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Biodegradable Sodium Alginate Films Incorporated With *Jateorhiza palmata* (Lam.) Miers Extract for Active Food Packaging

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ABSTRACT

Biodegradable packaging helps reduce environmental impact by decomposing naturally and preventing plastic accumulation in ecosystems. This study developed sodium alginate films incorporating *Jateorhiza palmata* (Lam.) Miers root extract at 5%, 10% and 20% (w/w, relative to polymer mass) for active food packaging. Films were evaluated for physicochemical, mechanical, optical, thermal, barrier and antioxidant properties. Extract incorporation enhanced flexibility and thermal stability, particularly in the 20% film, which showed the highest elongation at break ($23.86 \pm 1.28\%$) and decomposition temperature (229.77°C). Water affinity decreased with extract addition (moisture: 12.09%–18.56%, swelling: 41.46%–70.00%, solubility: 30.58%–67.13%), while water vapour permeability (WVP) ($0.153\text{--}0.194\text{ g}\cdot\text{mm}/\text{m}^2\cdot\text{h}\cdot\text{kPa}$) remained stable. The 20% film maintained peroxide values below $5.0\text{ mEq}\cdot\text{kg}^{-1}$ in sunflower oil for 14 days, with values 3.6 and 11 lower than PET and unpackaged controls, respectively. Biodegradability increased with extract content, reaching 4.5% in 20% films after 20 days. These findings support the use of *J. palmata* enriched alginate films as sustainable alternatives to synthetic packaging and antioxidants for lipid-rich food products.

1 | Introduction

The escalating environmental burden associated with the extensive use of synthetic polymer-based packaging materials represents a critical global challenge. The food and beverage industries alone account for the highest proportion of plastic consumption [1]. Although recycling technologies are available, the limited effectiveness of recycling practices, combined with the inherent resistance of petroleum-based plastics to degradation, has led to persistent environmental contamination and significant biodiversity loss [2].

In response to these environmental concerns, research has increasingly focused on the development of biodegradable packaging materials derived from renewable biopolymers. Among these, polysaccharides, proteins and lipids have gained prominence

due to their biodegradability, widespread availability and eco-friendly characteristics [3, 4]. Polysaccharide-based films, in particular, offer notable advantages, including favourable mechanical strength, effective gas barrier properties and cost-efficiency when compared to the protein- and lipid-based alternatives [5, 6].

Sodium alginate, a natural linear copolymer composed of β -D-mannuronic acid and α -L-guluronic acid and extracted from brown algae, has been widely explored as a film-forming agent. This interest stems from its biodegradability, non-toxicity and biocompatibility, as well as its capacity to form stable gel matrices through ionic cross-linking with divalent cations, particularly calcium ions [7, 8]. Calcium alginate networks improve significantly the structural integrity and barrier properties of the films, making them suitable candidates for food packaging applications [5, 9].

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Beyond providing basic mechanical and barrier functionality, biopolymer films can be engineered as active packaging systems by incorporating bioactive compounds. These include natural antioxidants and antimicrobial properties that impart preservative effects, extending product shelf life while minimizing the need for synthetic additives [10, 11]. Strategically including natural antioxidants is particularly relevant for protecting lipid-rich food matrices from oxidative degradation, discoloration and nutrient loss during storage and handling [12].

Recent advancements have aimed to enhance the physical, mechanical and functional properties of biodegradable films by incorporation of plant-derived extracts [13]. These additions have been shown to improve antioxidant and antimicrobial activity, modulate mechanical performance and alter permeability characteristics, thereby increasing the suitability of such films for active packaging applications [14, 15]. *Jateorhiza palmata* (Lam.) Miers, commonly known as calumba, is a medicinal plant from the Menispermaceae family, traditionally used in African medicine for its digestive, antiseptic and antiparasitic properties. Its root contains a high concentration of isoquinoline alkaloids, particularly palmatine, a compound recognized for its strong antioxidant activity and broad pharmacological potential [16, 17].

Given its promising phytochemical profile, the extract of *J. palmata* has attracted interest for innovative applications, such as incorporation into biopolymer films. Its unique phytochemical profile, particularly the presence of isoquinoline alkaloids such as palmatine, provides antioxidant properties that are uncommon among plant extracts used in active packaging systems. Therefore, calumba stands out as a natural source of bioactive additives capable of improving the technological and environmental value of biodegradable polymeric matrices [18]. Its unique phytochemical profile, particularly the presence of isoquinoline alkaloids such as palmatine, provides antioxidant properties that are uncommon among plant extracts used in active packaging systems.

In this context, the present study aimed to develop and characterize biodegradable films based on sodium alginate incorporated with different concentrations (F2: 0.05%, F3: 0.10% and F4: 0.20%) of root extracts from *J. palmata* (Lam.) Miers. The films were evaluated for their physicochemical, mechanical, optical, thermal and barrier properties, as well as antioxidant potential, to assess their suitability as active packaging materials for food preservation. To date, there are no scientific reports on the incorporation of *J. palmata* (Lam.) Miers root extract into biodegradable sodium alginate films. This originality highlights the novelty of the present work, which is the first to demonstrate the application of *J. palmata* as a bioactive additive in food packaging. By introducing a phytochemical source uncommon in packaging studies, particularly due to its alkaloid content such as palmatine, this study proposes an innovative approach for designing active, biodegradable films with enhanced antioxidant functionality.

2 | Materials and Methods

2.1 | Materials

The root of *J. palmata* (Lam.) Miers was provided by a pharmaceutical company located in Porto Alegre, Brazil. Sodium

alginate (90% purity) was obtained from Dynamica Química Contemporânea Ltda. (São Paulo, Brazil). Calcium chloride pentahydrate ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, 99.5% purity) was purchased from Nuclear (São Paulo, Brazil), and glycerin was supplied by Êxodo Científica (São Paulo, Brazil). All reagents employed were of analytical grade.

2.2 | Preparation of Extracts From *J. palmata* (Lam.) Miers

The roots of *J. palmata* (Lam.) Miers were ground using a Willey knife mill (Model SL-31, Qualiclen, Brazil). Approximately 3 g of root powder was weighed, placed into a Schott bottle and combined with 30 mL of distilled water to obtain the aqueous extract. Extraction was performed at room temperature, and the process was monitored over a 7-day period [19, 20].

