

Physical and Physicochemical Characterization of Umbu-Cajá (*Spondias bahiensis*) Fruit Throughout Ripening

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Research Article

Keywords: *Spondias bahiensis*, Postharvest, Technological yield, Semi-arid region

Posted Date: September 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10529078/v1>

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Additional Declarations: No competing interests reported.

Abstract

Umbú-cajá fruit (*Spondias bahiensis*) are of great socioeconomic importance to the Semi-Arid region due to their agroindustrial potential. The study aimed to evaluate the effect of ripening stages on the quality attributes of umbú-cajá fruit produced in Currais Novos, RN. Using a completely randomized design, the fruit were classified into four color stages: I (entirely green), II (light green), III (slightly yellow), and IV (entirely yellow), and biometric parameters, fraction yields, physicochemical properties, and vitamin C content were evaluated. Fruit in the green stage (I) stood out for their higher vitamin C content ($17.08 \text{ mg} \cdot 100 \text{ g}^{-1}$). As ripening progressed, the fully yellow stage (IV) showed progressive increases, reaching an average mass of 22.58 g, a longitudinal diameter of 32.64 mm, and a transverse diameter of 36.13 mm. At this stage of full ripeness, industrial yield was optimized, with 62% pulp, 29% peel, and a proportional reduction to 17.62% in seed content, accompanied by an accumulation of soluble solids (13.0%), a pH of 2.60, and a maximum SS/TA ratio of 12.03. It is concluded that ripening governs integrated and decisive metabolic changes, identifying the fully yellowed stage (IV) as the most suitable for fresh consumption and agroindustrial processing due to its superior chemical composition and technological yield.

1. Introduction

Fruit of the genus *Spondias* belong to the Anacardiaceae family, which includes fruit plants of great economic importance, such as the mango (*Mangifera indica*) and the cashew (*Anacardium occidentale*). Varieties of this genus are widely distributed in tropical and subtropical regions, found in countries such as Brazil, Mexico, and northern Peru, and have also been reported from Central America, Asia, and Oceania, with approximately 17 described species (Souza et al., 2020; Guimarães et al., 2020; Braga et al., 2019).

On a national scale, these fruits play a strategic socioeconomic role in the North and Northeast regions, particularly in the semi-arid areas of the Agreste and the Sertão. These are distinctly seasonal crops with short growing seasons. Among the perennial species, the umbu-cajazeira stands out, it is frequently propagated in home gardens or mixed orchards, and its exploitation still occurs primarily through extractive practices (Mendes et al., 2019; Silva et al., 2021; Lima et al., 2015).

Botanically, the fruit is classified as a drupe with thick, juicy pulp and a thin skin that turns entirely yellow when fully ripe. Due to the marked genetic variability observed in northeastern Brazil, there is significant diversity in the size, shape, and physicochemical profile of these fruits (Lima et al., 2015).

From an economic perspective, the marketing of the harvest boosts the flow of funds in producing regions, generating direct and indirect jobs, and establishing itself as an important source of income for family farming. The umbu-cajá is highly prized for its sensory attributes, such as its pleasant flavor and attractive appearance, and for its high pulp yield, estimated at between 55% and 65%. This high industrial

efficiency enables technological processing to produce derivatives, such as jams, jellies, and frozen pulps (Silva, 2015; Santos et al., 2018).

Given the crop's agroindustrial potential and perishability, research into postharvest quality parameters, including preservation techniques, chemical characterization, and the development of new products, is imperative. Such research is fundamental because it promotes the valorization of the raw material, aids in fruit identification, and facilitates an understanding of their postharvest physiology (Oliveira et al., 2018).

Thus, the characterization of fruit of the genus *Spondias* provides scientific evidence to differentiate between species, understand their properties, and collect data on these types of fruit plants from different production locations. In addition, this characterization contributes to economic growth and has the potential to support the establishment of commercial orchards, which boost the local economy and serve as a strategic tool for mitigating deforestation in the Caatinga biome (Pereira et al., 2021).

Therefore, the present study aimed to evaluate the physical and physicochemical quality attributes of umbu-cajá fruit from the municipality of Currais Novos, Rio Grande do Norte, at four distinct stages of ripeness, to expand the scientific understanding of this crop's physiological behavior.

2. Methodology

This study is an experimental investigation with a qualitative-quantitative approach, as described by (Menezes et al., 2019).

2.1 Collection and Selection of Plant Material

The fruit was harvested manually in May 2022 from between 8 and 9 a.m., at 23°C, from an orchard in the municipality of Currais Novos, Rio Grande do Norte, Brazil (06° 15' 39" S, 36° 30' 54" W), were harvested directly from 30 plants, selecting samples at different stages of physiological development. The fruit was transported to the Food Chemistry Laboratory of the Federal Institute of Education, Science, and Technology of Rio Grande do Norte. In the laboratory, the fruit were rigorously visually selected, with inclusion criteria based on uniformity of size, aesthetic conformity, and the absence of mechanical damage, fungal infections, or pest damage. The treatments were categorized based on the color changes in the peel, as illustrated in Fig. 1.

2.3 Physical Analyses

Physical evaluations of the fruit were conducted individually and included the following measurements:

Fresh Weight (M): Measured individually by weighing on a semi-analytical balance, results are expressed in grams (g). **Biometric Dimensions:** The longitudinal diameter (LD) and transverse diameter (TD) were measured using a digital caliper (0.01 mm). **Shape Index (SI):** Calculated as the geometric ratio of the longitudinal diameter to the transverse diameter (LD/TD). The fruit was classified morphologically and

biometrically according to the criteria established by Costa, Ataíde, and Bastos (2021) and was defined as: flattened ($FI < 1$), rounded ($FI = 1$), and elongated ($FI > 1$). Component Yield: The fruit was manually divided into its constituent parts to determine pulp yield (PY), peel yield (PY), and seed yield (SY), and then the difference between the fresh mass and the pulp was calculated, following the methodology proposed by (Costa et al., 2021).

2.4 Physicochemical Analyses

To conduct the physicochemical analysis, the pulp was obtained using a fruit processor without adding water. Analyses were performed in triplicate according to the Association of Official Analytical Chemists (AOAC) methodologies. Soluble solids (%) and pH were determined using a digital refractometer and a calibrated potentiometer, respectively, following AOAC guidelines. Titratable acidity, expressed as citric acid (%), according to (AOAC International, 1995). The ripeness SS/TA ratio was calculated between soluble solids and titratable acidity (SS/TA). Ascorbic acid content was determined by the Tillmans titrimetric method using the reduction of 2,6-dichlorophenolindophenol (mg. 100 g⁻¹), according to (Microsoft Corporation, 2015) .

