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Extraction of bioactive compounds from juçara palm residue and application in biodegradable packaging

Extração de compostos bioativos do resíduo da palmeira juçara e aplicação em embalagem biodegradável

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ABSTRACT: The processing of the fruit of the Juçara palm tree Euterpes edulis Martius generates solid residue that is discarded by the industry, although it still has a composition rich in bioactive compounds. This study aimed to extract bioactive compounds from the skin of the juçara palm fruit and apply them in the form of microcapsules in biodegradable packaging. The extract was obtained using thermal bath and ultrasound extraction techniques, followed by microencapsulation and freeze-drying. The capsules produced were added to films using the casting technique. The extracts were evaluated for total phenolic compounds, antioxidants (DPPH, ABTS, FRAP), flavonoids and anthocyanins. The films were evaluated for thickness, water vapor barrier properties and mechanical properties. The results were submitted to analysis of variance (ANOVA) and Tukey's test ($p<0.05$). The encapsulation and freeze-drying process of the extracts allowed an improvement in the antioxidant values of the extracts. The films presented a smooth surface and good malleability. In general, the films added to the capsules presented greater flexibility due to the greater value of elongation at break, lower stiffness due to the lower value of Young's Modulus, had greater permeability to water vapor (PVA) and did not present statistical differences in resistance. maximum traction, when compared to the control film (without addition of encapsulated extracts).

Keywords: Antioxidants; Anthocyanins; Films; Fruits; Mechanical properties.

RESUMO: O processamento do fruto da palmeira Juçara *Euterpes edulis Martius* gera resíduos sólidos que são descartados pela indústria, embora ainda apresentem uma composição rica em compostos bioativos. Esse estudo teve como objetivo extrair os compostos bioativos da casca do fruto da palmeira juçara e aplicá-los na forma de microcápsulas em uma embalagem biodegradável. O extrato foi obtido por meio das técnicas de extração em banho térmico e por ultrassom, seguido de microencapsulação e liofilização. As capsulas produzidas foram adicionadas em filmes pela técnica de casting. Os extratos foram avaliados quanto aos compostos fenólicos totais, flavonoides, antocianinas e atividade antioxidante (DPPH, ABTS, FRAP). Os filmes foram avaliados quanto à espessura, propriedades de barreira ao vapor de água e às suas propriedades mecânicas. Os resultados foram submetidos submetidas à análise de variância (ANOVA) e ao teste de Tukey ($p<0,05$). O processo de encapsulação e liofilização dos extratos permitiu uma melhora nos valores de antioxidantes dos extratos. Os filmes apresentaram superfície lisa e boa maleabilidade. De modo geral, os filmes adicionados das capsulas apresentou uma maior flexibilidade pelo maior valor de elongação na ruptura, menor rigidez dado pelo menor valor do Módulo de Young, teve uma maior permeabilidade ao vapor de água (PVA) e não apresentou diferenças estatísticas a resistência máxima à tração, quando comparados com o filme controle (sem adição dos extratos encapsulados).

Palavras-chave: Antioxidantes; Antocianinas; Filmes; Frutos; Propriedades mecânicas.

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1 INTRODUCTION

Euterpes edulis Martius, commonly known as juçara, is a tree species endemic to the Brazilian Atlantic Forest, predominantly found in the states of the South and Southeast regions of Brazil (Abdalla de Oliveira; Guimarães; Guimarães de Souza, 2017; Schulz *et al.*, 2016a). The species is listed on the Official List of Threatened Flora Species in Brazil, and government initiatives aim to provide guidance to rural producers for the sustainable ex-traction of the fruit. The goal is to consolidate the market for juçara and its agroindustrialization since the pulp can be used in the production of various foods, such as granola, juices, ice creams, creams, vitamins, yogurts, sauces, liqueurs, and even cakes (Embrapa, 2022).

The juçara palm tree produces round fruits that grow in clusters and have a pericarp covering a hard seed. The fruits are small, with a diameter of about 1 to 1.5 cm, with the seed constituting 85% of the fruit. As they ripen, the epicarp evolves from green to dark purple or almost black (Bicudo; Ribani; Beta, 2014). The fruit stands out for its organoleptic characteristics, particularly its sweet taste, and is widely used in açai production. The high consumption of its fruit pulp is intrinsically associated with its sensory properties and considerable nutritional value (Garcia *et al.*, 2019; Schulz *et al.*, 2016b).