2.3 | Preparation of Sodium Alginate Films

Sodium alginate was dissolved in distilled water (1% w/v) at 25°C, and the pH was adjusted to 6.5 ± 0.5 under mechanical stirring at 1000 rpm for 30 min. Glycerol was subsequently added as a plasticizer, followed by the addition of a 1% (w/v) calcium chloride solution to promote ionic crosslinking. *J. palmata* root extracts were incorporated at concentrations of F2: 5%, F3: 10% and F4: 20% (w/w, calculated relative to the dry mass of sodium alginate). To ensure reproducibility and provide a clear overview of the experimental design, the exact composition of all formulations, including sodium alginate, glycerol, calcium chloride and *J. palmata* extract, is summarized in Table 1.

Based on preliminary studies by our research group and literature reports on active films incorporating plant extracts, these concentrations were selected to represent low, moderate and high incorporation levels. This range was intended to evaluate the dose-dependent effects of *J. palmata* extract on film properties and antioxidant performance, while avoiding excessive incorporation that could compromise film integrity or processability.

The resulting solutions were homogenized by stirring for an additional 15 min, cast into Petri dishes (0.52 g/cm²) and dried at

TABLE 1 | Composition of sodium alginate films incorporated with *Jateorhiza palmata* root extract. Formulations were prepared with fixed concentrations of sodium alginate, glycerol, and calcium chloride, while the extract was incorporated at different levels (5%, 10% and 20%, w/w, relative to the polymer mass).

Formulation	Sodium alginate (% w/v)	Glycerol (% w/v)	CaCl_2 (% w/v)	Extract (% w/w, relative to polymer mass)
F1—Control	1.0	0.5	1.0	0
F2—5%	1.0	0.5	1.0	5
F3—10%	1.0	0.5	1.0	10
F4—20%	1.0	0.5	1.0	20

25°C for 24 h. Prior to characterization, all film samples were preconditioned in a controlled temperature and humidity chamber at 25°C and 58% relative humidity (RH) for 48 h to stabilize their moisture content.

3 | Film Characterization

3.1 | Thickness and Mechanical Properties

The mechanical properties of sodium alginate films were evaluated using a texture analyser equipped with a 5 kg load cell (Stable Micro Systems TA.XT2i, UK), according to the ASTM D882-2012 standard [21]. Film samples (100 mm × 10 mm) were clamped between grips with an initial separation of 50 mm and subjected to uniaxial tensile testing at a crosshead speed of 0.8 mm/s until rupture. Film thickness was measured using a digital micrometre (IP40, Digimess, Brazil), with measurements performed at randomly selected points on the film.

3.2 | Moisture and Solubility in Water

The moisture content and water solubility of the films were determined following the method described by Assis [22], with minor modifications. For moisture analysis, film samples were cut into 2 cm × 2 cm squares, initially weighed (W_i) and then dried at 105°C for 24 h in a drying oven (SSe 30 SolidSteel, Brazil). After drying, the samples were reweighed (W_f), and the moisture content (%) was calculated using the following Equation:

$$\text{Moisture (\%)} = \left(\frac{W_i - W_f}{W_i} \right) \times 100$$

The dried and weighed samples (W_{si}) were then used for water solubility analysis. Each sample was immersed in 30 mL of distilled water and kept under continuous agitation for 24 h at a controlled temperature of 25°C. After the solubilization step, the films were filtered to remove excess water, dried again at 105°C for 24 h and subsequently weighed (W_{sf}) to determine the mass of the undissolved dry matter. Water solubility (%) was calculated using the following Equation:

$$\text{Water solubility (\%)} = \left(\frac{W_{si} - W_{sf}}{W_{si}} \right) \times 100$$

3.3 | Swelling Capacity

The swelling capacity of the films was evaluated by immersing square samples (2 cm × 2 cm) in 30 mL of distilled water under controlled temperature (25°C) and continuous agitation. After 5 and 24 h of immersion, the samples were filtered, gently blotted with paper towels to remove excess surface water and weighed. The swelling capacity (%) was calculated using the following Equation:

$$\text{Swelling capacity (\%)} = \left(\frac{W_t - W_i}{W_i} \right) \times 100$$

where W_t represents the weight of the sample after the specified immersion time and W_i denotes the initial weight of the sample.

3.4 | Water Vapour Permeability

Circular film samples were cut and fixed in permeation cells (63 mm in diameter), containing anhydrous calcium chloride to maintain 0% relative humidity inside the capsules. The assembled units were sealed and placed in a glass chamber maintained at 25°C and 75% relative humidity, following ASTM guidelines (ASTM, 2000). WVP was determined gravimetrically after 24 h, according to the procedure described by Queiroz et al. [22].

3.5 | Oxygen Permeability (OP)

OP was determined according to Tosati et al. [23]. Measurements were conducted in accordance with the ASTM D1434 standard method.

3.6 | Optical Properties (Colour and Opacity)

The colour properties of the films were analysed according to the CIELab system using the L^* , a^* and b^* parameters, measured with a Chromameter CR-400 colorimeter (Konica Minolta, Japan). From these measurements, the chroma (C^*) and hue angle (h^*) values were calculated.

$$\text{Hue angle} = \tan^{-1} \frac{b^*}{a^*}$$

$$\text{Chroma factor} = \left[(a^*)^2 + (b^*)^2 \right]^{1/2}$$

The colour difference (ΔE) was obtained from the following:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

The light transmittance of the films was evaluated using a UV/Vis spectrophotometer (Shimadzu UV-1800, Japan) over a spectral range of 200–800 nm. Opacity measures the absorbance of the film at 210 and 500 nm using a UV spectrophotometer (Shimadzu UV-1800, Japan), calculated as (9) [24]:

$$\text{Opacity (mm}^{-1}\text{)} = \frac{\text{Abs}\left(\frac{210}{500}\right)}{x}$$

where $\text{Abs}^{210-500}$ is the absorbance value at 210 or 500 nm, and x is the film thickness (mm).