2.5 Statistical Analysis

Data tabulation, graphs, and plots were created using Microsoft Excel (Andriotti, 2003). Data were presented as means and standard deviations and subjected to analysis of variance (ANOVA) and Tukey's test using Statistica 7.0 software, with $p < 0.05$ considered significant. Pearson's correlation was also established, considering the correlation to be very strong ($0.90 \leq r < 1.00$), strong ($0.70 \leq r < 0.89$), moderate ($0.40 \leq r < 0.69$), and weak ($0.20 \leq r < 0.39$), at a significance level of 5%, according to (Dantas et al., 2016).

3. Results and Discussion

Regarding the fresh weight of umbu-cajazeira (*Spondias bahiensis*) fruit, no statistically significant difference ($p \geq 0.05$) was observed among the different ripening stages evaluated (Table 1). An increase was observed throughout physiological development, with the average ranging from 21.08 g at the fully green stage (I) to 22.58 g at the fully ripe stage (IV).

Table 1
Fresh weight, pulp yield, and peel yield of umbu-cajazeira (*Spondias bahiensis*) fruit at different stages of ripening.

Stage of ripening	Fresh weight (g)	Peel yield (%)	Pulp yield (%)	Seed yield (%)
I	21.08 ± 1,83	21.76 ± 3,60	57.68 ± 3,44	21.30 ± 2,81
II	22.07 ± 1,21	21.85 ± 4,21	59.74 ± 7,98	17.94 ± 2,48
III	22.30 ± 2,94	24.14 ± 5,70	60.23 ± 9,91	17.77 ± 2,84
IV	22.58 ± 2,38	29.41 ± 4,91	62.13 ± 9,31	17.62 ± 2,01

Source: Study authors (2022). Data are presented as mean $\pm$ standard error (SE). Means followed by the same letter in the same column do not differ significantly from one another according to Tukey's test ($p < 0.05$). I = green fruit; II = light green fruit; III = slightly yellow fruit with early wrinkling; IV = fully yellow fruit.

This stability in fresh weight during the transition between ripening stages indicates that weight gain due to the uptake of water and photoassimilates occurs most intensely during the early phases of fruit growth (cell division and expansion). Upon reaching the green stage (I), the fruit has already attained its maximum physical expansion (physiological ripening), triggering enzymatic processes strictly associated with the qualitative changes of ripening, such as chlorophyll degradation and carotenoid synthesis, without significant changes in volume or weight.

By comparing morphological data with the literature on the genus *Spondias*, Chaves Neto *et al.* (2018) evaluated the fruit quality of cajá-manga (*Spondias dulcis*) from Paraíba during ripening and observed that accessions P3 and P4 showed significant increases in mass between the green and predominantly yellow stages, increasing from 57 g to 61 g and from 52 g to 58 g, respectively. According to those authors, cajá-manga fruit typically exhibit larger dimensions and greater mass than other species of the genus *Spondias*, a pattern confirmed when compared to the average mass of approximately 22 g observed in the present study for umbu-cajá (*Spondias sp.*).

On the other hand, the umbu-cajá fruit evaluated in this study presented a higher mass when compared to that of umbuguela (*Spondias spp.*). In a study on the development of umbuguela in Paraíba, (Costa *et al.*, 2015) recorded a weight range from 9.62 g to 10.63 g in fully ripe fruit. This disparity highlights the marked phenotypic and genotypic variability among native plant resources of the Brazilian semiarid region. Although (Silva *et al.*, 2021) emphasize that fruit mass is a parameter intrinsically associated with the level of development and stage of maturity, which commonly results in significant weight gains as ripening progresses due to the accumulation of reserves, the pattern of statistical stability observed in the present study suggests early physiological development. In the fruit evaluated, the slight absolute increase in total fresh mass reflects the proportional behavior of the constituent fractions of pulp and peel yield (Table 1).

The pulp yield did not show a statistically significant variation ($p \geq 0.05$) throughout fruit ripening, with the highest absolute mean recorded at the fully ripe stage (IV), at 62% (Table 1). From an agroindustrial perspective, this percentage confers high potential for technological utilization on the crop, since pulp yields above 50% reduce operational waste and optimize efficiency in the production of derivatives, such as frozen pulp and jams.

In contrast, the peel yield differed significantly ($p \geq 0.05$) among the stages evaluated, showing a decrease and reaching 29% at the IV stage (Table 1). This divergent behavior between the fractions can be attributed to physiological processes of water loss through transpiration via the stomata and the peel's cuticle, concurrent with the hydrolysis of structural polysaccharides (such as protopectins)

present in the cell wall of the epicarp, which reduces its thickness and density, making it thinner as the fruit reaches full maturity.

The authors in (Lima et al., 2015), while investigating the physical characteristics of 10 genotypes of umbu-cajazeira in Bahia, obtained pulp yields ranging from 62% to 73%. The values recorded for fully ripe fruit (stage IV) in the present study are consistent with the range described by those authors. However, the same researchers found peel yields ranging from 7.83% to 12.78%, values substantially lower than those observed in the current study. This discrepancy confirms that the proportions of the fruit's constituent fractions are strongly influenced by edaphoclimatic factors, the geographical location of cultivation, management practices, and genotypic variability. This environmental and genetic effect is corroborated by the study of (Dutra et al., 2019), which reported a peel yield of 23.92% in ripe umbuzeiro (*Spondias tuberosa*) fruit in Rio Grande do Norte, aligning closely with the values identified for the umbu-cajá fruit evaluated in this study. In the present study, the pulp yield obtained at advanced stages of ripeness (stages III and IV, Table 1) exceeded that of other species of the genus *Spondias*. For example, ripe umbuguela (*Spondias* sp.) fruit collected in Pernambuco by (Costa et al., 2021) exhibited a pulp yield of 53%. On the other hand, the data from the present study are similar to those published by (Chaves Neto et al., 2019), who reported pulp yields ranging from 59% to 66% in umbuzeiro fruit at the intermediate ripeness stage ("de vez") collected from five municipalities in Bahia. In contrast, the results described here were lower than those reported by (Rodrigues et al., 2018), for fully yellow cajá-manga (*Spondias dulcis*) fruit in Paraíba, whose pulp contents ranged from 66% to 78%. Mapping these comparative data highlights the marked phenotypic diversity and potential for genetic improvement within the genus *Spondias*.