The fruits of the juçara palm tree have high nutritional value, including fatty acids, proteins, fibers, minerals, and vitamins, as well as bioactive compounds such as flavonoids, anthocyanins, and phenolic acids that are associated with biological activities (Bicudo; Ribani; Beta, 2014; Borges *et al.*, 2013; Cardoso *et al.*, 2015; Ribeiro *et al.*, 2011; Schulz *et al.*, 2015a). However, processing juçara fruits generates solid waste, such as the peel and seeds, which are typically discarded, although they remain a rich source of bioactive compounds. (Ray *et al.*, 2023). Inada *et al.*, for example, investigated the phenolic profile of jabuticaba (pulp, peel, and seeds), and the peel was the component that showed the highest content of total phenolic compounds (2252 mg/100 g). Therefore, the study of obtaining and ap-plications of these bioactive compounds is of great importance.

Furthermore, the use of fruits from Euterpe edulis (juçara) in human nutrition rep-resents a perspective of considerable economic and environmental value, valorizing remaining forest resources and playing a fundamental role in species conservation (Embrapa, 2022). Although there have been many studies focused on obtaining color and bioactive compounds from fruits and residues (Santos, *et al.*, 2023a; Santos, *et al.*, 2023b; Paraíso, *et al.*, 2019; Rodrigues, *et al.*, 2020; Romanini et al., 2021), little is known about extraction techniques applied directly to the residue from juçara processing, as studies with juçara commonly focus only on the pulp (Inada *et al.*, 2015). Given the importance of valorizing this fruit, the utilization of juçara fruit peel is interesting, as it represents a low-cost raw material rich in bioactive compounds with technological potential.

The use of plant extracts in the manufacturing of active films and coatings has been a significant practice. These extracts substantially influence the characteristics of the biopolymers used as a base, resulting in biodegradable films that exhibit notable antioxidant and antimicrobial activity. The incorporation of these plant extracts into biopolymers has also been shown to be effective in extending the shelf life of food products (Kola; Carvalho, 2023).

Although research related to the production and characterization of biodegradable films has increased significantly, there are still technological challenges in food application. Since the formed films exhibit poor properties such as mechanical properties, barrier properties, solubility, and water resistance. The addition of active compounds to the films can be an alternative to improve the properties of the materials, extending the shelf life of food products (Martins *et al.*, 2029).

In recent years, the scientific community has been focused on replacing petrole-um-based polymers with more eco-friendly alternatives (Zhang *et al.*, 2020). Studies indicate the potential use of fruit waste for packaging applications, as demonstrated by the research of Stoll et al. (2017), who evaluated the antioxidant activity and compatibility of anthocyanin micro-capsules (extracted from grape residue) formed by arabic gum (GA) and maltodextrin (MD) for application in active films, obtaining 2.44 times higher antioxidant activity for GA microcapsules than structures formed by MD. The incorporation of anthocyanin microcapsules and MD into sugar cane bagasse starch films revealed a greater protective effect against the formation of peroxides in sunflower oil, as well as better compatibility with the polymeric matrix than GA-based microcapsules. Films containing MD-based microcapsules showed higher tensile strength, greater elongation percentage, and lower water permeability than active packaging with GA. The functionality of biodegradable films depends on their bioactive and physical properties (Silva-Weiss *et al.*, 2013). The addition of tamarind seed extract improved the UV barrier property, antioxidant capacity, and antimicrobial ability of the film applied in meat (Kuchaiyaphum *et al.*, 2023). The isolation of starch from turmeric dye extraction residue enabled the bioactivity of the films due to the presence of antioxidant compounds (Maniglia; Silveira; Tapia-Blácido, 2022).