3.7 | Thermal Properties

Thermogravimetric analysis (TGA) was performed using a thermogravimetric analyser (Perkin Elmer—Pyris 1 TGA) to assess the thermal stability of the films and identify the onset and end temperatures of the degradation events. Approximately 5–10 mg of each film sample was placed in an open platinum crucible and analysed under a nitrogen atmosphere (20 mL·min⁻¹), with a heating rate of 10°C·min⁻¹ from 30°C to 650°C. The measurements were conducted in triplicate, and results were expressed

as mass loss (%) as a function of temperature. Differential Scanning Calorimetry (DSC) was conducted using a DSC 8500 model (PerkinElmer, Waltham, MA, USA) under a nitrogen atmosphere with a flow rate of 20 mL·min⁻¹. Approximately 5–10 mg of each film was sealed in standard aluminium pans and subjected to the following thermal program: heating from 30°C to 300°C at 10°C·min⁻¹, cooling to -30°C at 10°C·min⁻¹ and reheating to 300°C at the same rate. All analyses were performed in triplicate [25].

3.8 | Morphology by Scanning Electron Microscopy (SEM)

The morphological characteristics of the films were examined by SEM using a conventional tungsten filament microscope (Carl Zeiss EVO MA10, UK). Prior to analysis, the samples were mounted on aluminium stubs using double-sided carbon adhesive tape and coated with a thin layer of gold (~25 nm) using a BAL-TEC SCD 050 sputter coater, operating at 1 kV and 40 mA for 60 s, under a vacuum pressure of 5 × 10⁻² mbar. This procedure ensured surface conductivity and minimized charging effects during electron beam exposure.

SEM imaging was conducted at an accelerating voltage of 10 kV in secondary electron imaging (SEI) mode. Micrographs were acquired at different magnifications: (A) 1000×, (B) 5000× and (C) 10000×, allowing detailed evaluation of surface features, internal structure and homogeneity. Images were obtained without digital zoom or post-processing, and each magnification setting (1000×, 5000×, 10000×) was kept consistent across treatments for valid structural comparisons.

3.9 | Biodegradability

The biodegradability of sodium alginate films containing *J. palmata* (Lam.) Miers extract was evaluated by measuring mass loss after contact with soil over a period of 20 days, according to [26]. Film samples (2 cm × 3 cm) were initially dried in an oven at 60°C for 24 h (DeLeo, model B5AFD, Brazil). Subsequently, the films were placed on pre-dried and pre-weighed aluminium screens (screen/film set) and buried approximately 4 cm deep in non-sterile organic soil compartments. The soil used in the assay was an organic substrate obtained from a composting area, with visible plant-derived residues. Although not chemically characterized, the substrate was homogeneous and representative of naturally decomposing organic material. To maintain adequate microbial activity and moisture content, 2 mL of distilled water was added every 2 days to each soil compartment. The experiment was conducted at ambient temperature (22°C–25°C). At predetermined intervals (10, 15 and 20 days), the samples were carefully retrieved, gently rinsed with distilled water to remove soil residues and dried again at 60°C for 24 h. Weight loss, a biodegradability indicator, was calculated using Equation (10):

$$\text{Biodegradability} = \left(\frac{W_0 - W_t}{W_t} \right) \times 100$$

where W_0 is the initial mass of the sample (g) and W_t is the mass after soil exposure at time t .

3.10 | Antioxidant Performance of the Films in Preventing Sunflower Oil Oxidation

The oxidative stability of sunflower oil was assessed under controlled storage conditions (illumination of 4000–5000 lx, temperature of 30°C and relative humidity of 65%) as described by Vargas et al. [22]. A 10 mL aliquot of oil was sealed within film sachets (dimensions: 10 cm × 5 cm; surface area: 50 cm²). To seal the sachets, a 24.4% gelatin solution was prepared and applied following Prateepchanachai et al. [27] and Liu et al. [28]. At predetermined storage intervals, oil samples were collected and analysed for peroxide index (PI) and levels of conjugated dienes and trienes in accordance with AOAC [19]. Control samples were stored in low-density polyethylene (LDPE) films, polyethylene terephthalate (PET) bottles and without packaging (WP) in glass Petri dishes. All analyses were conducted in triplicate.

4 | Statistical Analysis

The results were evaluated by analysis of variance (ANOVA) followed by Tukey's test at a significance level of 5% using Statistica 12.0 software (StatSoft Inc., Tulsa, USA). All analyses were performed in triplicate, and the results were expressed as the mean ± standard deviation.

5 | Results and Discussion

5.1 | Thickness and Mechanical Properties

Tensile strength, Young's modulus and elongation at break are widely used parameters for characterizing the mechanical properties of polymeric films, as they reflect key structural aspects of the material. Young's modulus is associated with the stiffness and strength of biopolymer films [29, 30]; tensile strength represents the material's ability to withstand applied forces before breaking; and elongation is related to its flexibility or deformability. The mechanical properties, as well as the Hencky stress strain curves of sodium alginate films incorporated with 5%, 10% and 20% root extract of *J. palmata* (Lam.) Miers, are shown in Table 2 and Figure 1, respectively.

The incorporation of *J. palmata* root extract led to significant changes in film thickness. The F4 film (containing 20% extract) showed the highest thickness, with an average value of 71.44 ± 6.4 µm. All formulations differed significantly from each other and from the control group ($p < 0.05$).

