Influence of ripening stages on the phytochemical composition of the hydroethanolic extract of *Alibertia edulis* (Rich.) A. Rich. ex DC. fruits.

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*Influencia de los estadios de maduración en la composición fitoquímica del extracto hidroetanólico de los frutos de **Alibertia edulis** (Rich.) A. Rich. ex DC*

*Influència dels estadis de maduració en la composició fitoquímica de l'extracte hidroetanòlic dels fruits d'**Alibertia edulis** (Rich.) A. Rich. ex DC.*

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ABSTRACT

Alibertia edulis (Rich.) A. Rich. ex DC. is a native fruit-bearing tree species of the Brazilian Cerrado, known for its applications in food, medicine, and ecology. This study aimed to assess the impact of ripening stages on the accumulation of phenolic compounds, antioxidant activity, and photoprotection in *A. edulis* fruits. Fruits were collected from two locations at four distinct ripening stages. The quantification of phenolic compounds, flavonoid, and tannin content, as well as antioxidant activity (DPPH assay) and the Sun Protection Factor (SPF), was determined through spectrophotometric methods in both the epicarp and pulp of the fruits. The results revealed that phenolic content accumulation is influenced by ripening, with a decline in phenolics and antioxidant activity as the fruits matured. Furthermore, fruits from the native Cerrado area exhibited higher values in all evaluated parameters compared to those from a cultivated site in Dourados, MS, Brazil. In both sites, a positive correlation was found between phenolic compounds, antioxidant activity, and SPF. These findings suggest that ripening stages significantly affect the chemical composition and bioactive properties of *A. edulis*, with fruits from natural environments displaying enhanced metabolite production, antioxidant activity, and photoprotective potential.

Keywords: *Alibertia edulis*; antioxidants; Brazilian Cerrado; marmelo-do-cerrado; phenolic compounds; ripening stage.

RESUMEN

Alibertia edulis (Rich.) A. Rich. ex DC. es una especie arbórea frutal nativa del Cerrado brasileño, conocida por sus aplicaciones en alimentación, medicina y ecología. Este estudio tuvo como objetivo evaluar el impacto de los estadios de maduración en la acumulación de compuestos fenólicos, la actividad antioxidante y la fotoprotección en los frutos de *A. edulis*. Se recolectaron frutos en dos ubicaciones y en cuatro estadios de maduración distintos. La cuantificación de compuestos fenólicos, contenido de flavonoides y taninos, así como la actividad antioxidante (ensayo DPPH) y el Factor de Protección Solar (FPS), se determinó mediante métodos espectrofotométricos tanto en el epicarpio como en la pulpa de los frutos. Los resultados revelaron que la acumulación de contenido fenólico está influenciada

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por la maduración, con un descenso de los fenólicos y de la actividad antioxidante a medida que los frutos maduraban. Además, los frutos procedentes del área nativa del Cerrado mostraron valores más altos en todos los parámetros evaluados en comparación con los frutos de un sitio cultivado en Dourados, MS, Brasil. En ambos sitios se encontró una correlación positiva entre los compuestos fenólicos, la actividad antioxidante y el FPS. Estos hallazgos sugieren que los estadios de maduración afectan significativamente la composición química y las propiedades bioactivas de *A. edulis*, y que los frutos provenientes de ambientes naturales presentan una mayor producción de metabolitos, mayor actividad antioxidante y un mayor potencial fotoprotector.

Palabra clave*: Alibertia edulis*, antioxidantes, Cerrado brasileño, membrillo del Cerrado, compuestos fenólicos, estadio de maduración.

RESUM

Alibertia edulis (Rich.) A. Rich. ex DC. és una espècie arbòria nativa del Cerrado brasiler que produeix fruits, coneguda per les seves aplicacions alimentàries, medicinals i ecològiques. Aquest estudi va tenir com a objectiu avaluar l'impacte dels estadis de maduració en l'acumulació de compostos fenòlics, l'activitat antioxidant i la fotoprotecció en els fruits d'*A. edulis*.

Els fruits es van recollir en dues localitzacions i en quatre estadis diferents de maduració. Es va determinar, mitjançant mètodes espectrofotomètrics, la quantificació de compostos fenòlics, el contingut de flavonoides i tanins, així com l'activitat antioxidant (assaig DPPH) i el Factor de Protecció Solar (FPS), tant en l'epicarpi com en la polpa dels fruits.