Although research related to the production and characterization of biodegradable films has increased significantly, there are still technological challenges for application in food. Since the formed films exhibit poor properties such as mechanical properties, barrier properties, solubility, and water resistance. The addition of active compounds to films can be an alternative to improve the properties of materials, extending the shelf life of food products (Kola; Carvalho, 2023; Martins *et al.*, 2019). In this context, the question arises: could the residue of the juçara palm tree (bark) add bioactive compounds and improve the mechanical properties of biodegradable films? The present work is innovative because it is the first to study the juçara palm in terms of extraction followed by microencapsulation and application in biodegradable packaging.

The objective of this work was to extract bioactive compounds from the residue of the juçara palm tree (*Euterpe edulis Mart.)* under conventional and ultrasonic extraction conditions and evaluate the antioxidant content and mechanical properties when applied to biodegradable packaging in encapsulated form.

2 MATERIALS AND METHODS

2.1 OBTAINING THE RESIDUE AND PHYSICOCHEMICAL ANALYSIS OF JUÇARA PALM FRUIT PEEL

The juçara fruits were obtained fresh from a rural property in the Terra Boa region, Paraná, Brazil, all from the same batch (harvest 01/2022). The fruits were cleaned with a sodium hypochlorite solution under agitation at 200 rpm for 15 minutes. Then, the fruit was manually mashed to remove the seeds, and the pulp was sieved and frozen. The initial residue obtained consisted of peel and seed. For the analyses, the seeds were discarded, and the peel was fractionated into plastic bags (250 g each) and stored (protected from light) at -18°C. The juçara fruit peels were evaluated for pH, soluble solids content, moisture, and ash according to the methods proposed by the AOAC (2016). Thus, this research is quantitative *in nature* and presents numerical data regarding the analysis of the products.

2.2 EXTRACTION OF BIOACTIVE COMPOUNDS FROM JUÇARA FRUIT PEEL

The extraction of bioactive compounds from the juçara fruit peel was carried out using two different methods: conventional extraction in a thermostatic bath with temperature control and ultrasound-assisted extraction (40 kHz). Water was used as the solvent, in a ratio of 1:1 (residue: solvent), and the extraction was performed at 30°C for 30 minutes, as established in preliminary tests from previous research by the research group (Paraíso *et al.*, 2021). The resulting extract was stored under refrigeration in the dark for further processing.

2.3 ENCAPSULATION AND LYOPHILIZATION

The encapsulation was performed by ionic gelation, where sodium alginate at a concentration of 2% w/v (2 g/100 mL) was dispersed in the extract under stirring and heating at 70°C ± 4°C for complete dispersion. For the formation of the alginate capsule, the dispersion was dripped using the Caviar Box® kit into an aqueous solution of calcium chloride (1% w/v, 1 g/100 mL). The formed capsules were kept in the calcium chloride solution for 10 minutes, after which they were sieved and washed with deionized water to remove excess calcium and stop the complexation process (ROMANINI et al., 2021).

The encapsulated extract was subjected to the freeze-drying process (Liobras, L108 freeze dryer, Brazil). The extracts were maintained at a temperature of -36°C for two days before freeze-drying to ensure complete drying of the product. After freeze-drying, the dried extracts were stored in plastic packaging at -18 ^{0}C.

2.4 FILM PREPARATION

To produce the films, the casting technique was used. As a control, initially, a film without the addition of capsules (F) was prepared. For film preparation, 2 g of alginate, 3 g of gelatin, and 2 g of glycerol were pre-weighed on an analytical balance, placed in a beaker along with 100g of distilled water and a drop of Tween 80. The mixture was taken to a hot plate with constant stirring and heated to a temperature of 25°C for 10 min to ensure complete gelatinization of the film. Immediately after, the filmogenic solution formed was poured into polystyrene plates and placed in an oven with air circulation at a temperature of 25°C for evaporation drying for 24 hours. Similarly, films FC, with the addition of 1% of the extract obtained by the conventional bath method, and FU, with 1% of the extract obtained by the ultrasound extraction method, were obtained.

2.5 ANALYSIS OF BIOACTIVE COMPOUNDS AND ANTIOXIDANT ACTIVITY

The analysis of bioactive compounds was determined as follows: Total Phenolic Compounds (TPC) were determined according to the methodology described by Singleton & Rossi (1965). For the analysis of flavonoids and anthocyanins, the methodology described by Lees & Francis (1971). The total flavonoid content was expressed in mg equivalent of quercetin.100 g^{-1} of the product, and the total anthocyanin content was expressed in mg equivalent of cya-nidin-3-glucoside.100 g^{-1} of the product. For antioxidant activity, the degradation reaction of DPPH (2.2-Diphenyl-1-Picrylhydrazyl) was analyzed according to the (Thaipong *et al*, 2006).