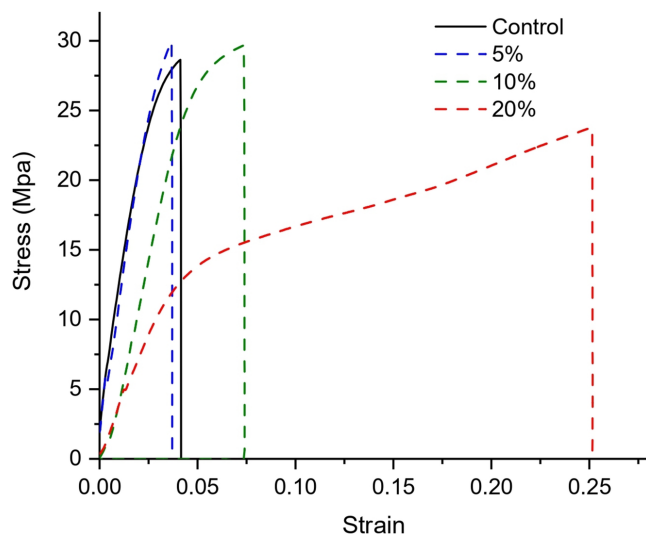
Regarding tensile strength and Young's modulus, the incorporation of *J. palmata* extract was identified as the primary factor influencing formulations F2 (5%) and F3 (10%), promoting a positive effect on both parameters. However, formulation F4 (20%) exhibited the lowest mechanical performance, with tensile strength and Young's modulus values of 23.86 MPa and 56.93 MPa, respectively. This decrease may be attributed to the heterogeneous dispersion of the extract at higher concentrations, as previously reported by Pastor et al. [31].

Regarding elongation at break, all treatments exhibited significant differences ($p < 0.05$). The lowest value was observed for

TABLE 2 | Thickness and mechanical properties of sodium alginate films incorporated with *Jateorhiza palmata* (Lam.) Miers root extracts.

Sample	t (μm)	TS (Mpa)	E (%)	YM
F1—Control	50.84 ± 0.4^a	28.93 ± 0.43^b	4.04 ± 0.25^a	603.72 ± 56.96^c
F2—5%	61.98 ± 2.2^b	28.37 ± 1.41^b	3.48 ± 0.54^a	522.52 ± 55.37^c
F3—10%	60.52 ± 1.4^b	30.99 ± 3.95^b	7.96 ± 0.61^b	245.13 ± 29.83^b
F4—20%	71.44 ± 6.4^c	23.86 ± 2.39^a	23.86 ± 1.28^c	56.93 ± 3.64^a

Note: Different lowercase superscript letters in the same column indicate statistically significant differences between treatments by the Tukey's test ($p < 0.05$). F1—Control of sodium alginate; F2—5%: films with 5% of *J. palmata* extracts; F3—10%: films with 10% of *J. palmata* extracts; F4—20%: films with 20% of *J. palmata* extracts; t : thickness; TS: tensile strength; E: elongation at break; YM: Young's modulus.

**FIGURE 1** | Stress-Hencky strain curves of the sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

formulation F2: 5% (3.48%), followed by the control (F1: control, 4.04%) and F3: 10% (7.96%). Notably, the F4 film (20% extract) showed a significant increase in elongation (23.86%) compared to the control, possibly due to a plasticizing effect of the extract. This behaviour may be attributed to molecular interactions between the bioactive compounds of *J. palmata* and the sodium alginate matrix, which is due to the reduction of intermolecular forces in the biopolymeric matrix.

The tensile strength and elongation at break observed in the 10% and 20% extract films (30.99 MPa and 23.86%, respectively) are considered high when compared to various biopolymer-based active packaging films reported in the literature. For instance, chitosan films incorporated with green tea extract typically present elongation values around 15% [32], while sodium alginate films containing norbixin reach values between 18% and 22% [33]. Starch-based films formulated with rosemary or oregano extracts generally exhibit elongation values ranging from 10% to 20%, depending on the specific formulation conditions [34, 35]. Therefore, the 23.86% elongation achieved in this study indicates superior flexibility and deformability compared to most reported films, which may be attributed to the plasticizing effect and molecular interactions induced by the *J. palmata* extract within the alginate matrix.

The incorporation of plant extracts into sodium alginate films leads to a series of molecular interactions that significantly modify the

film's structure and performance. The predominant interaction involves hydrogen bonding between the extract's bioactive compounds (mainly phenolics) and alginate polymer chains, which enhance the film's functionality and structural stability [36, 37].

Previous studies have demonstrated that the incorporation of plant-based extracts, such as rosemary and tea, can significantly enhance both tensile strength and elongation at break, thereby improving film durability. However, depending on the film matrix and the specific type of extract used, certain additives may also lead to a reduction in tensile strength or puncture resistance [13, 32, 34, 35, 38].

5.2 | Moisture Content, Solubility in Water, Swelling Capacity and Water Vapour Permeability

Sodium alginate, as a naturally hydrophilic polymer, tends to absorb and retain moisture, which directly influences both the flexibility and mechanical strength of the resulting films. Balancing properties such as moisture content, water solubility, swelling capacity and WVP is crucial to ensure that the films meet the functional requirements of packaging applications, including moisture protection, structural integrity and mechanical performance [39, 40]. Table 3 summarizes the results for moisture content, water solubility, swelling capacity and WVP of alginate films incorporated with F2 (5%), F3 (10%) and F4 (20%) root extract of *J. palmata* (Lam.) Miers.

The moisture content of films F2 and F3, containing 5% and 10% extract, respectively, exhibited a significant reduction, with values of 13.46% and 12.49%, compared to the control film F1 (17.14%). However, no statistically significant difference was observed between film F4 (20% extract, 16.73%) and the control. These results suggest that the lower concentration of total soluble solids in *J. palmata* root extract may contribute to a reduced hydrophilic character in the films, thereby lowering their moisture retention capacity [41]. The swelling capacity (SC) of films F2 (5%) and F4 (20%), both containing *J. palmata* extract, was significantly reduced ($p < 0.05$) compared to the control (F1) and the film F3 (10% extract), as presented in Table 3. These results suggest that formulations F2 and F4 reduced the films' susceptibility to water uptake, likely due to compositional or structural changes induced by the extract at those specific concentrations [42].

Previous studies have indicated that sodium alginate films generally exhibit moderate to high moisture content due to their inherently hydrophilic nature. The incorporation of additives such as norbixin salts or plant-derived extracts may reduce or modulate

TABLE 3 | Moisture content, solubility in water, and swelling capacity, water vapour permeability of sodium alginate films incorporated with of *Jateorhiza palmata* (Lam.) Miers Root extracts.