Els resultats van revelar que l'acumulació de fenòlics està influïda per la maduració, amb una disminució dels fenòlics i de l'activitat antioxidant a mesura que els fruits maduraven. A més, els fruits procedents de l'àrea nativa del Cerrado van mostrar valors més alts en tots els paràmetres avaluats en comparació amb els fruits d'un lloc cultivat a Dourados, MS, Brasil. En ambdues localitzacions, es va trobar una correlació positiva entre els compostos fenòlics, l'activitat antioxidant i el FPS.

Aquests resultats suggereixen que els estadis de maduració afecten significativament la composició química i les propietats bioactives d'*A. edulis*, i que els fruits procedents d'entorns naturals presenten una producció de metabòlits, activitat antioxidant i potencial fotoprotector més elevats.

Paraules clau*: Alibertia edulis*; antioxidants; Cerrado brasiler; marmelo-do-cerrado; compostos fenòlics; estadi de maduració.

INTRODUCTION

Fruits are a fundamental component of human health maintenance, providing fiber, vitamins, minerals, and phytochemicals[1]. Despite only a quarter of the Brazilian population consuming sufficient fruit[2], regular fruit consumption is linked to reduced mortality rates and offers various physiological benefits, such as antioxidant properties, and decreases the risks of cardiovascular disease, cancer, and type 2 diabetes mellitus[1]. In addition to their nutritional importance, fruits have potential to produce cosmetics[3], serve as a source of drug development[4], and contribute to many innovative fruit products[5].

Despite the economic potential of native fruits, production and consumption in Brazil are dominated by exotic species integrated into the food culture. Some native tropical fruits have gained ground in agribusiness, but many remain neglected, hindering the recognition of traditional knowledge and local products[6]. Studying native species can enhance the recognition of their economic and health benefits, encourage the appreciation and consumption of these products, and contribute to biodiversity preservation and agricultural diversification.

Alibertia edulis (Rich.) A. Rich. ex DC. (Rubiaceae), commonly known as puruí, apuruí, marmelada, marmelada-bola and marmelo-do-cerrado, is a tree that can reach 8 meters in height, and is widely distributed natively across Brazilian biomes, including the Amazon and Cerrado, demonstrating adaptability to diverse ecological conditions[7-8]. In traditional medicine, it has been used for circulatory improvement, anti-inflammatory effects, and general fortification[9]. Studies in animal models have shown its antioxidant, hypoglycemic[10], diuretic, hypotensive, and antihypertensive activities[11], supporting its popular use. These effects are attributed to its metabolite composition, particularly its richness in terpenes and phenolic compounds[12].

The species is valued for its edible fruits, sometimes described as sweet and savory[13], though not always considered pleasant[14]. Despite this, they are consumed fresh or used in juices, jellies, and other products. The fruits are round with smooth, hard skin, green in color, becoming light brown when ripe, with an average longitudinal diameter of 39 mm and an average transverse diameter of 44 mm. They contain numerous seeds (up to 300 per fruit), which are small, thin, irregular in shape, and light brown in color. Fruiting can occur at different periods of the year depending on the environmental characteristics[8, 15].

It is well-established that fruit ripening is a complex process characterized by dynamic changes in secondary metabolites, such as phenolic compounds, as well as alterations in flavor, texture, and color[16]. In light of these changes, this study aimed to evaluate the influence of ripening stages on the accumulation of phenolic substances, antioxidant activity, and photoprotection in *A. edulis* fruits, considering their potential applications in the food industry and consumption by local populations. By analyzing fruits at four distinct ripening stages from two different locations, the study seeks to identify the stage of greatest bioactivity, which will inform the development of food and cosmetic products derived from *A. edulis* and optimize their use for both nutritional and commercial purposes.

MATERIALS AND METHODS

Chemicals

The reagents, solvents, and standard compounds were purchased from Sigma-Aldrich Chemical Company (St. Louis, MI, USA).

