Active gelatin-based films incorporated with juçara (*Euterpe edulis* M.) extract: Mechanical, thermal, and antioxidant properties

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Abstract

The replacement of conventional plastic packaging with biodegradable materials derived from natural sources has driven research toward functional biopolymeric systems. Gelatin is a promising matrix for film formation, and juçara (*Euterpe edulis*) extract, rich in phenolic compounds, represents a potential bioactive additive. This study aimed to develop gelatin-based films incorporating juçara extract at concentrations of 0.1 g extract g^{-1} gelatin (S1) and 0.25 g extract g^{-1} gelatin (S2), in comparison with a control film without extract. The films were characterized in terms of water solubility, mechanical properties, water vapor permeability (WVP), color attributes, morphology, thermal behavior, and antioxidant activity. Data were statistically analyzed by analysis of variance followed by *Tukey's* test ($p \leq 0.05$). Extract incorporation significantly affected film properties. S2 exhibited the highest elongation at break (24.24%) and the lowest WVP (1.57 g mm m^{-2} day^{-1} kPa^{-1}), although tensile strength decreased compared to the control (22.81 MPa). Films containing juçara extract showed reduced solubility relative to the control. Colorimetric analysis indicated similarity to fresh fruit, with increased opacity upon extract addition. Scanning electron microscopy revealed uniform and homogeneous surfaces, with greater particle dispersion observed in S2. Thermal analysis demonstrated a glass transition temperature of 36.9 °C for all samples, while melting temperatures increased with extract concentration, reaching 142.3 °C in S2. Antioxidant activity increased markedly after extract incorporation, with inhibition percentages of 1.97%, 38.68%, and 55.91% for control, S1, and S2, respectively. The results indicate that *Euterpe edulis* extract enhances both functional and bioactive properties of gelatin-based films, particularly at 0.25 g extract g^{-1} gelatin, supporting its potential application in active biodegradable food packaging.

Keywords: juçara extract, biodegradable packaging, bioactive properties, antioxidant activity, *Euterpe* genus.

Filmes ativos à base de gelatina incorporados com extrato de juçara (*Euterpe edulis* M.): Propriedades mecânicas, térmicas e antioxidantes

Resumo

A substituição de embalagens plásticas convencionais por materiais biodegradáveis de origem natural tem impulsionado o desenvolvimento de sistemas biopoliméricos com propriedades funcionais aprimoradas. A gelatina destaca-se como uma matriz promissora para formação de filmes, enquanto o extrato de juçara (*Euterpe edulis*), rico em compostos fenólicos, representa um potencial aditivo bioativo. Este estudo teve

como objetivo desenvolver filmes à base de gelatina incorporados com extrato de juçara nas concentrações de 0,1 g de extrato g^{-1} de gelatina (S1) e 0,25 g de extrato g^{-1} de gelatina (S2), em comparação com um filme controle sem extrato. Os filmes foram caracterizados quanto à solubilidade em água, propriedades mecânicas, permeabilidade ao vapor de água (PVA), parâmetros de cor, morfologia, comportamento térmico e atividade antioxidante. Os dados foram analisados estatisticamente por análise de variância seguida do teste de *Tukey* ($p \leq 0,05$). A incorporação do extrato influenciou significativamente as propriedades dos filmes. A formulação S2 apresentou o maior alongamento na ruptura (24,24%) e a menor PVA (1,57 g mm m^{-2} dia^{-1} kPa^{-1}), embora tenha ocorrido redução da resistência à tração em relação ao controle (22,81 MPa). Os filmes contendo extrato apresentaram menor solubilidade em comparação ao controle. A análise colorimétrica indicou tonalidades semelhantes às do fruto in natura, com aumento da opacidade após a incorporação do extrato. A microscopia eletrônica de varredura revelou superfícies homogêneas e uniformes, com maior dispersão de partículas em S2. A análise térmica demonstrou temperatura de transição vítrea de 36,9 °C para todas as amostras, enquanto as temperaturas de fusão aumentaram com a concentração de extrato, atingindo 142,3 °C em S2. Observou-se aumento significativo da atividade antioxidante após a incorporação do extrato, com percentuais de inibição de 1,97%, 38,68% e 55,91% para controle, S1 e S2, respectivamente. Os resultados indicam que o extrato de *Euterpe edulis* melhora simultaneamente as propriedades funcionais e bioativas dos filmes à base de gelatina, especialmente na concentração de 0,25 g de extrato g^{-1} de gelatina, evidenciando seu potencial para aplicação em embalagens alimentícias biodegradáveis ativas.

Palavras-chave: extrato de juçara, filme biodegradável, propriedades bioativas, atividade antioxidante, gênero *Euterpe*.

1. Introduction

Conventional packaging, which is derived from petroleum, is known for its low cost, lightweight, flexibility, and mechanical and chemical resistance, although its poor biodegradability results in serious environmental pollution problems (Lu et al., 2022; Takma et al., 2024). In addition, plastic production is dependent on oil, a finite resource, and some plasticizers, such as phthalates, can migrate to food, posing risks to human health (Filho et al., 2024).

Considering the current scenario of growing concern about environmental pollution, the search for sustainable alternatives has driven the development of new technologies in the production of biodegradable food packaging, aimed at replacing plastic packaging from non-renewable sources (Mondal et al., 2022; Pessanha et al., 2018). Among the materials used to make biodegradable films, natural polymers, such as proteins, polysaccharides, lipids, or a combination of them, are highly valued for their non-toxicity and natural biodegradability (Filho et al., 2024; Takma et al., 2024).