For the analysis using the ABTS method (2.2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt), the methodology described by Rufino et al., (2007), was employed. The FRAP assay was conducted according to the methodology of Benzie and Strain (1996). Antioxidant results were expressed in µM Trolox Equivalent per milligram of extract.

2.6 CHARACTERIZATION OF THE FILMS

The thickness of the films was measured using a Mitutoyo digital micrometer. Eighteen random points within the area of each film sample were evaluated, and the result was the arithmetic average of these 18 measurements. The analysis of water vapor permeability was conducted according to the method of the American Society for Testing and Materials (ASTM, 2000) with some modifications. The samples were fixed in permeability determination capsules, containing anhydrous calcium chloride (2% RH) inside. The capsules were conditioned in desiccators with a relative humidity of 53%, and the tests were conducted in triplicate. Periodic weighing’s were performed until the rate of mass gain became constant. The water vapor permeability rate was determined according to Equation 1.

$$TPVA = (\frac{m}{t}).\ (\frac{1}{A}) \qquad (1)$$

Where m/t is the angular coefficient of the mass gain (g) versus time (h) straight line, and A (m^2) is the permeation area of the film. Thus, the value of water vapor permeability can be calculated according to Equation 2.

$$WVP = \frac{WVPR.e}{ps(URext - URint)}\ x\ 100 \quad (2)$$

Where:

WVP represents the water vapor permeability ($g.m/m^2.Pa.h$);
WVPR (water vapor permeation rate) ($g/m^2.h$);
e is the average film thickness (average of 6 measurements) (m);
ps is the vapor saturation pressure at the test temperature (Pa);
URext is the relative humidity outside the capsule (%) and
URint is the relative humidity inside the capsule (%)

For the color evaluation of the films, a portable colorimeter (Minolta® CR400 Konica Minolta Sensing, Inc., Japan) was used with the CIELAB system. In this color model, L* indicates the luminosity on a scale from 0 (black) to 100 (white); a* represents a hue scale ranging from red (positive a*) to green (negative a*), and b* represents a scale from yellow (positive b*) to blue (negative b*).

Tensile properties were determined using a Stable MicroSystem texture analyzer, employing a methodology based on ASTM standard D-8082-91 (ASTM, 1996). Specimens were cut to dimensions of 80 mm in length and 20 mm in width and fitted into the pneumatic grips of the equipment. The specimens were preconditioned for 3 days at 25°C and 53% relative humidity. A minimum of 15 analyses were conducted for each sample. The initial distance between the grips was set at 40 mm, and the traction speed was set to 120 mm/min. The determined tensile properties were: maximum tensile strength at break (MPa), elongation at break (%), and Young's modulus (MPa).

2.7 STATISTICAL ANALYSIS OF DATA

The analyses were subjected to analysis of variance (ANOVA) and Tukey's test at a significance level of 0.05 using the SISVAR software.

3 RESULT AND DISCUSSION

3.1 CHARACTERIZATION OF JUÇARA FRUIT PEEL

The physicochemical analysis of pH and soluble solids, as well as the levels of ash and moisture, were conducted for the residue (peel) of the Juçara fruit, and the values were compared with literature data obtained for other parts of the fruit (whole fruit, pulp, and seed), as presented in Table 1.

Table 1–Table 1. Physicochemical characteristics of the residue (peel), whole fruit, pulp, and seed of the juçara fruit

	Juçara peel	**Whole fruit**	**Pulp**	**Seed**
pH	4,91 ± 0,02	5,50 ± 0,01*	4,80 ± 0,00*	6,20 ± 0,00*
Soluble solids (°Bx)	4,70 ± 0,03	11,60 ± 0,1**	-	-
Ash (%)	0,54 ± 0,02	2,50 ± 0,00*	3,40 ± 0,00*	1,70 ± 0,00*
Moisture (%)	78,14 ± 0,49	51,90 ± 0,30*	83,80 ± 0,50*	48,90 ± 0,20*

SOURCE: Authors; *(Inada et al., 2015); ** (Silva et al., 2014)

The physicochemical characterization of the juçara fruit peel was explored in this study and complements the literature data characterizing the whole fruit, pulp, and seed. Although it is known that values in the physicochemical properties of the fruit and residue can vary significantly due to cultivation conditions and location, fruit species, and climatic conditions, for juçara fruits grown in different regions (Da Silva Campelo Borges *et al.*, 2011).