Plant material

Fruits of *A. edulis* were collected from two distinct locations in Dourados, Mato Grosso do Sul, Brazil: the Cultivated Site, corresponding to the Medicinal Plant Garden of the Federal University of Grande Dourados (22°08'05" S, 55°08'17" W), and the Native Site corresponding to a native Cerrado area (18°07'03" S, 54°25'07" W). In both locations, fruits were harvested at four ripening stages, classified based on the color and texture of the epicarp and pulp: **I)** unripe (green epicarp, white and firm pulp, Figure 1A), **II)** mid-ripe (green epicarp, less firm pulp, Figure 1B), **III)** near-ripe (green-brown epicarp, softer pulp, Figure 1C), and **IV)** fully ripe (dark brown epicarp, soft pulp, Figure 1D). After collection, all fruits were cleaned, dried at room temperature (23 °C) for 15 minutes, and separated into epicarp and pulp for further analysis. The authorization for sampling is registered with the Brazilian National System for the Management of Genetic Heritage and Associated Traditional Knowledge (SISGen) under number A147B57.

Extraction procedure

The extracts were prepared using 4 g of fresh fruit epicarp or pulp in 50 mL of 70% ethanol. The mixtures were subjected to ultrasonic bath agitation (Cristofoli, Brazil) for 50 minutes at room temperature and then left to rest for 24 hours. After resting, the solutions were filtered and directly used for analyses. Preparation of each sample was carried out in triplicate.

The moisture content in the samples was evaluated, which varied between 50-53% in the epicarp and 85-90% in the pulp.

Chemical composition analysis

Phenolic compounds content

The measurement was performed using the Folin–Ciocalteu method[17]. A 0.1 mL sample was mixed with 0.5 mL of Folin–Ciocalteu reagent and 1 mL of 70% ethanol. After 1 minute of incubation, 1.5 mL of 20% sodium carbonate was added. The assay was performed in triplicate and absorbance was measured at 760 nm using a spectrophotometer (Global Trade Technology, Brazil). Results were expressed as micrograms of gallic acid equivalent (GAE) per milliliter of extract (μg GAE mL^{-1}).

Flavonoid content

The analysis was determined using a colorimetric assay with aluminum chloride[17]. A volume of 1 mL of 2% aluminum chloride in methanol was added to 1 mL of the sample. After a 15-minute reaction, absorbance was measured at 430 nm using a spectrophotometer (Global Trade Technology, Brazil). The assay was performed in triplicate and results were expressed as micrograms of rutin equivalent (RE) per milliliter of extract (μg RE mL^{-1}).

Tannin content

The tannin content was determined using the Folin-Denis method[18]. A volume of 0.5 mL of Folin-Denis reagent was added to 0.5 mL of the sample, mixed, and left to react for 3 minutes. Subsequently, 0.5 mL of 0.75 mol L^{-1} sodium carbonate was added, homogenized, and incubated for 2 hours in the dark. The assay was performed in triplicate and absorbance was measured at 725 nm using a spectrophotometer (Global Trade Technology, Brazil), and results were expressed as micrograms of tannic acid equivalent (TAE) per milliliter of extract (μg TAE mL^{-1}).

Antioxidant activity

DPPH free radical scavenging activity

The scavenging activity was evaluated using 2,2-Diphenyl-1-picrylhydrazyl (DPPH)[19]. A 100 μL aliquot of the sample was added to 2 mL of 0.004% (w/v) DPPH solution and incubated in the dark for 30 min. Ethanol was used as the control. After the reaction time, absorbance readings were taken at 517 nm using a spectrophotometer (Global Trade Technology, Brazil). The assay was performed in triplicate and DPPH activity was calculated using the following Equation 1:

Inhibition % = (Control absorbance-Sample absorbance)/(Control absorbance) x100 (1)

Determination of the Sun Protection Factor (SPF)

The determination of SPF was performed as previously described[20]. Samples were analyzed at UV-B wavelengths ranging from 290 to 320 nm, with 5 nm increments and three readings at each point. 95% etha-