It was evident that pulp yield accounted for the largest weight fraction of the fruit total fresh mass (Table 1). As discussed by (Chaves Neto et al., 2019), fruit that exhibit a high proportion of pulpy tissue relative to lower percentages of peel and seed are highly desirable for the agroindustrial sector. Therefore, it can be inferred that the umbu-cajá fruit evaluated in this study exhibit satisfactory biometric characteristics and technological yield, qualifying this raw material for the industrial processing of derivatives.

Regarding seed yield (Table 1), statistically significant variations were observed between the I and III stages, followed by a decline that culminated in a percentage of 17.62% at the final stage. This pattern demonstrated an effect inversely proportional to the cumulative pulp yield throughout ripening.

From a physiological standpoint, this relative decrease occurs because the continuous uptake of water, associated with the accumulation of solutes in the pulp, promotes cell expansion of the mesocarp. Consequently, the rate of volumetric and weight growth of the pulp exceeds the development of the endocarp (seed) structure, reducing the seed's percentage share of the total fruit mass, even though its absolute mass remains constant.

The authors in (Menezes et al., 2019), while investigating the influence of ripening on the quality of umbuzeiro (*Spondias tuberosa*) fruit from the Paraíba hinterland, also reported fluctuations in the

physical mass of the seeds, recording values of 2.80 g in the green stage, 3.08 g in the “de vez” stage, and 2.26 g in the fully ripe stage. This behavior demonstrates that variations in weight and proportional reductions in internal structures are recurrent as ripening progresses in fruit of the genus *Spondias*.

The quantification of seed and peel yield constitutes a crucial biometric parameter, as it provides insights into the specific phenotypic and morphological characteristics. As recommended by (Chaves Neto et al., 2019), evaluating the yield of these fractions is essential for selecting genotypes with higher pulp content, a trait of significant commercial interest to the jellies, jams, and nectar industries. In the present study, it was found that fruit at the IV stage possesses the attributes most favorable for agroindustrial processing, as they exhibit maximum biometric optimization: higher pulp content associated with the lowest percentage of seeds.

Concerning the biometric dimensions of the fruit (Fig. 2), the longitudinal diameter (LD) did not show a statistically significant difference ($p \geq 0.05$) as the ripening stages progressed (Fig. 2a). However, a trend toward an increase in dimensions was observed, particularly at stage IV, which exhibited a mean LD of 32.64 mm. In contrast, the transverse diameter (TD) was significantly affected ($p \geq 0.05$) by the physiological stage, with a statistically significant difference observed between stages II and IV (Fig. 2b). The highest mean value for the transverse diameter (DT) was observed in the final ripening stage evaluated (36.13 mm), suggesting that late cellular expansion in the mesocarp of the umbu-cajá occurs more markedly along the fruit's equatorial axis.

Source: Study authors (2022). I = green fruit; II = light green fruit; III = slightly yellow fruit with early wrinkling; IV = completely yellow. The bars represent the standard error of the mean. Means followed by the same letter do not differ significantly from one another according to Tukey's test at the 5% probability level ($p \geq 0.05$).

This dynamic is also corroborated by the study of (Rodrigues et al., 2018), who observed significant oscillations in seed yield (ranging from 11.55% to 23.45%) in mature cajá-mangueira (*Spondias dulcis*) fruit collected from different locations in Paraíba.

When comparing biometric measurements with data from the literature, (Pereira et al., 2021) found variations in diameter ranging from 28.90 mm to 31.00 mm in ripe umbuzeiro (*Spondias tuberosa*) fruit obtained from different accessions in Paraíba, these values are lower than those observed in the present study for umbu-cajá. On the other hand, (Souza et al., 2019), when evaluating seriguelas (*Spondias purpurea*) at three stages of ripeness in the state of Goiás, recorded lengths ranging from 35.11 mm to 38.69 mm and increasing transverse diameters ranging from 29.01 mm to 31.26 mm, dimensions that are similar to and corroborate the physical characteristics of the fruit analyzed in the present study.

An overall trend of increase in fresh weight, pulp yield, and linear dimensions (diameters) of the umbu-cajás was evident as ripening progressed. According to (Costa et al., 2015), the progressive gain in mass and cell volume is a direct consequence of the accumulation of secondary metabolites during physiological development, which expand the fruit's external structural dimensions until its final size is

established. This morphometric behavior was fully confirmed in the present study, validating the expected growth pattern for the species.

The shape index (SI) of the fruit (Fig. 3) was not significantly influenced ($p \geq 0.05$) by the progression of ripening stages, showing a slight decrease throughout development to values consistently below unity ($SI < 1$). From a morphological standpoint, the maintenance of values below 1 indicates that the rate of expansion along the equatorial axis (transverse diameter) exceeded growth along the polar axis (longitudinal diameter). This behavior defines the anatomical shape of the umbu-cajá fruit, which was assessed as predominantly flattened or oblate, a stable phenotypic characteristic independent of the degree of ripeness of the peel.

The authors in (Costa et al., 2021), when characterizing ripe umbugueleira fruit (*Spondias* sp.) from Pernambuco, obtained an average shape index of approximately 1.32. This result is substantially higher than the values observed in the present study, which remained close to unity (1.0). This geometric difference stems from the of the longitudinal and transverse diameters observed in the evaluated umbu-cajás, resulting in a more balanced shape index.

Mapping and understanding this morphological parameter are of great importance to the agroindustrial sector, which prefers raw materials with a symmetrical and rounded shape to optimize the washing, peeling, and mechanical processing stages. Similarly, fruit shape is a relevant market classification criterion for fresh consumption, as consumers tend to show greater acceptance of fruit with a round, uniform appearance (Rodrigues et al., 2018).

About chemical attributes, a progressive increase in soluble solids (SS) content was observed throughout ripening (Table 2), with statistically significant variations ($p \geq 0.05$) among the first three stages (I, II, and III, respectively), whose mean values increased from 10.6% to 13.0%. This continuous accumulation of soluble solids is a classic indicator of advancing ripening, resulting mainly from the hydrolysis of storage polysaccharides (such as starch) into simple, soluble sugars (glucose, fructose, and sucrose), in addition to the concentration of solutes due to water loss from the fruit.

Table 2
Physicochemical characteristics (hydrogen ion potential, titratable acidity, *ratio*, and vitamin C) of umbu-cajazeira (*Spondias bahiensis*) fruit at four stages of ripeness.