Sample	MC (%)	SC (%)	WSI (%)	WVP (g mm/m ² h kPa)
F1—Control	17.14 ± 1.42 ^c	64.53 ± 4.62 ^b	63.25 ± 3.88 ^c	0.167 ± 0.006 ^a
F2—5%	13.46 ± 1.30 ^{ab}	45.32 ± 3.86 ^a	49.58 ± 2.80 ^b	0.176 ± 0.006 ^a
F3—10%	12.49 ± 0.40 ^a	69.19 ± 0.81 ^b	53.27 ± 0.73 ^b	0.167 ± 0.014 ^a
F4—20%	16.73 ± 1.11 ^{bc}	47.30 ± 2.02 ^a	33.14 ± 2.56 ^a	0.177 ± 0.017 ^a

Note: Different lowercase superscript letters in the same column indicate statistically significant differences between treatments by the Tukey's test ($p < 0.05$). F1—Control of sodium alginate; F2—5%: films with 5% of *J. palmata* extracts; F3—10%: films with 10% of *J. palmata* extracts; F4—20%: films with 20% of *J. palmata* extracts; MC: moisture content; WS: water solubility in water; SC: swelling capacity; WVP: water vapour permeability.

both moisture content and swelling capacity, depending on the film composition and the concentration of the added extract [33, 43]. Abdin et al. [44] reported that the incorporation of *Thymus vulgaris* extract led to a reduction in swelling capacity of up to 30% and a decrease in moisture content of approximately 10%.

The solubility analysis of films containing *J. palmata* root extract revealed statistically significant differences among formulations. Films F2 and F3 (5% and 10% extract, respectively) did not differ significantly from each other; however, both the control film (F1) and film F4 (20% extract) showed significant differences compared to the others, with solubility values of 63.25% and 33.14%, respectively. As observed for moisture content, solubility decreased with increasing extract concentration. This trend suggests that higher levels of total soluble solids contributed to reductions in both moisture retention and solubility. Furthermore, increased incorporation of *J. palmata* root extract into the film-forming solution may have enhanced the degree of complexation within the polymer matrix, thereby reducing water solubility [45].

Several studies have demonstrated that the incorporation of additives such as plant extracts, tannic acid or nanoparticles can reduce water solubility and enhance moisture resistance without compromising the film's biodegradability [43, 46, 47]. For instance, *T. vulgaris* extract was shown to reduce solubility by approximately 20%, while silver nanoparticles led to reductions of up to 59% [43, 48].

Regarding WVP, all formulations containing *J. palmata* extract, F2 (5%), F3 (10%) and F4 (20%) exhibited similar values, with no statistically significant differences compared to the control sodium alginate film. The WVP values observed for all formulations (0.153–0.194 g·mm/m²·h·kPa) are within the range reported for sodium alginate films containing rosemary or thyme extracts (0.140–0.210 g·mm/m²·h·kPa) [47, 49]. These findings suggest that extract incorporation may have contributed to the formation of a more compact film structure by reducing matrix porosity. Similar effects were reported by Li et al. (2022), who observed reductions in WVP of up to 22% and 14% when cellulose nanocrystals and rosemary extract were added to rice protein/sodium alginate films, respectively, depending on the formulation.

5.3 | OP

OP is a critical parameter in food packaging applications, as it directly influences the oxidative stability of the packaged

TABLE 4 | Thicknesses and oxygen permeability coefficients of sodium alginate films incorporated with of *Jateorhiza palmata* (Lam.) Miers Root extracts.

Sample	OP (×10 ⁻⁹ mol·μ/m ² ·Pa·s)	Thickness (μm)
F1—Control	2.09 ± 0.01 ^b	51 ± 6 ^b
F2—5%	2.01 ± 0.05 ^b	55 ± 2 ^b
F3—10%	2.67 ± 0.06 ^a	75 ± 3 ^a
F4—20%	2.14 ± 0.10 ^b	67 ± 4 ^a

Note: Different lowercase superscript letters in the same column indicate statistically significant differences between treatments by the Tukey's test ($p < 0.05$). F1—Control of sodium alginate; F2—5%: films with 5% of *J. palmata* extracts; F3—10%: films with 10% of *J. palmata* extracts; F4—20%: films with 20% of *J. palmata* extracts; O₂P: Oxygen permeability.

product [50]. Table 4 presents the thickness and OP values of sodium alginate films incorporated with 5%, 10% and 20% of *J. palmata* (Lam.) Miers root extract.

Sample F3, containing 10% extract, exhibited the highest OP (2.67 × 10⁻⁹ mol·μ/m²·Pa·s), which was significantly higher than that of the control (F1) and the other formulations. This increase in OP may be attributed to the greater thickness of the film (75 ± 3 μm), possibly associated with structural reorganization of the polymer matrix induced by phytochemical compounds present in the extract. Such reorganization could have reduced network density or created diffusion pathways, as previously reported by Sothornvit and Krochta [51], who observed that the addition of hydrophilic components can generate preferential gas diffusion channels in biodegradable films.

Additionally, Luong et al. [20] highlighted that those changes in film microstructure, such as increased porosity or decreased network compactness, may lead to higher oxygen permeability. Therefore, it is plausible that compounds present in the 10% extract promoted a relaxation of the alginate network, thereby facilitating oxygen permeation. Conversely, films F2 (5%) and F4 (20%) did not show significant differences in OP compared to the control, despite their increased thicknesses. This behaviour suggests that the effect of the extract on permeability is not directly proportional to its concentration, as also noted by Perdonés et al. [52], who reported a nonlinear behaviour when incorporating plant extracts into chitosan-based films.

5.4 | Optical Properties

Colour, opacity and light transmittance are critical parameters in food packaging, as they directly influence the product's protection against light exposure, particularly UV and visible radiation, which can lead to nutrient degradation, lipid oxidation and sensory changes such as alterations in colour, taste and flavour [53, 54]. Table 5 presents the colour and opacity parameters of the biodegradable alginate films. Colorimetric analysis revealed significant variations in the parameters L^* , a^* , b^* , h^* , C^* and ΔE with the incorporation of *J. palmata* extract into formulations F2 (5%), F3 (10%) and F4 (20%), in comparison with the control film (F1) (Figure 2).