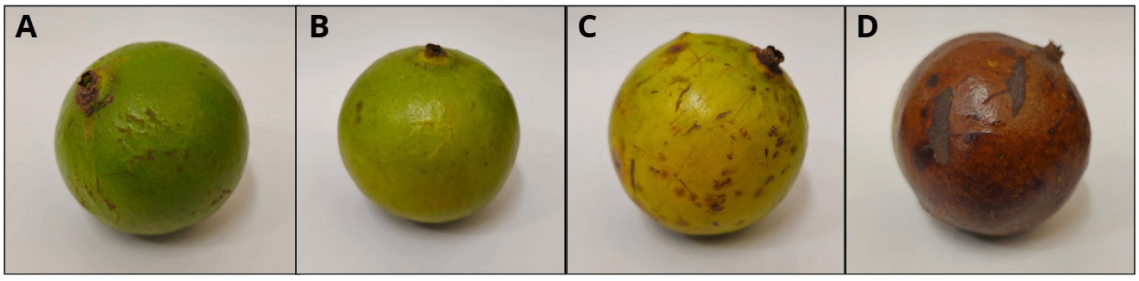

Figure 1. *Four ripening stages of A. edulis fruit.*

nol was used as the blank. The SPF calculation was performed according to Mansur's equation:

$$SPF = CF \times \sum_{290}^{320} EE_{\lambda} \times I_{\lambda} \times Abs_{\lambda} \quad (2)$$

Where CF represents the correction factor (=10); EE(λ) corresponds to the erythemal efficiency spectrum; I(λ) represents the solar light intensity spectrum; and Abs(λ) indicates the absorbance of the solution. The values of EE(λ) × I(λ) are constant, as described previously[21].

Statistical analysis

All statistical analyses were conducted using the R platform[22]. Before multivariate and correlation analyses, all datasets were inspected for compliance with the assumptions of normality and homogeneity. Normality of the residuals was verified using the Shapiro–Wilk test, and homogeneity of variances among groups was tested using Levene's test. Each sample, representing an individual combination of plant part and ripening stage, was considered an independent experimental unit. To evaluate the representativeness of the distance matrices used for ordination, a cophenetic correlation test was performed using Euclidean distances with the vegan package[23]. The obtained cophenetic correlation coefficients (0.7849 for the Cultivated Site and 0.9528 for the Native Site) indicated that the clustering structure adequately reflected the dissimilarities among samples. Subsequently, a Principal Coordinates Analysis (PCoA) was conducted using the same Euclidean distance matrices to visualize the overall similarities and differences in volatile profiles among plant parts and ripening stages. The first two principal coordinates were retained to illustrate the major sources of variation, and the percentage of variance explained by each axis was reported. Pearson correlation analyses were then applied to explore the linear relationships among the content of metabolites and the antioxidant and SPF. Correlation coefficients (r) were computed using the corrplot package[24], and their statistical significance was determined using the psych package[25] with a 95% confidence level ($p < 0.05$).

Finally, Permutational Analysis of Variance (PERMANOVA) was performed using the adonis function in vegan with 999 permutations. The analysis tested the effects of ripening stage, plant part, and their interaction on the overall chemical composition, antioxidant potential, and SPF. Euclidean distance matrices were used as input, and the *pseudo*-F statistics and corresponding p-values were interpreted to determine whether the group centroids differed significantly in multivariate space.

RESULTS AND DISCUSSION

This study is the first to describe the changes in the content of phenolic compounds, flavonoids, tannin, antioxidant activity, and SPF during the ripening of *A. edulis* fruits, both in epicarp and pulp hydroethanolic extract.

The unripe stages (Stage I) exhibited the highest levels of metabolites, antioxidant activity, and SPF in both the Cultivated and Native sites, as shown in Table 1. The most pronounced metabolite expression was observed in the epicarp at Stage I in the Native Site, with a phenolic compounds content of 276.80 ± 4.23 μg GAE mL^{-1}, flavonoid content of 115.95 ± 1.23 μg RE mL^{-1}, and tannin content of 97.62 ± 0.57 μg TAE mL^{-1}. The fruits of *A. edulis* are widely recognized for their high quantity of phenolic substances. An evaluation of the pulp from ripe *A. edulis* fruits[12] revealed a high concentration of phenolic compounds and flavonoids, a result consistent with previous findings[26]. Elevated levels of these substances, particularly during the unripe stages, likely serve as a defense mechanism against frugivores, pathogens, and other environmental stressors, thereby supporting the survival and growth *of A. edulis* fruits[27].