Formulation	pH	Titratable acidity (% citric acid)	SS/TA Ratio	Vitamin C (mg 100 g ⁻¹)
I	2.31 ± 0,06	2.30 ± 0,12	4.47 ± 0,02	17.08 ± 2,01
II	2.32 ± 0,05	1.38 ± 0,10	8.88 ± 0,23	16.48 ± 0,38
III	2.46 ± 0,15	1.33 ± 0,13	9.82 ± 0,36	14.25 ± 1,97
IV	2.60 ± 0,07	1.08 ± 0,07	12.03 ± 0,05	11.42 ± 0,81

Source: Study authors (2022). I = green fruit; II = light green fruit; III = slightly yellow fruit with early wrinkling; IV = fully yellow fruit. Means followed by the same letter in the column do not differ statistically from one another according to Tukey's test ($p \geq 0.05$).

Regarding pH, a statistically significant difference ($p \geq 0.05$) was observed specifically between fruit at stages II and IV, with mean values rising from 2.32 to 2.60 (Table 2). This subtle yet continuous increase in pH reflects the gradual consumption of free organic acids present in the cell vacuoles via the respiratory pathway, which serves as a cellular energy substrate during the ripening phase, thereby reducing total free acidity and raising the pH of the pulp during the fully ripe stage.

The authors in (Rodrigues et al., 2018), when studying yellow-colored cajarana (*Spondias* sp.) from Paraíba, reported soluble solids content ranging from 13.25% to 15.40%. In turn, (Campos et al., 2018) evaluated umbuzeiro (*Spondias tuberosa*) fruit at different stages of ripeness, originating from Pernambuco and Bahia, and observed a progressive increase from 7.0% to 12.30%. The values obtained by these authors demonstrate equivalence and consistency with the results of the present study, indicating a metabolic pattern for the accumulation of soluble solids in different species of the genus *Spondias*.

From a commercial and technological standpoint, high soluble solids content is highly desirable. From the consumer market's perspective, they are directly associated with greater sensory acceptability due to their sweet flavor. From an industrial standpoint, high levels reduce the need for external sucrose addition, thereby optimizing the quality and physicochemical yield of nectars and beverages made from the pulp (Souza et al., 2022).

Regarding pH, (Menezes et al., 2019) evaluated umbuzeiro fruit in Paraíba and observed pH values of 2.79, 2.82, and 2.88 across three successive stages of ripening. Similarly, (Freitas et al., 2020) investigated cajá (*Spondias mombin*) pulp from different accessions in the state of Goiás and obtained pH values as low as 2.95. The results of both studies showed pH values higher than those identified in the present study. However, the data obtained here are fully consistent with those reported by (Lima et al., 2015) for umbu-cajá fruit in Bahia, whose pH values fell within a narrow range of 2.39–2.63.

Higher pH values are associated with better palatability for fruit intended for fresh consumption, as they reduce the perception of astringency. However, maintaining lower pH values, such as those observed in this study, plays a crucial post-harvest technological role, since the acidic environment acts as a natural barrier, helping to control enzymatic degradation activity and inhibiting the development of pathogenic or spoilage microorganisms (Chaves Neto et al., 2019).

In the present study, the concurrent increase in soluble solids and pH as ripening progresses constitutes a connected ripening process. This phenomenon occurred by the starch hydrolysis into reducing and soluble sugars, in parallel with the metabolism of free organic acids, which, when utilized as a cellular respiratory substrate in the Krebs cycle, see their concentration reduced, resulting in a consequent increase in pulp pH.

This process, associated with fruit respiration, is confirmed by the behavior of titratable acidity (TA), which decreased significantly ($p < 0.05$) with ripening, declining from 2.30% to 1.08% citric acid, with a statistical difference between stages I, II, and IV (Table 2). As for the SS/TA ratio, an inverse and ascending trend was observed, with a statistically significant increase ($p < 0.05$) from 4.47 to 12.03, showing evident statistical effects between stages I, II, and IV (Table 2). The effect on the SS/TA ratio at the end of the cycle reflects the balance achieved between the loss of acidity and the gain in sugars, which is the main indicator of the fruit's ripeness and sensory quality.

The authors in (Freitas et al., 2015), in their study of umbu-cajazeira clones in Rio Grande do Norte, observed a range of 0.94 to 1.95 g·100 g⁻¹ in total acidity. Similarly, (Campos et al., 2018) observed a decrease from 4.50 to 0.88 g·100 g⁻¹ in titratable acidity during the ripening of umbuzeiro (*Spondias tuberosa*) fruit from Pernambuco and Bahia. Both studies demonstrate strong convergence and behavioral equivalence with the results identified in the present study (Table 2). The progressive decrease in acidity is a characteristic and widely documented phenomenon. According to (Pereira et al., 2019), this decline is associated with the fruit's respiratory activity, in which vacuolar organic acids are transported and consumed as primary energy substrates in the Krebs cycle.

From a food engineering perspective, high acidity levels are highly desirable for the processing industry. This chemical profile significantly reduces the need for citric acid additives in juices, pulps, or nectars and also acts to inhibit the growth of spoilage microorganisms, thereby optimizing postharvest preservation and reducing operational costs (Souza et al., 2022). It has been observed that the acidity of the umbu-cajá, even in advanced stages of ripeness, remains at levels considered high. These values exceed those of other species in the Anacardiaceae family, such as the Tommy Atkins mango evaluated by (Costa et al., 2019), which recorded a decreasing range of acidity between 1.21 and 0.13 g·100 g⁻¹. The values in the present study were also higher than those of cashew fruit analyzed by (Silva et al., 2022), whose values in artisanal and industrially processed pulp ranged strictly between 0.18 and 0.35 g·100 g⁻¹.

Regarding the soluble solids to titratable acidity ratio (SS/TA ratio), (Lima et al., 2015) reported values ranging from 7.83 to 10.77 for umbu-cajá (*Spondias* sp.) fruit, which align with the values observed in the present study. Conversely, (Souza et al., 2019) evaluated this index in seriguela (*Spondias purpurea*) fruit from Bahia, recording an increase from 3.45 in unripe fruit to 9.14 in fully ripe fruit, these values remain below those obtained in this work. These comparisons underscore the metabolic similarities regarding quality indices among umbu-cajá, umbu, and seriguela fruit. The SS/TA ratio is a primary determinant of flavor quality in tropical fruit. This balance between chemical components serves as a direct indicator of sweetness and astringency perception, which is intrinsically linked to the physiological maturity stage (Souza et al., 2022).