The L^* value, which indicates film brightness, showed that the control film exhibited the highest lightness, appearing visually clearer than the films containing plant extract. Formulations F2 (5%), F3 (10%) and F4 (20%) showed significant decreases in L^* , indicating progressive darkening with increasing extract concentration. This change may be attributed to the presence of phenolic compounds and natural pigments in the extract, which interfere with light transmission and impart more intense coloration to the films [55, 56]. The a^* and b^* values were positive for all formulations, including the control, indicating

a predominance of reddish and yellowish tones, respectively. These results are consistent with the characteristic coloration of compounds present in the plant extract, which contain conjugated double bonds capable of absorbing visible light, thereby altering the visual appearance of the films [57, 58].

Regarding the h^* parameter, the hue angle remained close to 90° across all formulations, indicating a dominant yellowish hue and confirming the trend observed in the b^* values. This uniformity suggests that although colour intensity changed, the primary colour tone remained consistent across different extract concentrations. Chroma, which measures colour saturation and purity, showed statistically significant differences between the control and the extract-containing formulations, with F4 (20%), exhibiting the highest value (53.72 ± 2.29). This result indicates that formulation F4 displayed the most vivid and saturated coloration, reflecting a higher visual intensity of the incorporated pigment. Overall ΔE revealed that all extract-containing formulations (F2—5%, F3—10% and F4—20%) differed from each other and from the control. ΔE values above 10 in all extract-containing films are in line with sodium alginate films with turmeric or tannic acid ($\Delta E \sim 15\text{--}40$) [47, 55], and similar trends in opacity reduction were observed in phenolic-enriched starch films [59]. The ΔE values indicate perceptible differences to the

TABLE 5 | Colour and opacity of the films incorporated with of *Jateorhiza palmata* (Lam.) Miers root extracts.

Colour parameters	F1—Control	F2—5%	F3—10%	F4—20%
L^*	94.50 ± 0.28^d	92.93 ± 0.80^c	90.19 ± 0.58^b	87.09 ± 0.61^a
a^*	0.47 ± 0.02^a	4.50 ± 0.20^b	7.60 ± 0.22^c	8.40 ± 0.10^d
b^*	6.93 ± 0.76^a	20.03 ± 0.97^b	41.26 ± 1.36^c	53.06 ± 2.32^d
h^*	86.26 ± 0.08^d	77.34 ± 0.08^a	79.56 ± 0.39^b	80.99 ± 0.45^c
C^*	6.94 ± 0.76^a	20.53 ± 0.99^b	41.96 ± 1.35^c	53.72 ± 2.29^d
ΔE	—	13.83 ± 1.14^a	35.34 ± 1.77^b	47.41 ± 2.64^c
Opacity (mm^{-1})				
210	54.28 ± 0.24^c	50.79 ± 0.06^{bc}	46.83 ± 2.26^{ab}	44.41 ± 1.26^a
500	2.65 ± 0.31^a	2.63 ± 0.17^a	3.63 ± 0.56^{ab}	4.36 ± 0.82^b

Note: Mean values of 3 replications ($\pm$ SD). Different lowercase superscript letters in the same line indicate statistically significant differences between treatments by Tukey's test ($p < 0.05$). F1—Control of sodium alginate; F2—5%: films with 5% of *J. palmata* extracts; F3—10%: films with 10% of *J. palmata* extracts; F4—20%: films with 20% of *J. palmata* extracts; L^* , brightness; a^* , redness/greenness; b^* , yellowness/blueness; h^* , hue angle; C^* , chroma; ΔE , overall ΔE between control and sodium alginate films with *J. palmata* extracts.

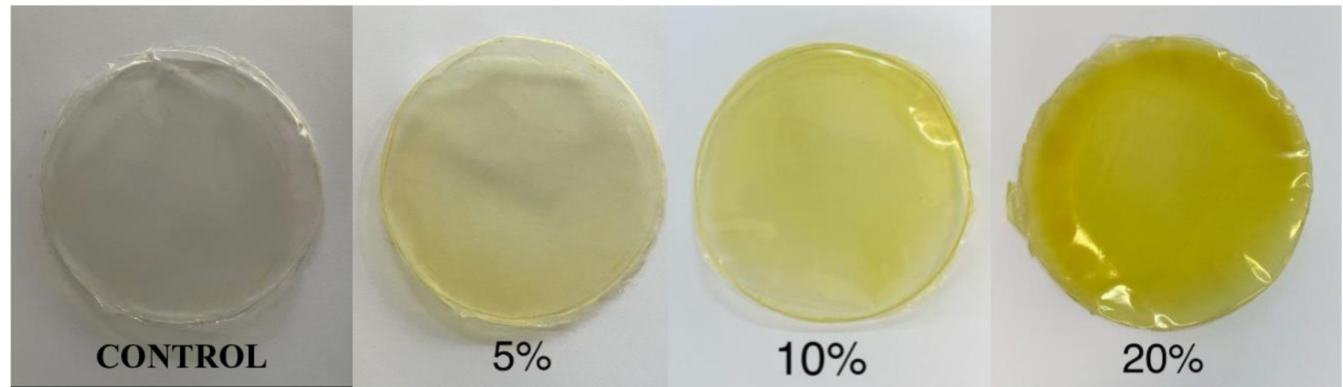


FIGURE 2 | Sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

naked eye, which may affect the sensory and aesthetic acceptance of the films depending on the intended application.

Light transmission was assessed across wavelengths ranging from 200 to 600 nm (Figure 3), while opacity was specifically analysed at 210 nm (UV-C region) and 500 nm (visible region) to evaluate the optical impact of incorporating *J. palmata* extract. At 210 nm, all extract-containing formulations (F2—5%, F3—10% and F4—20%) exhibited significant differences both among themselves and compared to the control film (F1). The control displayed the highest opacity value (54.28 mm^{-1}), followed by F2 (50.79 mm^{-1}), F3 (46.83 mm^{-1}) and F4 (44.41 mm^{-1}), demonstrating a progressive reduction in UV opacity with increasing extract concentration. This behaviour may be attributed to the extract constituents interfering with the films' optical density, reducing UV absorption. Such a reduction could negatively affect the protection of photosensitive compounds, particularly in applications where UV barrier properties are essential, such as in food preservation or pharmaceutical formulations [60].