Regarding physicochemical characteristics of the residue (peel), whole fruit, pulp, and seed of the juçara fruit (Table 1), as expected, differences in values were found for each part of the fruit when compared, due to the difference in structural composition of the different parts of the fruit. The values allowed the identification of advantages in extracting bioactive compounds from the peel, compared to the whole fruit, since the peel has a slightly lower pH compared to the entire fruit. This is interesting for its use in the development of bioactive products, as the lower pH contributes to the stabilization of anthocyanins (Enaru *et al.*, 2021). The moisture content found for the peel in this study was 78%, while Schulz et al. (2015) found values between 56.36% and 64.56% for the whole fruit at different ripening stages, probably because it considers the lower moisture content represented by the seed. Since this moisture content value can be even higher when considering only the pulp, as indicated by Inada et al. (2015), who found a value of 83.8%. Regarding the soluble solids content (°Brix), the peel presented a lower value (4.7) compared to the value found by Silva et al. (2014) who studied the composition of the juçara pulp. The ash content exhibited by the residue (peel) is below those reported in the literature for the residue (seed), whole fruit, and fruit pulp.

3.2 BIOACTIVE COMPOUNDS OF JUÇARA FRUIT PEEL EXTRACTS

The extracts from juçara palm residue obtained by conventional and ultrasound methods were evaluated for bioactive compounds at different stages of the process (ex-tracts, extracts added with alginate, and lyophilized alginate-added extracts), as presented in Table 2.

Table 2- Levels of bioactive compounds and antioxidant activity of the extracts at different stages of the process.

	EC	**EU**	**ECA**	**EUA**	**CCAL**	**CUAL**
DPPH	7,60^{b} ±0,16	7,48^{b} ±0,05	5,97^{b} ±0,08	6,15^{b} ±0,16	27,78^{a}±17,51	40,07^{a} ±0,05
ABTS	4,51^{b} ±2,72	2,14^{b} ±0,36	10,32^{b}±8,41	13,40^{b}±5,69	68,65^{a}±41,43	75,29^{a} ±2,72
FRAP	12,95^{c}±0,75	12,93^{c}±4,35	4,74^{c} ±1,12	2,69^{c} ±0,06	128,90^{a}±8,52	108,84^{b}±6,88
CFT	0,79^{b} ±0,14	0,99^{b} ±0,07	0,80^{b} ±1,12	0,85^{b} ±0,02	6,41^{a} ±4,01	8,18^{a} ±0,11
Flavonoids	10,67^{d}±4,13	11,46^{d}±3,30	10,81^{d}±1,80	34,88^{c}±3,33	156,18^{b}±5,22	215,66^{a}±13,76
Antocyanins	0,19^{a} ±0,19	0,10^{a} ±0,07	0,07^{a} ±0,09	0,10^{a} ±0,00	0,16^{a} ±0,07	0,25^{a} ±0,07

DPPH, ABTS, FRAP (mg Trolox/g), CFT (mg EAG/g), flavonoids (mgEQ/g), and anthocyanins (mgCy-3-glu/g). Mean ± standard deviation in the same row, followed by different letters, indicate statistically significant differences at $p < 0.05$ (n = 3). Extract obtained by ultrasound (EU); Extract obtained by thermal bath (EC); Extract obtained by thermal bath added with alginate (ECA); Extract obtained by ultrasound added with alginate (EUA); Capsules of extract obtained by thermal bath added with lyophilized alginate (CCAL); and Extract obtained by ultrasound added with lyophilized alginate (CUAL).