One of the most studied polymers due to its abundance and low cost is gelatin, a hydrophilic protein derived from collagen found in the hides and bones of cattle, pigs, and fish (Lu et al., 2022; Villasante et al., 2020). Gelatin is a hydrocolloid polymer highly soluble in water and can be used to produce transparent films that are easy to handle but have moderate mechanical resistance (Choi et al., 2023; Zhang et al., 2026). The addition of plasticizers, such as glycerol, in their formulation improves the mechanical properties of the films, minimizing possible practical application limitations (Bandeira; Pinto, 2015; Zhang et al., 2026). Furthermore, polymeric films can act as carriers of some active substances, such as antioxidants and antimicrobial agents, which tend to reduce the oxidation process of the packaged product, preserving the quality of the food and extending its shelf life (Villasante et al., 2020).

Polyphenols, a diverse group of plant-derived antioxidants, combat the harmful effects of free radicals, safeguarding cells from oxidative stress and promoting overall health (Lu et al., 2022). As consumer concern about food safety grows, questions have arisen regarding the use of synthetic antioxidants in food packaging due to potential health risks (Crozatti et al., 2023; Filho et al., 2024). As an alternative, natural antioxidants, such as plant extracts and essential oils, have been widely studied (Choi et al., 2023; Mondal et al., 2022; Rangaraj et al., 2021; Takma et al., 2024). These options have shown good results both in terms of food quality and in improving the mechanical and thermal properties of the films (Lu et al., 2022).

In this context, the juçara (*Euterpe edulis* Martius), a native fruit of the Atlantic Forest, has garnered significant attention due to its nutritional value, high anthocyanin content, and antioxidant activities (Crozatti et al., 2023; Silva et al., 2025). The use of juçara extract in the development of biodegradable

packaging could offer an innovative and sustainable solution that aligns with consumer concerns about food quality and safety. Therefore, this study aimed to develop gelatin-based films with the incorporation of juçara extract.

2. Materials and Methods

2.1 Materials

Powdered type B gelatin (225 g Bloom), 2,2-diphenyl-1-picrylhydrazyl (DPPH), and glycerol (purity ≥ 99%) were purchased from Sigma-Aldrich Brasil Ltda. Juçara fruits (*Euterpe edulis*) were obtained from farmers in the municipality of Caraá, RS, Brazil. Chemical reagent companies in Brazil provided the other analytical-grade chemical reagents used in this study.

2.2 Obtaining the freeze-dried extract of juçara fruit

The method for obtaining the juçara fruit extract was described by Crozatti et al. (2023), with some modifications. Initially, the fresh fruit picked the day before was cleaned, sorted, and sanitized. Then, the fruit was cold macerated at 20 ± 1 °C using 96% ethyl alcohol as the extracting solvent and acidified with the gradual addition of hydrochloric acid until pH 2.0 was reached. The material was left to macerate for 48 h at 20 ± 1 °C in a closed amber glass container. After, the material was vacuum filtered and the extract obtained was concentrated in a rotary evaporator (Fisatom, 810, Brazil) at 35 °C. Then, the concentrated extract was subjected to freeze-drying in a bench-top freeze-dryer (Terroni, LS3000, Brazil) with an operating temperature of -50 °C for 48 h. Finally, the dried extract was stored in a freezer at -23 °C until it was added to the films.

2.3 Production of films incorporated with juçara extract

The gelatin-based films were produced using the casting technique, according to the method described by Bandeira & Pinto (2015), with minor modifications. Three types of samples were produced: a film incorporated with extract at a concentration of 0.1 g extract g^{-1} gelatin (S1), a film incorporated with extract at 0.25 g extract g^{-1} gelatin (S2), and the control film (C) with no extract incorporated. The film solutions were prepared by dissolving 2 g of gelatin, 0.2 g of glycerol, and the corresponding mass of dry extract in 100 mL of distilled water, and kept under constant agitation (240 rpm) in a magnetic stirrer (Fisatom, 752A, Brazil) for 30 min at 35 °C. The solution was then sonicated for 1 min to remove air bubbles. Next, 17 mL of the film solution was transferred to acrylic Petri dishes (9 cm diameter x 1 cm height) and placed in an oven (Lucadema, LUCA-80/150, Brazil) at 28 °C for 20 h to evaporate the solvent. The dried films were removed manually and placed in a desiccator, kept at 25 °C and 75% relative humidity (controlled with a 40% NaCl solution) until the analysis.

2.4 Film thickness

The thickness of the films was determined using a digital external micrometer (Digimess, 110.284-NEW, Brazil), with a resolution of 1 μm, measuring 10 random points for each sample. Thickness was measured using the average obtained for three films from each treatment.

2.5 Water solubility

The water solubility of the films was evaluated in triplicate, according to the method described by Rangaraj et al. (2021), with minor modifications. The film samples were cut into 2 cm diameter disks and dried in an oven with air circulation (105 °C for 24 h) and weighed to a constant mass. The dried samples were then immersed in a container with 50 mL of distilled water and placed on a shaking table (Lucadema, LUCA-183, Brazil) for 24 h at 25 °C. After, the remaining residue was dried in an oven with air circulation (105 °C for 24 h) and weighed to obtain the final dry mass. The percentage of mass solubilized in solution was determined by dividing the difference between the initial dry mass and the mass after solubilization by the initial mass.