During ripening, as the epicarp and pulp transitioned from Stage I to Stage IV, a slight decrease in metabolite levels was observed in samples from both sites. However, this reduction was more pronounced in the phenolic compounds content at the Cultivated Site, decreasing from 234.13 ± 8.11 to 80.80 ± 7.58 μg GAE mL^{-1} in the epicarp and from 233.46 ± 9.16 to 46.80 ± 6.76 μg GAE mL^{-1} in the pulp (Table 1). The decline in phenolic compounds, flavonoids, and tannins during fruit ripening suggests a shift in metabolite dynamics, as a portion of these substances undergoes degradation or metabolic transformation. This process reduces astringency, enhances palatability, and facilitates fruit dispersion by animals and consumption by humans[28-29].

Regarding the Rubiaceae family, the metabolite profile typically changes throughout fruit ripening. For instance, a decrease of more than 90% in total iridoid content was reported in *Genipa americana* L.[30], whereas an increase in total phenolic compounds and rutin was observed in *Morinda citrifolia* L.[31]. Similarly, an accumulation of fatty acid esters, methyl esters, and carboxylic acid esters was detected in *Alibertia patinoi* (Cuatrec.) Delprete & C.H. Perss[32] and *Morinda royoc* L.[33] during the late stages of ripening.

From a nutritional perspective, Tomás et al.[34] and Becker et al.[35] evaluated the effects of maturation on the pulp, peel (epicarp), and seeds of *A. edulis*, reporting an increase in soluble solids content (SSC), SSC/TA (titratable acidity) ratio, and total soluble sugars, parameters that indicate a progressive increase in sweetness and reduction in acidity during ripening. As maturation progressed, the different fruit parts also exhibited a decline in the total mineral content, although potassium (K) and calcium (Ca) remained quantitatively predominant. These findings suggest that, although fruits at early ripening stages may present higher levels of secondary metabolites and antioxidant activity, their nutritional value for consumption is optimized when the fruits are fully ripe, as this stage combines favorable sensory attributes with nutritional and functional properties.

Considering that phenolic compounds also serve physiological functions, it is known that these substances possess high antioxidant capacity, acting as detoxifying agents and protecting against UV damage[27].

Table 1. *Phytochemical composition, antioxidant properties, and Sun Protection Factor of A. edulis fruit at four ripening stages in two locations*

Fruit part - ripening stage		Phenolic compounds content (μg GAE mL^{-1})	Flavonoid content (μg RE mL^{-1})	Tannin content (μg TAE mL^{-1})	Antioxidant activity (%)	Sun Protection Factor
Cultivated Site						
Epicarp	I	234.13 ± 8.11	32.35 ± 0.50	71.68 ± 4.43	41.28 ± 0.99	13.12 ± 0.01
	II	154.13 ± 31.58	28.86 ± 0.11	60.12 ± 3.82	18.72 ± 5.85	13.44 ± 0.01
	III	114.80 ± 16.76	16.43 ± 1.28	55.29 ± 0.06	11.95 ± 2.21	10.65 ± 0.01
	IV	80.80 ± 7.58	12.06 ± 0.16	46.29 ± 0.84	2.80 ± 1.21	7.88 ± 0.01
Pulp	I	233.46 ± 9.16	4.68 ± 0.45	69.23 ± 3.78	38.68 ± 1.71	14.34 ± 0.01
	II	159.46 ± 3.79	2.45 ± 0.20	57.79 ± 1.57	17.70 ± 1.05	10.21 ± 0.01
	III	142.80 ± 38.11	2.26 ± 0.50	50.07 ± 3.33	6.95 ± 4.61	10.65 ± 0.03
	IV	46.80 ± 6.76	1.09 ± 0.45	47.07 ± 1.11	0.76 ± 0.66	6.58 ± 0.01
Native Site						
Epicarp	I	276.80 ± 4.23	115.95 ± 1.23	97.62 ± 0.57	38.80 ± 0.66	16.73 ± 0.03
	II	257.47 ± 7.70	81.19 ± 1.74	96.18 ± 0.50	37.03 ± 0.61	16.22 ± 0.01
	III	256.13 ± 5.45	73.23 ± 1.10	92.07 ± 1.23	31.43 ± 0.51	16.11 ± 0.02
	IV	251.46 ± 5.75	58.96 ± 1.42	83.73 ± 7.31	27.54 ± 0.84	15.61 ± 0.02
Pulp	I	162.80 ± 5.00	16.43 ± 0.48	90.96 ± 0.94	38.15 ± 0.42	13.84 ± 0.02
	II	156.80 ± 0.38	15.50 ± 1.36	90.18 ± 1.15	29.14 ± 0.32	14.60 ± 0.01
	III	150.80 ± 8.35	15.02 ± 0.55	89.84 ± 0.46	26.83 ± 0.84	16.11 ± 0.02
	IV	145.47 ± 2.77	12.16 ± 0.25	78.95 ± 1.33	17.53 ± 0.72	12.87 ± 0.01

