Javed, Ali, Afzal, Osman, and Riaz, 2022). Additionally, electrical conductivity was negatively correlated with clay content ($\rho = -0.94$), indicating that soils with higher clay fractions may offer more favorable conditions for the accumulation of functional compounds due to their moisture retention and CEC capacity (Abbaslou, Hadifard, and Ghanizadeh, 2020).

Potassium showed significant correlations with °Brix, indicating that this element is associated with soluble sugar accumulation and, therefore, fruit flavor (Galván-Cardona *et al*., 2024). This relationship highlights the importance of adequate potassium nutrition to improve organoleptic attributes.

Principal component analysis (PCA) on standardized variables (Figure 2) explained 60.1% of the total variation in the first two axes (PC1: 31.2%, PC2: 28.9%). PC1 describes a gradient opposing functional compounds—phenolics, flavonoids, AOX, firmness, and bulk density (negative loadings; collinear vectors)—against Brix, EC, OM, sand, and nitrogen (positive loadings), revealing a trade-off between nutraceutical quality and soluble solids content. In PC2, pH, clay, rind thickness, phosphorus, and CEC showed positive loadings, while EC, OM, sand, Brix, silt, organic carbon, bulk density, and the nutraceutical block (phenolics–flavonoids–AOX) and firmness loaded negatively. Fruit weight, polar/equatorial diameters, and pulp thickness were located near the origin, indicating minor contributions to PC1–PC2.

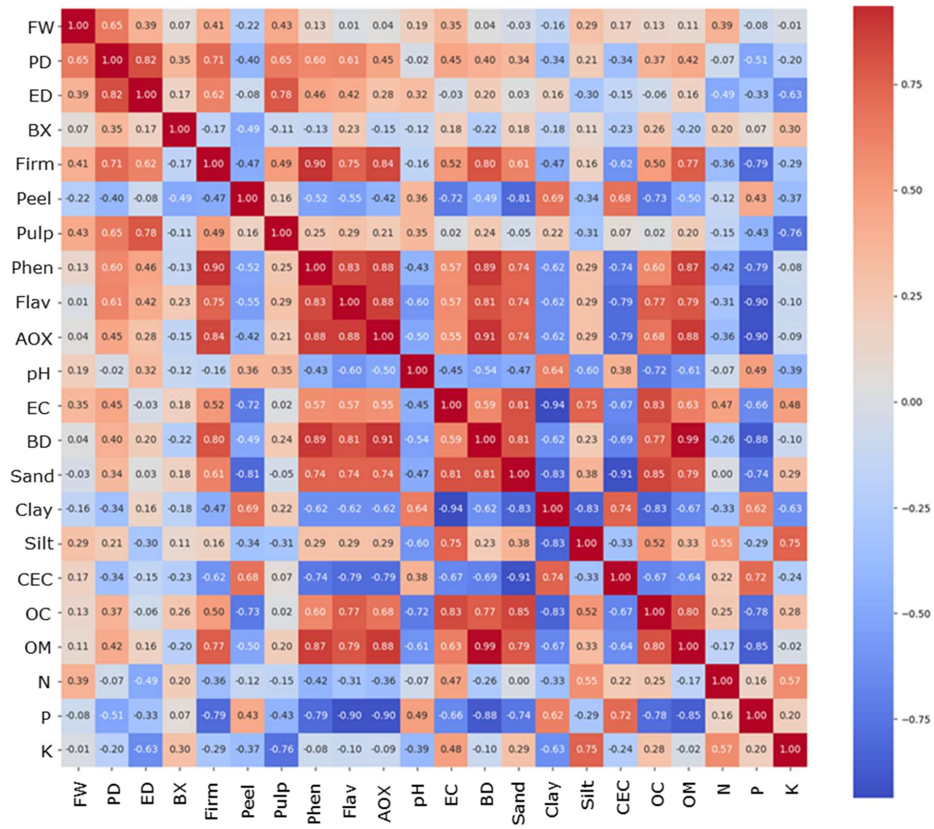

Figure 1. Spearman correlation diagram of physicochemical soil variables and melon fruit quality traits.