2.6 Mechanical properties

The tensile strength (TS) and elongation at break (EB) of the films were determined according to the official method D00882-00 (ASTM, 2000a). The samples were cut into rectangles 40 mm long and 25 mm wide and attached to a texturometer (Stable Microsystems, SMD TA.XP2i, UK) with a 5 kg interchangeable cell. The initial distance between the grips was 40 mm, at an operating rate of 50 mm min^{-1}.

2.7 Water vapor permeability

The water vapor permeability (WVP) of the films was determined gravimetrically using the E96/E96M-05 method (ASTM, 2000b). The films in the form of 9 cm diameter disks were sealed with paraffin in permeation cells (diameter 4.2 cm), containing anhydrous calcium chloride ($CaCl_2$) up to half the cell volume. The permeation cells were then placed in a desiccator at 25 °C and 75% relative humidity controlled by a saturated NaCl solution. The water vapor transferred through the film was determined by the mass gain of the $CaCl_2$, measured every 24 h for 5 days. The WVP was calculated according to Equation 1:

$$WVP = \frac{e}{A\,\Delta P} M \qquad (1)$$

where: WVP = water vapor permeability through the films, in g mm m^{-2} day^{-1} kPa^{-1}; M = moisture absorption rate, in g day^{-1}; *e* = film thickness, in mm; A = exposed surface area, in m^2; ΔP = partial vapor pressure difference across the film, in kPa and equal to 3.164 kPa.

2.8 Optical properties

The optical properties were measured using a colorimeter (Konica Minolta, CR-400, Japan) to determine L^* (luminosity), a^* (green to red), and b^* (blue to yellow). The colorimeter was calibrated with a white standard before the analyses.

The color difference (ΔE) was calculated using Equation 2:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (2)$$

where: ΔL^*, Δa^*, and Δb^* represent the color differences between the films with juçara extract and the control. The Hue angle was calculated using Equation 3 to determine the color tones of the films.

$$Hue = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad (3)$$

2.9 Film opacity

Opacity was determined according to the method described by Siripatrawan & Harte (2010) by measuring the absorbance of the films at 600 nm using an ultraviolet-visible spectrophotometer (Metash, UV-8000A, China). The films were cut into rectangular shapes (0.4 x 4.5 cm) and placed directly into a spectrophotometer test cuvette. An empty test cuvette was used as a reference, and the opacity of the film was estimated using Equation 4:

$$Opacity = \frac{Abs_{600}}{e} \qquad (4)$$

where: Abs_{600} = absorbance value at 600 nm; *e* = film thickness, in mm.

2.10 Scanning electron microscopy (SEM)

Micrographs of the film surfaces were generated using a scanning electron microscope (Jeol, JSM 6010LV, Japan), with an acceleration voltage of 10 kV. The samples were prepared by metalizing them with gold in a vacuum chamber (Denton Vacuum, Desk Sputtering V, USA) so that energy conduction would occur when they were micrographed.

2.11 Differential scanning colorimetry (DSC)

Differential scanning calorimetry (Shimadzu, DSC-60, Japan) was performed on 8 mg samples in hermetically sealed aluminum pans. Scans were conducted from 22 °C to 230 °C at 10 °C min^{-1} with a N_2 flow rate of 50 mL min^{-1}. An empty aluminum pan was used as a reference.

2.12 Antioxidant activity of the films

The extract was prepared from each film sample according to the method described by Jamróz et al. (2022), with some modifications. Briefly, 0.1 g of film was cut into small pieces and mixed with 10 mL of distilled water. The mixture was then stirred for 22 h and centrifuged for 10 min at 5000 rpm (2780 xg) in a centrifuge (Fanem, Excelsa II, Brazil), where the supernatant was collected for analysis.

The antioxidant activity of the films was evaluated in triplicate using the free radical scavenging assay with DPPH, according to Bhattarai & Janaswamy (2023), with minor modifications. In summary, 1 mL of film extract was mixed with 3 mL of 0.1 mM DPPH in ethanol and stirred in a vortex mixer. The mixture was incubated in the dark for 30 min at 25 °C. Afterward, the absorbance was measured at 517 nm on a spectrophotometer (Dynamica, Halo-SB-10, UK) using a sample prepared with distilled water instead of the film extract as a blank. The percentage of DPPH free radical scavenging activity was quantified by the ratio of the difference between the absorbance of the ethanolic DPPH solution and the absorbance of the extract, to the absorbance of the ethanolic DPPH solution.

2.13 Statistical analysis

All statistical calculations were performed using Statistica® 7.0 software (Statsoft, USA). The results were evaluated by analysis of variance (ANOVA) and comparison of means by *Tukey's* test, considering a significance level of 95%.

3. Results

3.1 Thickness and visual appearance

The thickness of the biopolymeric films was significantly influenced by the addition of juçara extract ($p \leq 0.05$), as detailed in (Table 1). While the control film exhibited the lowest thickness, both formulations containing the extract (S1 and S2) showed a significant increase in this parameter. However, no significant differences were observed between the two extract concentrations ($p > 0.05$).