Consequently, the SS/TA ratio observed in this study indicates that the evaluated umbu-cajá possesses high potential for consumer market acceptability. This pattern reflects the characteristic climacteric respiratory behavior of the genus *Spondias*, wherein increased postharvest metabolic activity accelerates

the enzymatic hydrolysis of reserve macromolecules into soluble sugars, concurrent with the degradation of organic acids. Regarding the antioxidant profile, a significant difference ($p < 0.05$) was observed in ascorbic acid levels between maturity stages I and IV, which decreased from 17.08 to 11.42 mg.100 g⁻¹ (Table 2).

Regarding the antioxidant profile, a significant difference ($p \geq 0.05$) was observed in ascorbic acid levels between maturity stages I and IV, showing a decrease from 17.08 to 11.42 mg.100 g⁻¹ (Table 2). This marked decline indicates the direct influence of advancing ripeness on the degradation of this component. From a biochemical perspective, the reduction in vitamin C levels occurs due to its susceptibility to enzymatic oxidation, triggered by the action of ascorbate oxidase and peroxidase, which use ascorbic acid as a substrate during the oxidative processes associated with the fruit cellular senescence.

The authors in (Souza et al., 2022), while investigating the physicochemical characteristics of fully ripe cajá-manga (*Spondias dulcis*) from different accessions in the state of Goiás, observed high levels of ascorbic acid, ranging from 58.87 to 67.70 mg.100 g⁻¹. These reported levels are higher than those obtained in the present study for umbu-cajá. In contrast, (Lima et al., 2015), in a study aimed at evaluating the quality of umbu-cajá pulp, found a range of 7.33 to 18.17 mg.100 g⁻¹ across different genotypes, yielding results that are similar and consistent with those observed in the present study. This comparison confirms that vitamin C concentration in the genus *Spondias* exhibits marked variability, modulated by genotype, local soil and climate conditions, and the species evaluated.

Additionally, the decrease in total vitamin C content is strongly influenced by environmental stressors, such as temperature, to which the fruit is exposed in the field and during postharvest. This progressive reduction occurs naturally as physiological maturity advances and is associated with oxidation and bioactive compounds that were synthesized and accumulated more intensely during the early stages of cellular development (Souza et al., 2022; Matos et al., 2021). Thus, it can be inferred that the interaction of these physiological and biochemical factors drove the degradation and consequent decrease in vitamin C in umbu-cajá fruit throughout the ripening process.

To comprehensively evaluate the metabolism of the physical, chemical, and bioactive attributes during the ripening of umbu-cajá fruit (*Spondias bahiensis*), Pearson's linear correlation analysis was applied, the correlation coefficients (r) are summarized in Table 3.

Table 3
Pearson correlation coefficients between the physical and physicochemical characteristics of umbu-cajá (*Spondias bahiensis*) fruit.

Variable	M	RP	DL	DT	SS	pH	AT	R	VC
M	1.00								
RP	0.97	1.00							
DL	0.99	0.94	1.00						
DT	0.96	0.90	0.98	1.00					
SS	0.98	0.92	0.97	0.96	1.00				
pH	0.80	0.87	0.71	0.62	0.80	1.00			
AT	-0.99	-0.95	-0.99	-0.98	-0.97	-0.73	1.00		
R	0.99	0.99	0.97	0.93	0.96	0.84	-0.98	1.00	
VC	-0.82	-0.91	-0.73	-0.63	-0.78	-0.98	0.76	-0.87	1.00

Source: Survey data. M = mass; RP = pulp yield; DL = longitudinal diameter; DT = transverse diameter; SS = soluble solids; pH = hydrogen ion concentration; AT = titratable acidity; R = ratio; VC = vitamin C.

Analysis of the correlation matrix revealed that fruit mass showed a very strong positive linear correlation with pulp yield, longitudinal diameter, transverse diameter, soluble solids, and the SS/TA ratio ($r \geq 0.95$). These indices demonstrate that the increase in total fresh fruit mass is intrinsically associated with volumetric expansion (biometry), the accumulation of pulp tissue, and changes in sugar content. In contrast, a very strong negative correlation was found between mass and titratable acidity ($r = -0.99$), indicating that fruit weight gain throughout development occurs concurrently with the degradation and metabolic consumption of primary organic acids in the umbu-cajá.

Similarly, pulp yield showed a very strong negative correlation with titratable acidity ($r = -0.95$) and a positive correlation with the SS/TA ratio ($r = 0.99$). These effects indicate that fruit with higher pulp yield concentrates the biochemical transformations favorable to flavor, which are characterized by a reduction in acid astringency and the optimization of the sensory profile.

The longitudinal and transverse diameters showed a very strong positive correlation with each other ($r = 0.98$), indicating proportional growth along both geometric axes of the fruit. These biometric dimensions also showed strong positive correlations with soluble solids content ($r \geq 0.69$) and the SS/TA ratio ($r = 0.97$), while showing negative correlations with titratable acidity ($r = -0.99$ and $r = -0.98$, respectively). Based on these correlations, it can be inferred that larger fruit reached a more advanced stage of cell expansion and physiological maturity, a period in which metabolic activity intensifies the enzymatic conversion of reserve macromolecules into simple sugars, accompanied by a decline in organic acid content.

Regarding the bioactive profile, the ascorbic acid content showed a very strong negative correlation with pH ($r = -0.98$). This relationship demonstrates that umbu-cajá fruit with higher concentrations of vitamin C, as observed at the mature green stage (Stage I), exhibit an acidic cellular matrix and, consequently, lower pH values. This environment is favorable because a lower pH (higher acidity) helps stabilize the ascorbic acid molecule, protecting it against premature oxidation.

Furthermore, a strong synergistic behavior between soluble solids content and the SS/TA ratio was confirmed by a very strong positive correlation between them ($r = 0.96$), while both variables were inversely proportional to titratable acidity ($r = -0.97$ and $r = -0.98$, respectively). Mapping these linear correlations clearly demonstrates that the progression of physiological ripening drives the primary changes in the quality attributes of umbu-cajá, guiding ripe fruit (Stage IV) toward an optimal balance of flavor and consumer acceptability.