At 510 nm (visible light, green region), a distinct pattern was observed. No statistically significant differences were found between the control (2.65 mm^{-1}) and formulation F2 (2.63 mm^{-1}), suggesting that low extract concentrations do not substantially alter the film's visual transparency. However, F4 exhibited a significantly higher value (4.36 mm^{-1}), indicating increased visible opacity at higher extract levels. Li et al. [61] reported that edible sodium alginate films containing tannic acid demonstrated improved water vapour and UV light barrier properties, as well as antioxidant activity, while slightly reducing light transmittance results consistent with those observed in the present study.

5.5 | Thermal Properties

Thermal analysis techniques such as DSC and TGA are essential for the thermal characterization of biopolymer matrices containing bioactive compounds, as they enable the evaluation of thermal stability, phase transitions and interactions among formulation

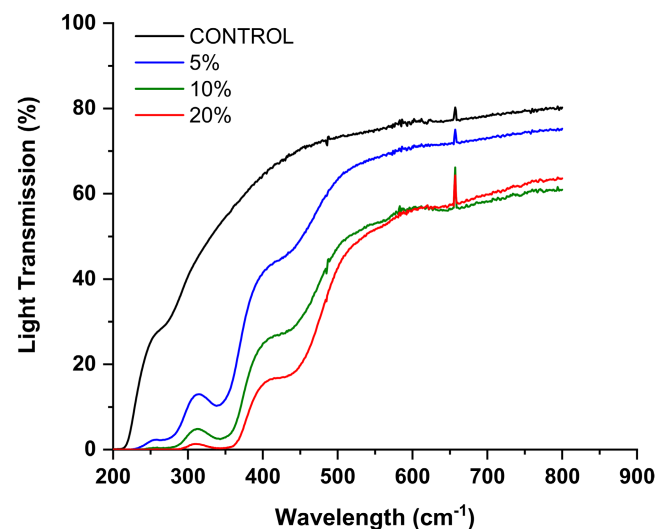


FIGURE 3 | Light transmission of the sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

components [62, 63]. In this study, TGA and DSC analyses were performed to investigate the thermal behaviour of sodium alginate films incorporated with *J. palmata* (Lam.) Miers root extracts. The TGA curves are presented in Figures 4 and 5, and the parameters obtained from thermal analyses are summarized in Table 6.

In the DSC analysis, the onset temperature (T_{on}) increased progressively with the addition of the extract, reaching a maximum in formulation F3 (10%) at 236.24°C , compared to 213.39°C in the control. This result suggests an enhancement in the thermal stability of the film during the initial degradation stage, possibly due to interactions between the phytochemicals present in the extract and the alginate matrix, which may increase chain rigidity and delay the onset of thermal degradation. Similar findings were reported by Sothornvit and Krochta [51], who observed that the addition of hydrophilic components can significantly affect the thermal behaviour of biopolymer films.

The enthalpy change (ΔH) drastically decreased in formulation F2—5% ($7.41 \text{ J}\cdot\text{g}^{-1}$), followed by an increase in F3—10% and F4—20% (21.39 and $29.85 \text{ J}\cdot\text{g}^{-1}$, respectively), indicating that extract concentration has a pronounced effect on the degree of crystallinity and molecular interactions within the matrix. Lower ΔH values may reflect a disruption in the ordered structure of the alginate network due to extract incorporation, while higher concentrations may partially restore these interactions through secondary bonding mechanisms [64]. Thermal degradation assessed by TGA revealed four main weight loss (WL) events. The first WL, occurring around 33°C , associated with water evaporation, was lower in all extract-containing films, particularly F4—20% (1.11%), suggesting increased surface hydrophobicity or stronger water retention due to matrix reorganization. This behaviour has also been reported in films containing phenolic-rich plant extracts, which can influence water absorption and retention dynamics [65].

The major degradation event, observed around 224°C – 230°C and attributed to the decomposition of the alginate backbone, exhibited similar patterns for all samples, except for the formulation F4 (20%) that presented the highest decomposition temperature (229.77°C), suggesting that higher extract concentrations may contribute to the structural reinforcement of the polymer matrix. According to Rhim et al. [66] and Ling et al. [61], natural antioxidant compounds in plant extracts can enhance thermal stability by protecting against oxidative degradation. The maximum decomposition temperature of the 20% extract film (229.77°C) is slightly higher than values observed in starch-based films with yerba mate ($T_{max} 220^{\circ}\text{C}$) [67] and similar to sodium alginate films containing polyphenols (230°C) [68]. The final degradation temperature (550°C – 574°C) was highest in formulation F3—10% (573.66°C), suggesting enhanced residual thermal resistance, possibly due to the formation of more stable carbonaceous residues. This behaviour has also been reported by Luong et al. [20], who associated increased residual degradation temperatures with the presence of complex polyphenols in films, which enhance thermal stability and promote char formation.

5.6 | Morphology by SEM

Figure 6 shows SEM images of the cross-sections of sodium alginate films incorporated with 5%, 10% and 20% *J. palmata* (Lam.)