Table 1. Thickness, solubility, water vapor permeability (WVP), tensile strength (TS), and elongation at break (EB) of the control film and the films incorporated with juçara extract.

Parameter	Control	S1	S2
Thickness (mm)	0.058 ± 0.007b	0.068 ± 0.006a	0.074 ± 0.007a
Solubility (%)	35.78 ± 0.45a	31.25 ± 0.08b	29.39 ± 0.12c
WVP (g mm m^{-2} day^{-1} kPa^{-1})	2.05 ± 0.08a	1.94 ± 0.18a	1.57 ± 0.05b
TS (MPa)	29.65 ± 0.47a	24.72 ± 1.56b	22.81 ± 1,29b
EB (%)	9.55 ± 0.13c	15.10 ± 0.20b	24.24 ± 0.26a

Note: Average values from triplicate. Averages followed by the same letter in the row do not differ significantly according to the *Tukey* test at 5%. Source: Authors, 2026.

Figure 1 illustrates the visual aspect of the developed films. All films produced in this study were glassy, glossy, and uniform in their central area. The incorporation of juçara extract imparted a purple hue to the films, with a more intense coloration observed in the central region compared to the edges.

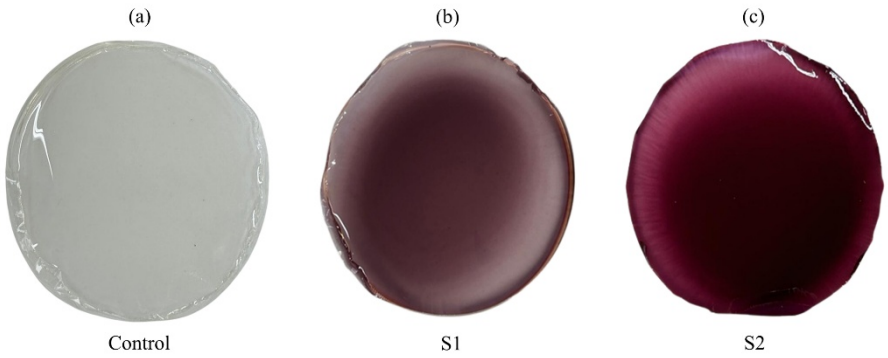

Figure 1. The visual appearance of the biopolymeric films: (a) control sample; (b) S1; and (c) S2. Source: Authors, 2026.

3.2 Water vapor permeability and solubility

The water solubility and WVP values for the control, S1, and S2 films are presented in Table 1. The incorporation of juçara extract significantly affected the solubility of all samples ($p \leq 0.05$). Regarding WVP, the lowest value was observed for the film with the highest concentration of extract (S2), while the highest values were obtained for the control film and the S1 formulation, which did not differ significantly from each other ($p > 0.05$). Conversely, the WVP of the S2 film was significantly reduced ($p \leq 0.05$) compared to both the control and S1 samples.

3.3 Mechanical properties

The tensile strength (TS) and elongation at break (EB) values for the gelatin-based films are presented in (Table 1). No significant difference ($p > 0.05$) was observed between the TS of the films incorporated with juçara extract (S1 and S2). However, a significant difference ($p \leq 0.05$) was found between the average values of the films containing the extract and the control sample. The data indicate that increasing the concentration of extract in the film matrix favored a reduction in TS, although the increase from 0.1 to 0.25 g extract g^{-1} gelatin was not sufficient to cause a statistically significant further reduction.

In contrast, the EB showed significant differences among all samples ($p \leq 0.05$). The percentage of elongation increased progressively with the concentration of juçara extract in the gelatin matrix, with the S2 formulation reaching the highest elasticity among the tested samples.

3.4. Optical properties

The color parameter data for the films developed in this study are presented in Table 2. The results indicate that all films exhibited a significant difference ($p \leq 0.05$) among them. The control film demonstrated typical results for bovine gelatin matrices. The incorporation of juçara extract led to a decrease in L^* values for S1 and S2, indicating a higher tendency toward darkness as the concentration of the extract increased. The color parameters further show that the films containing the extract shifted toward a purplish-red Hue.

Regarding the total color difference, both S1 and S2 films exhibited significantly higher values than the control film ($p \leq 0.05$). Increasing the extract concentration from S1 and S2 resulted in a non-proportional increase in color difference, with a more pronounced variation occurring at the lower concentration level. Additionally, extract incorporation significantly increased ($p \leq 0.05$) the opacity of the films compared to the control.

Table 2. Color parameters, opacity, and antioxidant activity (AA) of the control film and the films incorporated with juçara extract (S1 and S2).

Parameter	Control	S1	S2
L^*	99.07 ± 0.12a	43.52 ± 1.70b	29.56 ± 0.46c
a^*	-0.49 ± 0.03c	13.00 ± 0.33a	9.10 ± 1.34b
b^*	1.82 ± 0.22b	1.65 ± 0.04b	2.78 ± 0.23a
Hue (°)	74.77 ± 1.51a	7.37 ± 0.19c	17.08 ± 1.01b
ΔE	-	57,92 ± 1.60b	70,28 ± 0.25a
Opacity	0.86 ± 0.14c	7.55 ± 0.47b	16.53 ± 0.99a
AA (%)	1.97 ± 0.19c	38.68 ± 1.28b	55.91 ± 1.54a

Note: Average values from triplicate. Averages followed by the same letter in the row do not differ significantly according to the *Tukey* test at 5%. ΔE calculated relative to the control film; not applicable for the control sample. Source: Authors, 2026.