SOURCE: Authors

The extraction method (thermal bath or ultrasound) did not show significant differences for the antioxidant values DPPH, ABTS, FRAP, CFT, flavonoids, and anthocyanins. Under the studied condition (30°C/30min), suggesting that extraction can be carried out by either method. Overall, lyophilization allowed for the concentration of bioactive compounds, resulting in higher values ($p<0.05$) for encapsulated and lyophilized products.

Encapsulation is an effective process to preserve encapsulated bioactives from surrounding conditions, while also aiding in optimized delivery and controlled release of transported active compounds (Alu'datt *et al.*, 2022). Although the anthocyanin content did not show significant differences ($p>0.05$) among the studied samples, for all other analyses of bioactive compounds (CFT and flavonoids) and antioxidant activity (DPPH, ABTS, FRAP), there was an increase in antioxidant power when the extracts were encapsulated (CCAL and CUAL). The encapsulation indicates an effective method for better preservation of compounds extracted from juçara fruit peel. Another study, conducted by Rezende et al., (2018), showed a 50% improvement in antioxidant values (phenolic compounds and flavonoids) when encapsulating extracts from acerola pulp and residue. This result reinforces the improvement in preservation of bioactive compounds through encapsulation, providing better utilization of agro-industrial residue by maintaining good antioxidant activity.

3.3 APPLICATION OF BIOACTIVE COMPOUNDS IN FILMS

After the bioactive compounds were obtained through extraction and underwent encapsulation and lyophilization processes, they were applied to biodegradable films produced by the casting method. The appearance of the films elaborated without extract addition (F), with addition of extract obtained by thermal bath (FC), and with addition of extract obtained by ultrasound (FU) can be observed in Figure 1.

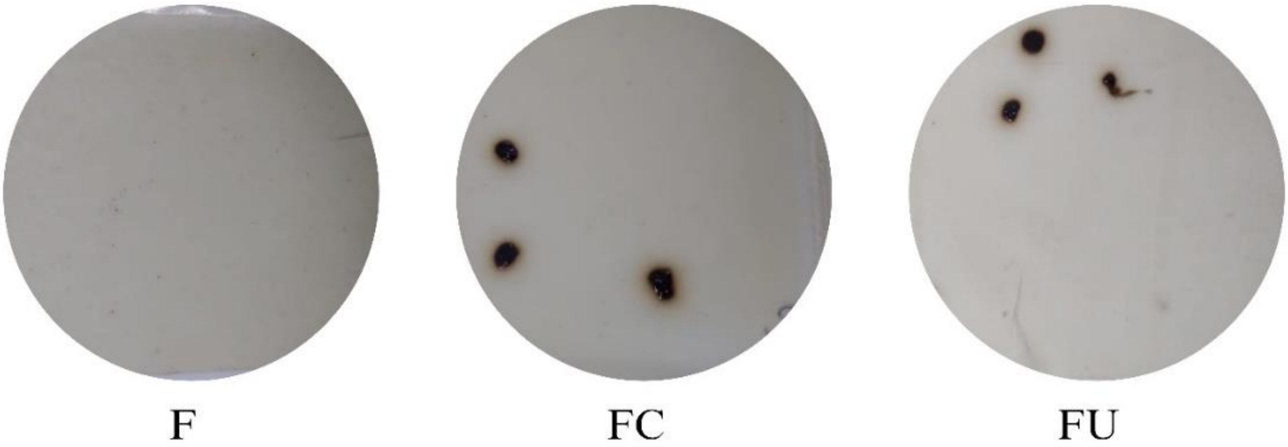

Figure 1 –Biodegradable films without extract addition (F); with addition of extract obtained by thermal bath (FC); and with addition of extract obtained by ultrasound (FU).
SOURCE: Authors

Although the films added with extract showed darker spots (due to the color of the extract), resulting in a non-homogeneous appearance, the prepared films exhibited a smooth surface, good malleability, and were easily removed from the plates, demon-starting their potential as self-supporting films. The appearance of the films elaborated without extract addition (F), with the addition of extract obtained by thermal bath (FC), and with the addition of extract obtained by ultrasound (FU) corroborates with characteristics highlighted in the literature. Polyol plasticized films (such as glycerol and sorbitol) are known to produce smooth, clear, homogeneous surfaces with good mechanical resistance (JEYA JEEVAHAN et al., 2020). The addition of extracts can be easily identified by the concentration of spots where they were applied, likely due to the encapsulation technique used.