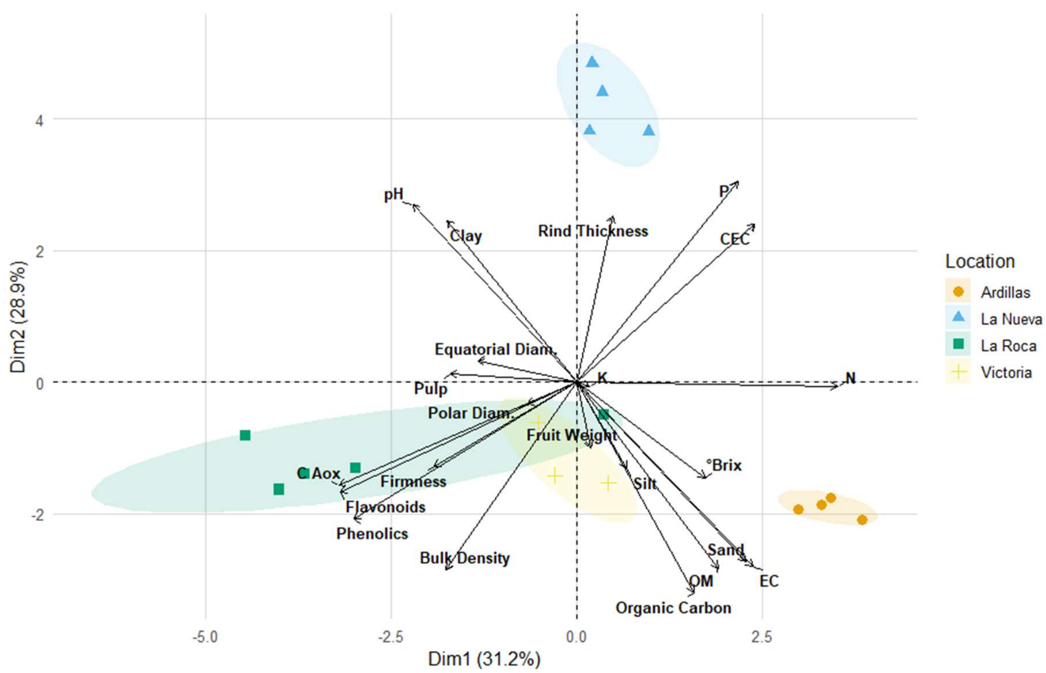

Figure 2. PCA biplot of soil and melon fruit quality variables by location.

The projection of the plots shows clear separation: La Roca is located in the quadrant with high values of functional compounds (negative PC1), Ardillas aligns with higher Brix and the EC–OM–sand set (positive PC1, negative PC2), La Nueva is positioned in the zone of higher pH, clay, and rind thickness (positive PC2), and Victoria is near the origin with intermediate values and slight association with silt/fruit weight. The orientation and length of the vectors confirm that phenolics–flavonoids–AOX covary strongly (nearly parallel vectors), while their opposition to Brix/EC suggests inverse relationships. These patterns are consistent with the Spearman correlation matrix, reinforcing that organic matter, texture, and soil nutrient conditions differentially modulate melon internal quality depending on location.

CONCLUSIONS

Soil properties did not affect melon fruit size or weight, but they significantly influenced nutraceutical quality. Organic matter and potassium promoted the accumulation of bioactive compounds and soluble sugars, while excess phosphorus negatively impacted flavonoids and antioxidant capacity. To improve fruit quality, sustainable management practices are recommended, including reducing soil salinity, increasing organic matter, and applying potassium and phosphorus fertilizers in a balanced and site-specific manner.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

Data sets used or analyzed during the current study are available from the corresponding author upon reasonable request.

COMPETING INTERESTS

The authors declare that there are no conflicts of interest related to this article.

FINANCING

Not applicable.

AUTHORS' CONTRIBUTIONS

Conceptualization: G.Z.S., and P.P.R. Formal analysis: J.M.G.D., J.A.T.R. Research: L.ZE. Methodology: A.G.T. Project management: A.B.G. Supervision: G.Z.S. Validation: P.P.R. Visualization: A.G.R. Writing - original draft: G.Z.S., Writing - review and editing: P.P.R. The authors read and approved the final manuscript.

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