3.5. Microstructure

The surface morphology of the biopolymeric films was examined by SEM micrographs at magnifications of x500 and x2000 (Figure 2). The control film (Figures 2a and 2b) exhibited a high degree of uniformity and homogeneity compared with the other evaluated samples. In the S1 and S2 formulations (Figures 2c to 2f), an increase in the number and dispersion of surface particles was observed, proportional to the concentration of the juçara extract. At higher magnification (x2000), these particles presented irregular shapes and a rough surface morphology. Despite their presence, all films maintained a structural surface without irregularities, cracks, or evidence of phase separation, indicating that the particles were well-integrated into the biopolymeric matrix. The S2 film displayed the highest density of dispersed particles across the gelatin network.

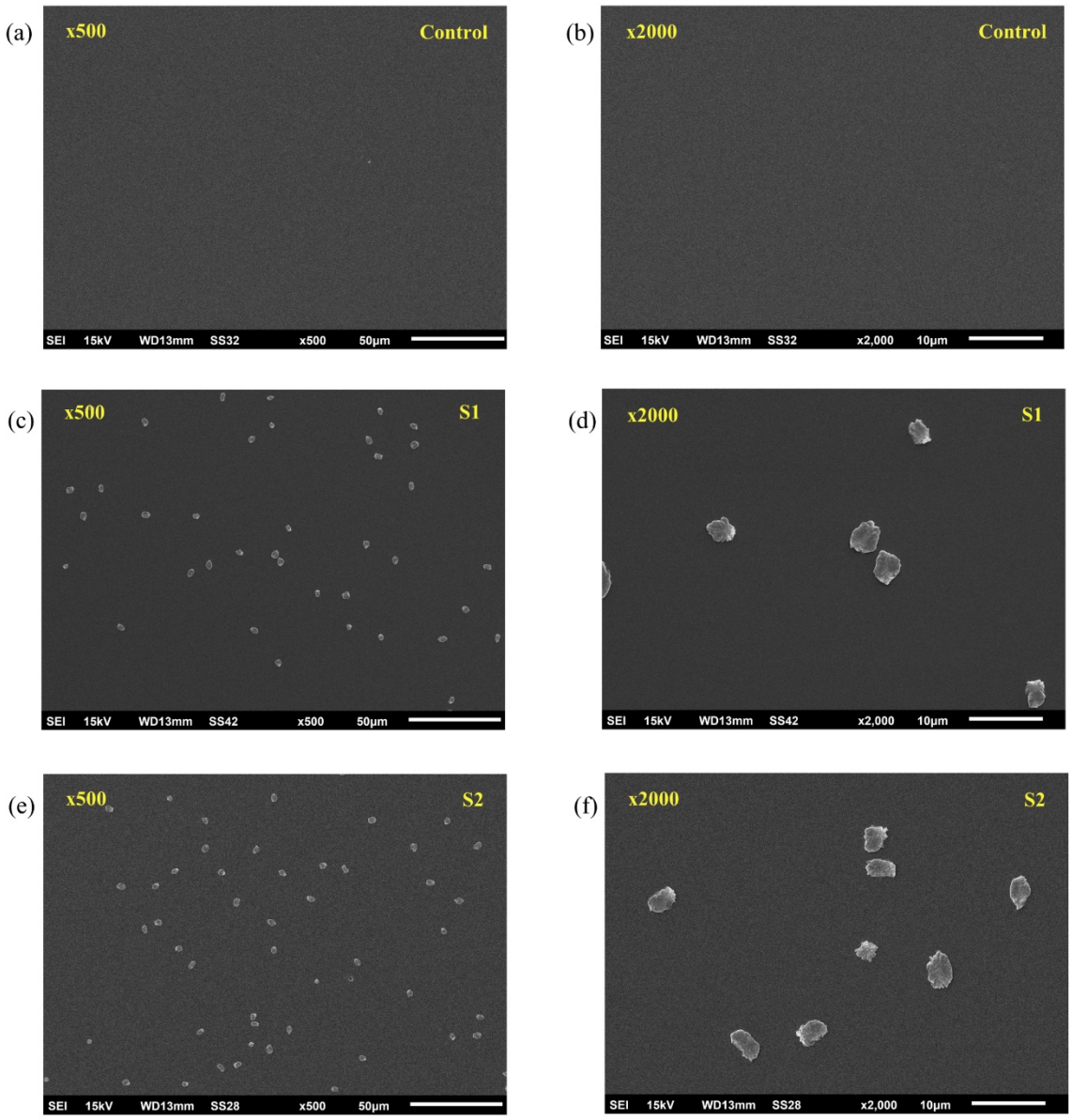

Figure 2. SEM micrographs at different resolutions: (a) control film at x500; (b) control film at x2000; (c) S1 at x500; (d) S1 at x2000; (e) S2 at x500; and (f) S2 at x2000. Source: Authors, 2026.

3.6. Thermal analysis (DSC)

The DSC thermograms for the control, S1, and S2 films are illustrated in Figure 3. Weak endothermic peaks were observed in all thermograms at temperatures within the glass transition (T_g) range of gelatin. The results indicated that the incorporation of juçara extract did not affect the T_g of the biopolymeric matrix, which remained stable across all samples.