Ripening stages are I = unripe, II = mid-ripe, III = near-ripe and IV = fully ripe; GAE = gallic acid equivalent; RE = rutin equivalent; TAE = tannic acid equivalent. Values are presented as mean followed by the standard deviation (mean ± SD).

In the epicarp and pulp at Stage I in both locations, high antioxidant capacities were observed with values ranging from 41.28 ± 0.99% to 38.15 ± 0.42% (Table 1). Similar reports show that the pulp exhibits potent antioxidant activity using different methodologies, reaching EC_{50} values of 1021.65 ± 5.9 μg/mL for the DPPH assay[36].

As for FPS, it presented values from 16.73 ± 0.03 to 13.12 ± 0.01. According to the guidelines of the Brazilian Health Regulatory Agency (Agência Nacional de Vigilância Sanitária – ANVISA)[37], these FPS values correspond to low (SPF 6.0–14.9) or medium (SPF 15.0–29.9) protection levels, indicating that the extracts could be suitable for skin that is slightly or moderately sensitive to sunburn. Therefore, although the extracts display relevant antioxidant and photoprotective potential, their use should be considered as complementary agents in formulations or as natural SPF boosters, possibly contributing to protection in sensitive skin. The high accumulation of phenolic compounds in these fruits enhances their sun protection and antioxidant capacity, which, when applied in cosmetic products, can offer direct benefits to the skin, including photoprotection, hydration, anti-inflammatory effects, wrinkle reduction, and anti-aging properties[38].

A gradual decrease in both functionalities (antioxidant and FPS) was observed as the fruits ripened and secondary metabolites diminished. By Stage IV, antioxidant activity values dropped to as low as 0.76 ± 0.66% (pulp) at the Cultivated Site and 17.53 ± 0.72% (pulp) at the Native Site. A similar trend was noted for the SPF, which also declined with ripening at both collection sites (Table 1). This phenomenon has been reported in various fruit species, including *Feronia limonia* (L.) Swingle (Rutaceae), *Prunus* spp. (Rosaceae), and *Phoenix dactylifera* L. (Arecaceae)[39-42]. The observed patterns may be associated with the progressive loss of green coloration during ripening, which reflects a decline in antioxidant and photoprotective compounds. Becker et al.[35] reported a similar trend, describing changes in the pigmentation dynamics of *A. edulis* fruits that shift from green to dark brown as maturation advances. This transition results from a decrease in total chlorophyll and total carotenoids, accompanied by an increase in anthocyanin content at the final stages of ripening.

The influences of the variables considered (fruit part and ripening stage) varied in intensity across different locations. In the Cultivated Site, as the fruits ripened, the similarity between the epicarp and pulp increased, as shown by PCoA analysis (Figure 2A). This finding aligns with the greater statistical relevance of the ripening stage ($F = 29.0265$, $p < 0.05$) compared to the fruit part ($F = 2.1905$, $p > 0.05$) in the PERMANOVA results. In contrast, in the Native Site, PCoA analysis (Figure 2B) indicated an increase in similarity between epicarp and pulp only from stage I to II, with pulp

showing greater similarity across ripening stages than epicarp. Furthermore, PERMANOVA analysis confirmed that the fruit part ($F = 112.9494$, $p < 0.05$) had greater statistical relevance than the ripening stage ($F = 2.3309$, $p > 0.05$).