3.4 EVALUATION OF COLOR OF BIODEGRADABLE FILMS

The color of the film is essential for enhancing consumer acceptability (JEYA JEEVAHAN et al., 2020). There-fore, the biodegradable films produced in this study were evaluated for instrumental color parameters L*, a*, b*, and H, as presented in Table 3.

Table 3- Instrumental color parameters for the films

Parameters	**F**	**FC**	**FU**
L*	82,01^{a} ±0,41	72,39^{a} ±6,13	76,07^{a} ±6,05
a*	-1,27^{a} ±0,01	-1,22^{a} ±0,70	-0,82^{a} ±0,53
b*	10,98^{b} ±0,71	13,30^{a} ±1,11	13,37^{ab} ±1,05
H	96,62^{b} ±0,38	95,40^{a} ±3,39	93,87^{a} ±2,62

Mean ± standard deviation in the same row, followed by different letters, indicate statistically significant differences at $p = 0.05$ ($n = 3$).
SOURCE: Authors

In general, plant extracts alter the color of polymers (Silva-Weiss *et al.*, 2013). Indeed, significant differences ($p<0.05$) were observed for some color parameters of films with and without capsule addition. Films incorporated with capsules showed a higher value of the parameter b* (yellow-blue component) compared to films without capsule. Regarding the parameter H (hue), films added with bioactive compounds showed a more intense color compared to films without capsules addition. As for the parameters L* (luminosity) and a* (red-green component), no significant differences ($p>0.05$) were found.

Films incorporated with capsules showed a higher value of the parameter b* compared to films without capsules, this difference implies a more yellowish color, probably due to the interaction of the capsules with the biodegradable film material, which forms yellow halos around the capsule when applied to the biofilm, as can be observed in Figure 1. Other studies also point out an impact on color difference, where the change in the color of films depends on the source of the extract and the quantity used (Mir *et al.*, 2018). Differences in the color parameters were found probably due to the heterogeneous and concentrated distribution of the extracts only at certain points of the film, resulting in similar colors. Most non-plasticized films are clear and transparent, making them more acceptable (Jeya Jeevahan *et al.*, 2020), so it was interesting to observe that the addition of the extracts proposed in this work did not affect the luminosity of the films.

3.5 MECHANICAL PROPERTIES OF BIODEGRADABLE FILMS

The final functionality of the films is related to their bioactivity, such as antioxidant activity; physical properties such as color; and their functionality, such as their ability to serve as barriers to water vapor, oxygen, carbon dioxide, and UV-visible light (Silva-Weiss *et al.*, 2013). Thus, mechanical properties such as thickness (T); maximum tensile strength (TS); elongation at break (EB); Young's modulus (MY); and water vapor permeability (WVP) were evalu-ated for the biodegradable films. Table 4 displays the mechanical properties of the manufactured films, without extract addition and with extract addition obtained by conventional and ultrasound extraction methods, in order to highlight the influence of adding bioactive compounds on the mechanical behavior of the produced films.

Table 4. Mean values for thickness, mechanical properties, and water vapor permeability of biodegradable films without extract addition and with extract addition obtained by different methods.

Proprieties	**F**	**FC**	**FU**
T (mm)	0,17^{b} ± 0,07	0,28^{a} ± 0,12	0,35^{a} ± 0,12
TS (MPa)	2,7090 ^{a} ± 1,2771	2,0513^{a} ± 1,159209	2,2143^{a} ± 1,7807
EB (%)	0,0086^{b} ± 0,0033	0,0127^{a} ± 0,0073	0,0174 ^{a} ± 0,0059
MY (MPa)	0,0218^{a} ± 0,0066	0,0204^{b} ± 0,0135	0,0205^{b} ± 0,0106
WCP x 10^{-4} (g mm/m^2 h kPa)	1,04^{b} ± 0,03	1,87^{a} ± 0,21	1,64^{a} ± 0,25