Differences in the thermal stability were evidenced by the melting temperature (T_m), where the control film presented the lowest value, followed by the S1 film (Table 1). A notable increase in the energy required for melting was observed for the S2 film. Additionally, the final stages of the thermographic analysis revealed a second visible peak for all samples at elevated temperatures.

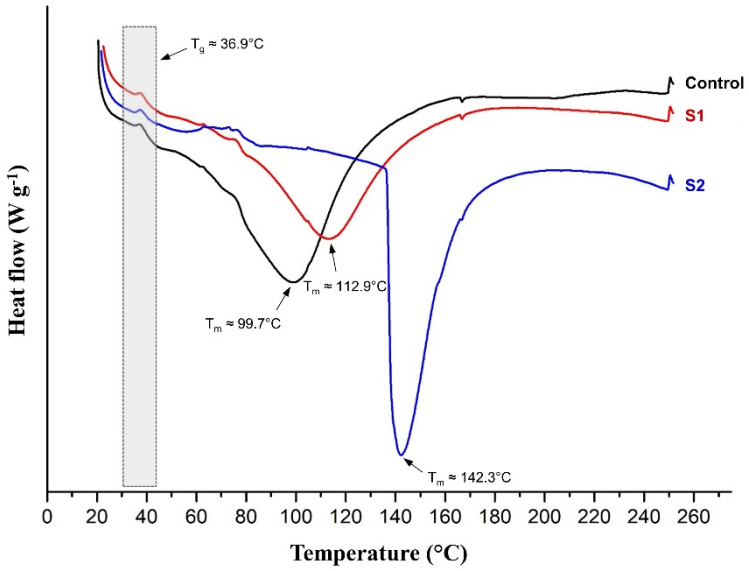

Figure 3. DSC thermogram for the control film and the films incorporated with juçara extract (S1 and S2). Source: Authors, 2026.

3.7. Antioxidant Activity

The antioxidant activity of the gelatin-based films is presented in Table 2. The results indicate a significant increase in the radical inhibition percentage for films S1 and S2 compared to the control group ($p \leq 0.05$). A significant difference was also observed between all samples ($p \leq 0.05$), demonstrating that the evaluated response was directly influenced by the increase in juçara extract concentration.

4. Discussion

4.1 Thickness and visual appearance

The increase in film thickness with the addition of juçara extract is probably associated with the higher total solids content in the biopolymeric matrix (Villasante et al., 2020). Furthermore, this structural modification may result from molecular interactions within the system. While glycerol acts as the primary plasticizer, enhancing gelatin chain mobility as described by Zhang et al. (2026), phenolic compounds from the juçara extract may also interact with amino groups in the gelatin structure. These interactions could modify intermolecular bonding patterns and influence the free volume of the matrix, contributing to the observed structural changes without compromising film integrity.

The increase in film thickness with the addition of juçara extract structural modifications observed in the films may be associated with competitive interactions within the biopolymeric matrix. Although glycerol acts as the primary plasticizer—enhancing gelatin chain mobility, as described by Zhang et al. (2026)—bioactive compounds from the juçara extract may interact with similar functional groups along the polypeptide chains. Such interactions, particularly those involving polyphenols, could modify intermolecular bonding patterns and influence the free volume of the matrix, contributing to increased chain mobility and the improvement in elongation at break.

Visually, the characteristic purple color is attributed to the anthocyanins present in the *Euterpe edulis* fruit. The concentration of these pigments in the central region during the drying process suggests a mass transfer phenomenon where water evaporation at the edges induces a solute flux toward the center of the films. To ensure an accurate characterization and minimize the effect of transparency variations observed at the edges, only the homogeneous central region was utilized for the properties analyses.

4.2. Water vapor permeability and solubility

The WVP values obtained in this study were equivalent to those reported by Nakashima et al. (2016), who obtained a range from 0.77 to 4.99 g mm m^{-2} day^{-1} kPa^{-1} in collagen-based films, and Bandeira & Pinto (2015), who reported 1.80 g mm m^{-2} day^{-1} kPa^{-1} for corvina skin gelatin films.

The reduction in WVP observed in the S2 film suggests that higher concentrations of juçara extract promote a more compact and homogeneous matrix. This behavior suggests that the extract components may occupy the interstitial spaces within the gelatin network, increasing the tortuosity of the diffusion pathway for water vapor molecules (Yong et al., 2019). Similar reduction in water barrier properties has been reported when natural plant extracts are added to different biopolymer films (Lu et al., 2022; Siripatrawan; Harte, 2010).

Low solubility values are highly desirable for biodegradable packaging to ensure greater water resistance. According to Fakhouri et al. (2007), solubilities ranging from 24.38% to 30.20% in native starch and gelatin films are suitable for food packaging, a range that encompasses the findings of our study. The reduction in both WVP and solubility may be attributed to the hydrophobic compounds in the juçara extract. These compounds can interact with the gelatin matrix, reducing its affinity for water and hindering the passage of water vapor (Villasante et al., 2020). This effect was most evident at the highest concentration (0.25 g extract g^{-1} gelatin), indicating that the concentration of these hydrophobic compounds is a critical factor in modifying the functional properties of the films.