Similar results were reported by (Costa et al., 2021), when evaluating mbuguela (*Spondias sp.*) fruit, noting strong positive correlations between equatorial diameter and longitudinal length. These authors also identified positive interactions among soluble solids, pH, and the SS/TA ratio, all of which correlated negatively with titratable acidity, thereby reinforcing the consistent metabolic patterns observed for the genus *Spondias* in the present study. In summary, the application of linear correlation models serves as an indispensable methodological tool in food science. It effectively identifies quality attributes of high biological and technological relevance, providing a scientific basis for raw material selection and enabling process optimization by reducing the number of analytical variables required for quality monitoring (Reis et al., 2015).

4. Conclusion

This study enabled the mapping and characterization of the physical and physicochemical attributes of umbu-cajá (*Spondias bahiensis*) fruit grown in the municipality of Currais Novos, RN, demonstrating that progression through the stages of ripening drives metabolic changes for the final quality of the raw material.

Although fruit at the mature green stage (Stage I) exhibits the highest content of bioactive compounds, marked by elevated vitamin C levels ($17.08 \text{ mg} \cdot 100 \text{ g}^{-1}$), it is at the fully yellow stage (Stage IV) that the umbu-cajá fruit achieves its maximum biometric and chemical optimization. At this fully ripe stage, the fruit displays the most favorable attributes for commercial and industrial application: a high pulp yield (62%), a proportional reduction in the seed fraction (17.62%), maximum accumulation of soluble solids (13.0 %), and a flavor balance reflected by the SS/TA ratio (12.03).

These parameters qualify the ripe fruit both for the competitive fresh market and as an excellent high-yield raw material for agroindustrial processing into derivatives, such as jams, jellies, and frozen pulps. Ultimately, these scientific data provide an essential foundation for the valorization of native fruit species and the reinforcement of the regional economy in the Seridó region of Rio Grande do Norte, supporting postharvest management strategies and the development of the local production chain.

Declarations

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FUNDING

This study was conducted with support from the Coordination for the Improvement of Higher Education Personnel—Brazil (CAPES)—Funding Code 001.

ETHICS APPROVAL

No approval from the Ethics Committee was required to conduct this type of research.

CONFLICT OF INTEREST

There is no conflict of interest.

AUTHORS' CONTRIBUTION

B.L. Costa conceptualized the study, conducted the investigation, developed the methodology, performed the formal analysis and data curation, and wrote the original draft of the manuscript. **R.S. Cruz** contributed to the methodology and revised and edited the manuscript. **R.J. da Silva, E.F.A. Faustino**, and **C.F.A. Faustino** participated in the validation of the results and formal analysis. **P.A. de Souza** and **R. Chastinet Braga** were responsible for project administration, resources, and supervision. All authors reviewed, approved, and agreed to the published version of the manuscript.

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Figures

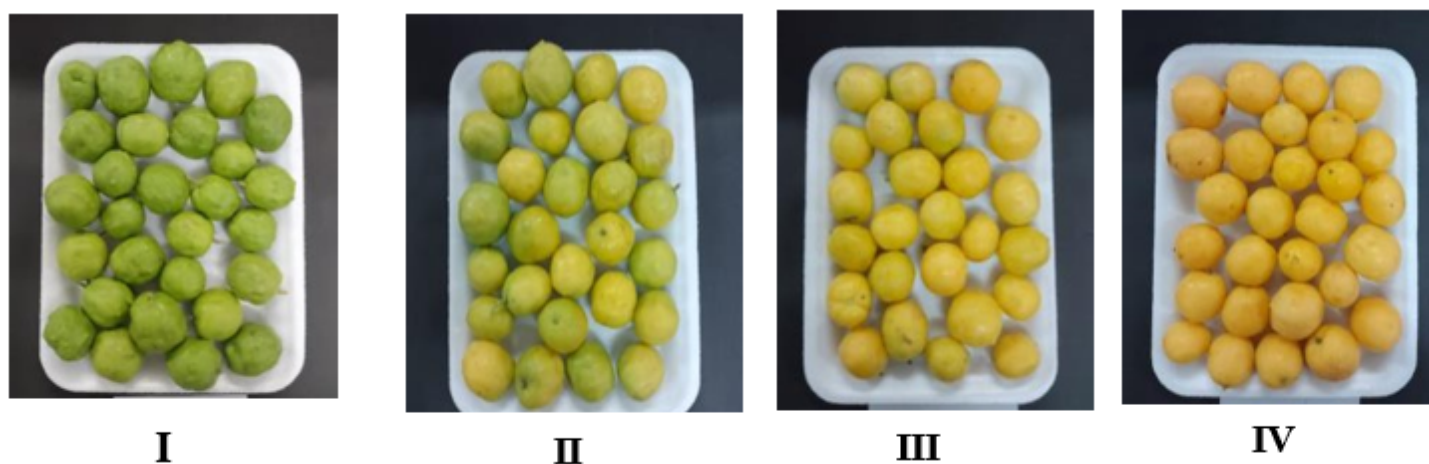


Figure 1

Umbu-cajá (*Spondias* sp.) fruit arranged in four distinct stages of ripeness (I, II, III, and IV).

Source: Author (2022). Stage 1 (I): Entirely green; Stage 2 (II): II (light green); Stage 3 (III): Slightly yellow (predominantly yellow with traces of green); Stage 4 (IV): Entirely yellow (full maturity). Source: Authors (2022).



I



II



III



IV

Figure 1

Umu-cajá (*Spondias* sp.) fruit arranged in four distinct stages of ripeness (I, II, III, and IV).

Source: Author (2022). Stage 1 (I): Entirely green; Stage 2 (II): II (light green); Stage 3 (III): Slightly yellow(predominantly yellow with traces of green); Stage 4 (IV): Entirely yellow (full maturity). Source: Authors (2022).



I



II



III



IV

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Umu-cajá (*Spondias* sp.) fruit arranged in four distinct stages of ripeness (I, II, III, and IV).