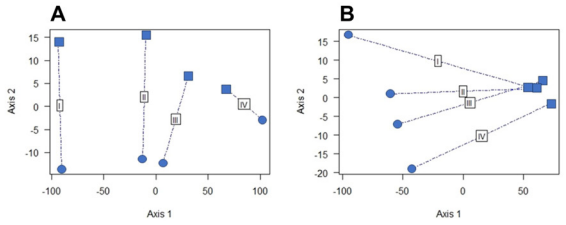

Figure 2. *Principal Coordinate Analysis (PCoA) of Cultivated Site (2A) and Native Site (2B). The square symbol represents fruit pulp, while the circle represents the fruit epicarp at different ripening stages: I (unripe), II (mid-ripe), III (near-ripe), and IV (fully ripe).*

The decrease in secondary metabolites (phenolic compounds, flavonoid, and tannin content), along with the reduction in antioxidant activity and FPS as the fruits ripen, shown in Table 1, can also be observed in Figure 3 through the positive correlations among all parameters, in both sites. At the Cultivated Site (Figure 3A), a strong statistically significant association ($p<0.05$) was observed between antioxidant activity and both phenolic compounds and tannin content, with Pearson correlation coefficients of 0.95 and 0.99, respectively. Similarly, FPS showed a strong significant correlation ($p<0.05$) with phenolic compounds content and tannin content, with Pearson correlation coefficients of 0.91 and 0.88, respectively. Among the secondary metabolites, a statistically significant correlation ($p<0.05$) was found between phenolic compounds content and tannin content, with a Pearson correlation coefficient of 0.94.

At the Native Site (Figure 3B), a statistically significant positive correlation ($p<0.05$) was observed between antioxidant activity and tannin content, with a Pearson correlation coefficient of 0.89. Meanwhile, FPS exhibited a significant correlation ($p< 0.05$) with all secondary metabolites, with Pearson correlation coefficients ranging from 0.71 to 0.75. Among the secondary metabolites, a statistically significant correlation ($p<0.05$) was found between phenolic compounds and flavonoid content, with a Pearson correlation coefficient of 0.96. These findings suggest that the reduction in phenolic compounds, flavonoids, tannins, antioxidant activity and FPS during the ripening of *A. edulis* may be influenced by species-specific factors and environmental conditions.

The well-established free radical-scavenging mechanisms of phenolic substances highlight their antioxidant activity, which inhibits or regulates substrate oxidation. This protective effect contributes to photoprotection by mitigating UV-induced oxidative damage, as evidenced in this study by the correlation between the phytochemical composition, antioxidant activity, and photoprotective potential of *A. edulis* fruits. Phenolic compounds exert antioxidant effects through multiple mechanisms, including direct free radical neutralization via electron or hydrogen donation, modulation of antioxidant enzymes, and inhibition of pro-oxidant enzymes, thereby reducing oxidative stress and inflammation[43]. These properties are crucial for developing fruit-based technologies and functional products with health benefits while also encouraging the consumption of native fruits, enhancing their nutritional value, and promoting biodiversity conservation.

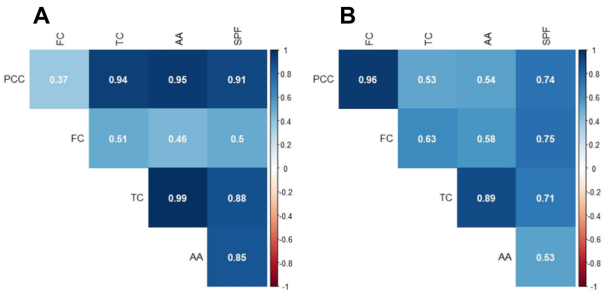

Figure 3. *Pearson correlation between secondary metabolites, antioxidant activity, and SPF for A. edulis samples at the Cultivated Site (3A), and Native Site (3B). PCC = phenolic compounds content; FC = flavonoid content; TC = tannin content; AA = antioxidant activity; and SPF = Sun Protection Factor. Correlations were considered statistically significant when p<0.05.*

CONCLUSION

This study highlights the significant impact of ripening stages on the accumulation of phenolic compounds, antioxidant activity, and photoprotection in *A. edulis* fruits. The findings reveal that unripe fruits exhibit the highest levels of metabolites, antioxidant activity, and Sun Protection Factor (SPF), particularly in the epicarp at the Native Site. As fruits ripen, there is a notable decline in these bioactive properties, suggesting a shift in metabolite dynamics. The positive correlations between phenolic compounds, antioxidant activity, and SPF offers valuable information for the development of food and cosmetic products derived from this native species.

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