4.3. Mechanical properties

The reduction in TS following the addition of plant extracts is a phenomenon well-documented in biopolymeric matrices. According to Said & Sarbon (2022), bovine gelatin-based films incorporated with plant extracts typically exhibit lower TS values compared to films without extracts, which aligns with the results observed in this study. The presence of polyphenolic compounds in the juçara extract may have promoted the formation of hydrogen bonds with amino and hydroxyl groups in the polypeptide chain, disrupting protein-protein interactions and, consequently, weakening the structural stability of the matrix (Rangaraj et al., 2021).

Although the tensile strength of the S1 and S2 samples was lower than that of the control, it remains within the range reported in the literature for other packaging materials. Specifically, the TS values were higher than those found by Peighambardoust et al. (2021) for pure polypropylene (7.7 MPa) and He et al. (2022) for recycled polyethylene (10.1 MPa). Furthermore, the values were close to those reported by Zighed & Benotmane (2022) for high-density polyethylene (26.7 MPa), by Satapathy & Palanisamy (2021) for PVC films with 20% dioctyl phthalate (24.24 MPa), and by Zhang et al. (2022) for PVC films with 50% dioctyl phthalate (27.0 MPa).

The increase in EB suggests that the juçara extract components acted as effective plasticizing agents within the gelatin matrix. Rangaraj et al. (2021) reported a similar response profile for gelatin films incorporated with date fruit waste extract, where TS decreased while EB increased. In a similar study, Yong et al. (2019) found that adding purple or black rice extract to chitosan films increased the EB, although TS gradually decreased for concentrations above 1% (m/m), suggesting that extract agglomeration could disrupt the homogeneity of the film network. The molecular rearrangement caused by the presence of phenolic compounds contributed to improved flexibility and deformability, which may be due to the plasticizing effect of polyphenols that increases chain mobility (Said; Sarbon, 2022; Kola; Carvalho, 2023; Lu et al., 2022).

Notably, the films developed in this study exhibited promising elongation properties that fall within the range of common synthetic packaging materials. While synthetic polymers such as polypropylene, recycled polyethylene, high-density polyethylene, low-density polyethylene, and PVC typically exhibit a wide range of elongation at break (22.7% to 586.5%) (He et al., 2022; Peighambardoust et al., 2021; Zighed; Benotmane, 2022), the S2 formulation successfully surpassed the lower threshold of this commercial range. This performance indicates that gelatin-based films incorporated with juçara extract possess adequate flexibility for various flexible packaging applications, effectively addressing the limitations often associated with biopolymeric matrices.

In this context, gelatin-based films incorporated with juçara extract emerge as a promising alternative to commercial food-grade PVC films. While traditional PVC relies on synthetic plasticizers that often pose migration and toxicity risks to human health, the use of a natural extract provides a distinct advantage by ensuring functional safety without compromising mechanical integrity (Filho et al., 2024). The S2 formulation achieved an elongation at break comparable to several plasticized PVC applications, with the added benefit of antioxidant protection. Therefore, these films represent a high-performance and

sustainable option for the food industry, balancing competitive mechanical properties with environmental and toxicological safety.

4.4. Optical properties

The colorimetric parameters of the control film were similar to those measured by Bastos et al. (2021), who found values of L^* = 89.35; a^* = 0.37; b^* = -2.25, and Hue of 99.80. The shift toward purplish-red hues in the S1 and S2 samples can be highlighted as an attractive differentiator, as it provides the appearance of a natural and vibrant product. These results were expected since the juçara fruit possesses a considerable concentration of bioactive compounds, such as flavonoids (anthocyanins and phenolic acids), where the characteristic purple color is attributed to the presence of anthocyanins (Crozatti et al., 2023; Silva et al., 2025).

The colorimetric measurements found for the S2 film are close to those reported by Pessanha et al. (2018) for starch-based films with freeze-dried açaí (*Euterpe oleracea*) (L^* = 27.43; a^* = 11.87; b^* = 1.58; Hue = 18.02). Additionally, the results demonstrated a profile comparable to the parameters identified by Borges et al. (2011) for the fruit of *E. edulis* (L^* = 25.65; a^* = 5.95; b^* = 2.54). This indicates that the S2 sample successfully maintains colorimetric characteristics similar to those of the fresh fruit. The data reveal that higher extract concentrations lead to greater color differences compared to the control, with these changes being easily noticeable.

Regarding the physical structure, the significant increase in opacity is consistent with reports on biopolymeric films incorporated with natural extracts, such as green tea (Siripatrawan; Harte, 2010). This effect is attributed to the presence of phenolic pigments, which interfere with light transmission through the matrix. The increase in opacity following extract incorporation represents a relevant advantage for food packaging applications. According to Ding & Fu (2025), reduced light transmittance is crucial for protecting photosensitive foods, as it limits photooxidative reactions. Accordingly, the enhanced light barrier properties observed in the films decrease product exposure to fluorescent, solar, and incandescent light sources (Takma et al., 2024). This characteristic is particularly important for the food industry, as it contributes to the preservation of nutritional quality and oxidative stability by attenuating photodegradation processes (Mohan et al., 2023).

4.5. Microstructure

The high uniformity observed in the control film is consistent with previous reports on gelatin and gelatin-casein films (Kadam et al., 2015). The particles in S1 and S2, representing solids such as fibers and phenolics, influenced the functional properties without compromising the structural integrity. This dispersion may act as a physical barrier within the polymer network, increasing the tortuosity of the diffusion pathway for water molecules and thereby contributing to the reduction in WVP observed in Table 1.