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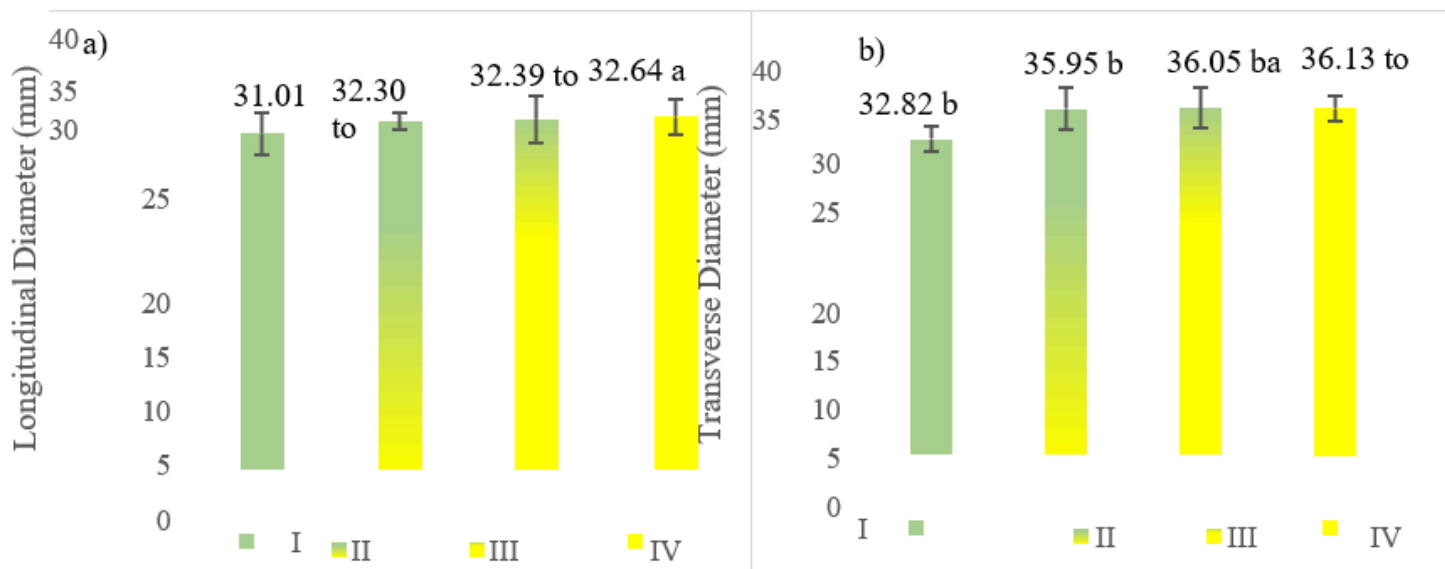


Figure 2

Longitudinal diameter (a) and transverse diameter (b) of umbu-cajá (*Spondias bahiensis*) fruit at four stages of ripening.

Source: Study authors (2022). I = green fruit; II = light green fruit; III = slightly yellow fruit with early wrinkling; IV = completely yellow. The bars represent the standard error of the mean. Means followed by the same letter do not differ significantly from one another according to Tukey's test at the 5% probability level ($p \geq 0.05$).