Mean ± standard deviation in the same row, followed by different letters, indicate statistically significant differences at $p < 0.05$ (n = 18) for thickness (T), maximum tensile strength (TS), elongation at break (EB), Young's modulus (MY), and (n=3) for water vapor permeability (WVP). F = control film; FC = film with addition of 1% extract obtained by thermal bath; FU = film with addition of 1% extract obtained by ultrasound.
SOURCE: Authors

The thickness of the film is a very important parameter in determining the physical properties of packaging materials; it can affect the biological properties and shelf life of coated foods (Pająk; Przetaczek-Rożnowska; Juszczak, 2019). The mechanical strength of the films typically depends on the relationship of certain parameters such as thickness and the quantity of additives (GÜRLER et al., 2020). This study found that films with added capsules of bioactive compounds have a greater ($p<0.05$) thickness than films without capsule addition. Therefore, the quantity of additives had an impact on the thickness, while the extraction method of the compounds (conventional and ultrasound) showed statistically equal results, ranging from an average of 0.28 mm for FC to 0.35 mm for the FU film. The thickness of the films in this study was very similar to the thickness values found by Fernandes et al., (2015), who obtained a thickness of 0.19 mm, resulting from the same film production technique, the casting method, where the films are dried on a support.

Tensile strength (TS, MPa) is the maximum strength that measures the resistance of the film, while the percentage of elongation at break (EB%) is a measure of the film's stretching or flexibility capacity before rupture. There were no significant differences ($P>0.05$) for the maximum tensile strength of the developed films, but differences were found for elongation at break (EB%). The maximum tensile strength ranged between 2.17 and 3.05 MPa. The maximum tensile strength of films was variable, probably because all films were produced using the same base, a mixture of alginate and gelatin with or without the addition of capsules. Composite films are typically superior to simple polymeric films and represent a straightforward approach to enhance the mechanical properties of films (Rezvanian; Mohd amin; Ng, 2016). Thus, the composition of this base may have influenced the strength of the films regardless of the addition of capsules. As for the elongation at break (ER %), the film with the addition of extract capsules showed greater elongation at break, likely due to increased flexibility at the more concentrated extract points.

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The Young's modulus is the ratio between stress (force applied per unit area) and strain (relative change in original length) in the longitudinal direction of the material. The higher the Young's modulus, the stiffer the material and the more resistant to elastic deformation (Hibbeler, 2010). Films added with bioactive compounds from juçara fruit peel in encapsulated form showed slightly lower values for the Young's modulus com-pared to films without capsule addition, revealing that, in general, the addition of the capsule did not increase the stiffness of the material.

The mechanical strength and barrier properties to water vapor and gases (mainly oxygen and carbon dioxide) of non-plasticized films are inferior to petroleum-derived plastics. Plasticizers are added to the film-forming solution to improve its flexibility. The plasticizer molecules disrupt polymer-polymer interactions and create polymer-plasticizer interactions. As a result, the addition of plasticizer makes the film soft and flexible (Jeya Jeevahan *et al.*, 2020; Jia *et al.*, 2023). In addition to the addition of plasticizers in the formulation of biodegradable films, this study observed that the addition of capsules influenced the water vapor permeability, with films with encapsulated extract showing higher values ($p<<0.05$) compared to the average value found for the film without extract.

4 CONCLUSION

The bioactive properties of a wide range of plants and their by-products have not yet been fully explored in the literature. The by-product of juçara (peel) contains antioxidants with potential application in the food industry. In this study, the green ex-traction and followed by encapsulation of antioxidants from juçara peel were performed under different conditions and applied in biodegradable films.

The results showed that the application of these compounds, regardless of the ex-traction method, can be an alternative to improve the mechanical properties of biodegradable films while adding bioactive compounds, which may eventually enhance the stability of foods. The contact between the bioactive compounds in the film and the food is a point that should be further studied in future research.

The extraction of bioactive compounds from juçara palm peel to produce biodegradable packaging not only valorizes an agro-industrial waste but also effectively contributes to the United Nations Sustainable Development Goals (SDGs), particularly addressing SDGs 2, 12, and 15, related to reducing food waste, sustainable agriculture, and forest conservation through the valorization of fruit peel. This strategy represents an innovative and sustainable approach, aligning with the promotion of food security and responsible consumption and production practices.

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