Furthermore, polyphenolic compounds may have exerted a plasticizing effect, particularly in the S2 film. The incorporation of these bioactive components into the polymer matrix without forming structural defects contributed to the enhanced flexibility, as evidenced by the higher EB values. Similar behavior has been reported by Villasante et al. (2020) and Mondal et al. (2022), who also observed dispersed surface particles and improved mechanical responses in biopolymer films containing natural extracts, suggesting that such particles can modulate matrix interactions while preserving deformability.

4.6. Thermal analysis (DSC)

The DSC analysis allowed for the definition of the limit temperatures to which the materials can be exposed without undergoing degradation (Khedri et al., 2021). The T_g peaks observed near 37 °C suggest that the films become more flexible above this temperature. While most foods are stored below this range, this property may be advantageous for coating hot-processed foods, where flexibility is essential to prevent cracking and ensure integrity. The fact that the extract did not alter the T_g suggests that it can be used as an additive without compromising the thermal stability and safety of packaged foods.

The main peak observed for the control film (approximately 99.7 °C) is consistent with the findings of Farokhi et al. (2024) and Villasante et al. (2020), who attributed this phenomenon to dehydration and the loss of free water molecules or unstable components during analysis. The significant increase in T_m as a

function of extract concentration (reaching 142.3 °C in S2) may be due to a greater interaction between the gelatin matrix and the phenolic compounds. As noted by Jamróz et al. (2022), such interactions restrict the mobility of the polymer chains. These differences are also attributed to the formation of more intra- and intermolecular hydrogen bonds, potentially generating a more crystalline state compared to the control (Khedri et al., 2021).

The second peak, observed at approximately 250 °C, is likely related to the thermal destruction of the gelatin structure (Farokhi et al., 2024). The data suggest that the juçara extract promotes the formation of a compact structure, which requires higher energy levels to break the intermolecular bonds, further confirming the reinforcing effect of the bioactive compounds on the biopolymeric network. While DSC analysis provided a comprehensive characterization of the phase transitions and thermal reinforcement of the films, future studies involving Thermogravimetric Analysis (TGA) are encouraged to offer a more detailed understanding of the mass loss kinetics and long-term thermal stability of the juçara-loaded matrices.

4.7. Antioxidant activity

The low antioxidant activity observed in the control film is consistent with the findings of Kadam et al. (2015) and Villasante et al. (2020). This baseline activity is attributed to the presence of specific amino acids, such as glycine and proline, within the molecular structure of gelatin. In contrast, the substantial increase in the bioactive potential of the S1 and S2 films is primarily driven by the phenolic compounds present in the juçara extract.

The radical scavenging percentage achieved by the S2 film is similar to the results obtained by Siripatrawan & Harte (2010), who found that chitosan-based films with high concentrations of green tea extract exhibited DPPH inhibition of approximately 50%, characterizing them as active films. Similar antioxidant trends have been reported for various biopolymeric films incorporated with plant or fruit extracts. For instance, Li et al. (2014) noted that DPPH scavenging capacity increased with the addition of extracts from green tea, grape seed, ginger, and ginkgo leaf. Furthermore, Yong et al. (2019) confirmed that radical scavenging activity improves significantly as a function of extract concentration in chitosan matrices.

These findings are in agreement with the SEM analysis and colorimetric parameters, which confirmed the successful integration of the juçara fruit extract into the S1 and S2 matrices, as evidenced by the presence of surface particles and the characteristic purplish hue of the films. The development of such antioxidant properties is essential for protecting food products against lipid oxidation, thereby extending shelf life and maintaining nutritional quality.

5. Conclusion

This study demonstrates the potential of juçara extract (*Euterpe edulis*) as a functional additive in gelatin-based biodegradable films. The incorporation of the extract resulted in materials with adequate tensile strength and improved elongation at break. Notably, the S2 formulation (0,25 g extract g^{-1} gelatin) showed elastic performance exceeding the lower limits reported for certain commercial synthetic films, suggesting its suitability for flexible packaging applications.

The films presented a purplish-red Hue similar to that of fresh juçara pulp, serving as a natural visual indicator of the presence of bioactive compounds. In addition, juçara extract incorporation enhanced antioxidant activity, increased opacity, and improved water vapor barrier properties, which are highly desirable for food preservation.

Differential scanning calorimetry analysis revealed an increase in melting temperature upon extract addition, indicating interactions between phenolic compounds and the gelatin matrix that promote a more thermally stable structure. Furthermore, the glass transition temperature remained unaffected, suggesting preservation of the fundamental thermal behavior of gelatin. Overall, the film containing 0.25 g extract g^{-1} gelatin emerged as the most promising formulation for the development of active, biodegradable food packaging, offering a sustainable alternative to conventional materials.

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7. Authors' Contributions

Joelmir Grassi Presente: conceptualization; methodology; investigation; writing - original draft. *Marta dos Santos Diniz Freitas*: investigation. *Bruna Moura Bastos*: investigation. *Neusa Fernandes de Moura*: resources; supervision; writing - review & editing. *Roberto de Souza Gomes da Silva*: conceptualization; supervision; writing - original draft; writing - review & editing.

8. Conflicts of Interest

No conflicts of interest.

9. Ethics Approval

Not applicable.

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