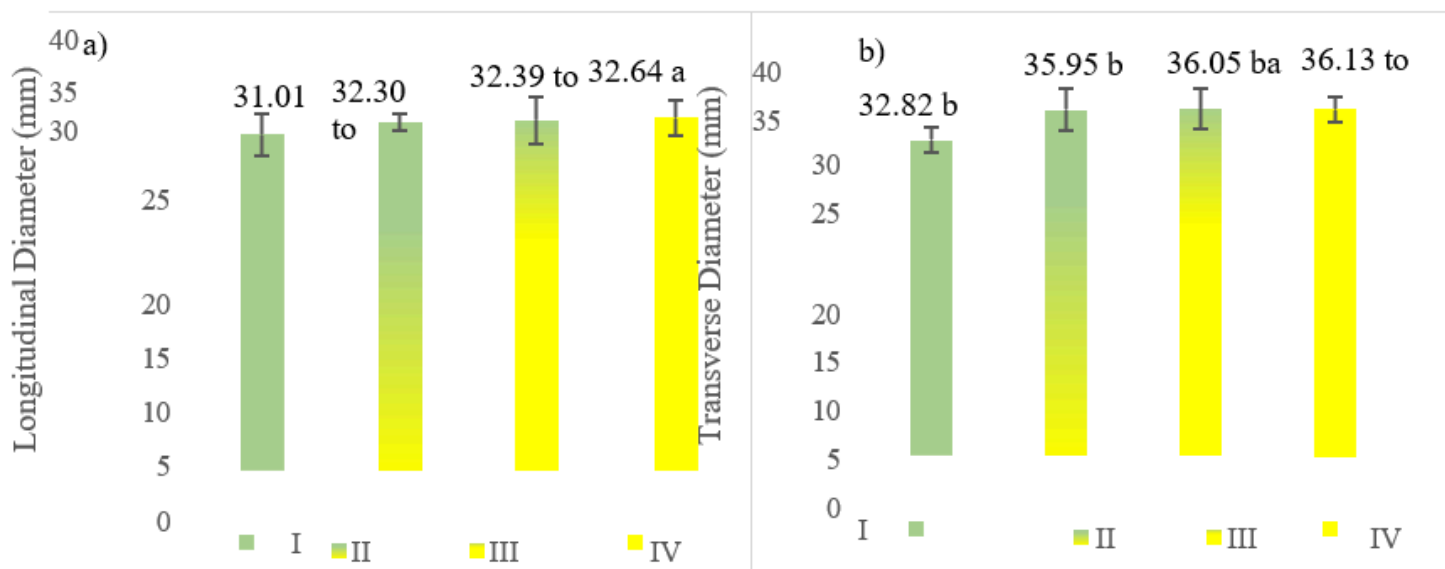


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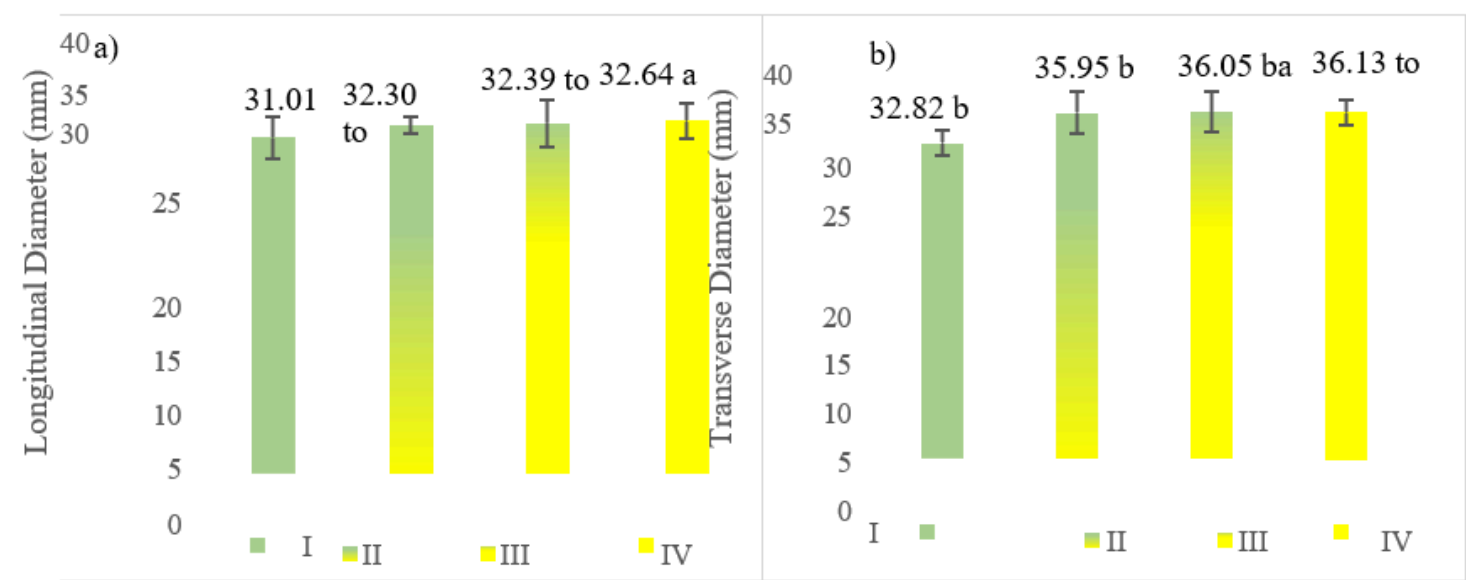


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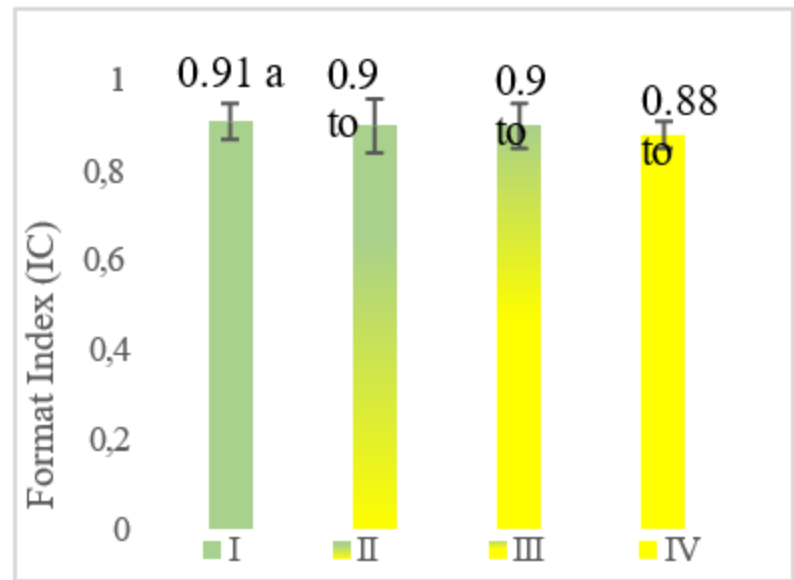


Figure 3

Shape index (SI) of umbu-cajá (*Spondias bahiensis*) fruit at four stages of ripeness (I: completely green; II: light green; III: slightly yellow; IV: completely yellow). Means followed by the same letter do not differ statistically from one another according to Tukey's test ($p \geq 0.05$).

Source: Research authors (2022).

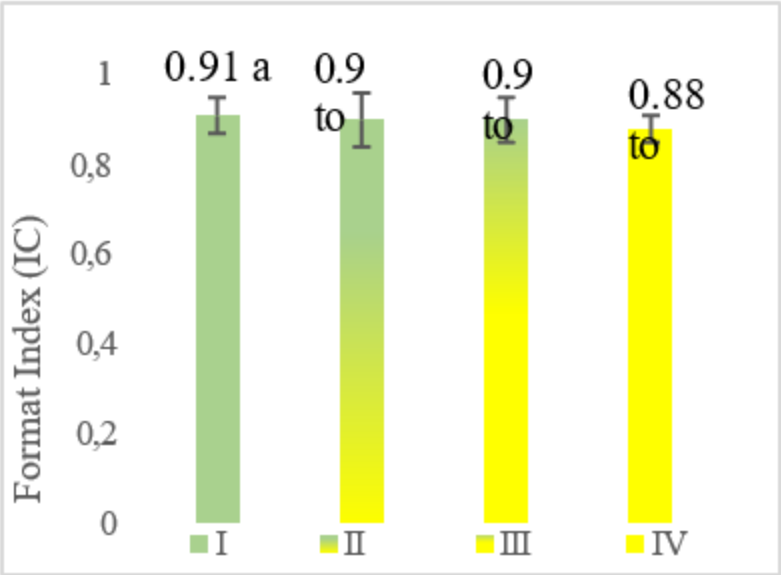


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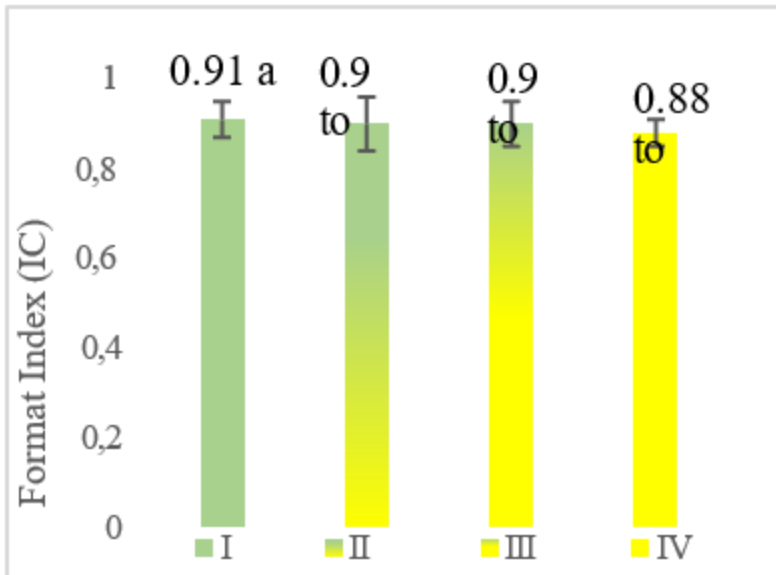


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