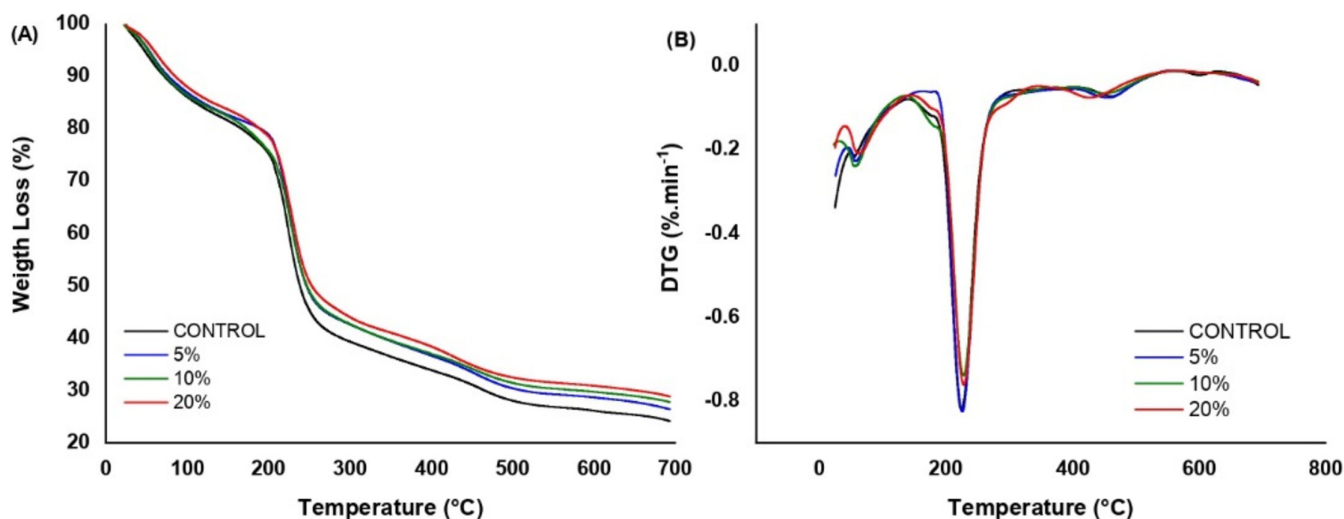


FIGURE 4 | TGA (A) and DTG (B) curves of the sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

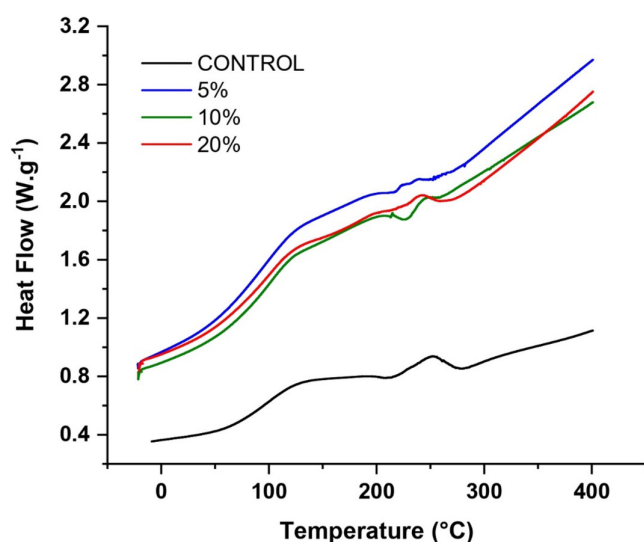


FIGURE 5 | DSC curves of the sodium alginate films incorporated with 5%, 10%, and 20% of *Jateorhiza palmata* (Lam.) Miers Root extracts.

Miers root extracts. The control film (F1), composed solely of sodium alginate, exhibited a relatively compact matrix but showed evidence of discontinuities and cracks, especially at higher magnifications. This behaviour may be associated to the absence of additional plasticizers, which otherwise promote greater cohesion between polymer chains and result in improved morphological uniformity [11].

With the addition of 5% extract (F2), a more homogeneous structure with fewer cracks was observed. This effect can be attributed to the compatibility and plasticizing effect between the extract and the polymer matrix, promoting a uniform distribution of bioactive compounds and enhancing the structural integrity of the film. Such favourable interactions are also associated with improved mechanical properties and reduced water vapour permeability, consistent with findings reported by Riaz et al. [28].

The cross-sections of films containing 10% (F3) and 20% (F4) extract exhibited compact and homogeneous microstructures,

without irregularities or phase separation, indicating excellent structural integrity and compatibility between the polymer matrix and the *J. palmata* (Lam.) Miers root extracts. The increased interactions between the biopolymer and bioactive compounds may contribute to the formation of more compact structures in active films containing plant extracts [69].

5.7 | Biodegradability

The biodegradability of sodium alginate films incorporated with plant extracts represents a significant advancement toward clean and sustainable technologies, which are essential to mitigating the environmental impacts associated with the extensive use of plastic materials [39]. The biodegradation results of sodium alginate films containing 5%, 10% and 20% root extracts of *J. palmata* (Lam.) Miers are presented in Figures 7 and 8.

After 10 days of burial in sand, the films began to exhibit visible signs of fragmentation, indicating the onset of the degradation process. Although complete degradation was not achieved within 20 days, a progressive breakdown of the films was observed over time (Figure 8). A significant increase ($p < 0.05$) in weight loss was recorded for F3 (films containing 10% *J. palmata* extract) and F4 (20% extract). Among them, F3 (10%) exhibited the highest weight loss at 4.5% after 20 days, whereas the control film (F1) presented a weight loss of only 1.8% (Figure 7).

Although the maximum weight loss observed was approximately 4.5% over 20 days, this result is consistent with previous reports using sodium alginate-based films and other biopolymers. For instance, Martucci and Ruseckaite [26] reported less than 5% degradation in 30 days for alginate-starch films under sandy soil conditions. Similarly, Chanatinat et al. [70] demonstrated that neat PLA films buried in soil under the same conditions reached only 3.33% weight loss after 90 days, while PLA composites with natural rubber (NR) and rice straw (RS) exhibited accelerated degradation. Thus, the trend observed in our study is consistent with the early degradation phase characteristic of

TABLE 6 | Thermal parameters obtained from the thermograms (TGA/DSC) of sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

Analysis		Parameters	F1—Control	F2—5%	F3—10%	F4—20%
DSC	Peak _{exo}	Ton (°C)	213.39	216.88	236.24	229.45
		Tp (°C)	251.73	238.85	245.00	241.22
		Tmax (°C)	273.70	261.25	265.70	265.00
		ΔH (J.g ⁻¹)	167.33	7.41	21.39	29.85
TGA events		WL (%)	2.04	1.50	1.43	1.11
		T (°C)	32.79	33.26	32.19	33.90
		WL (%)	16.69	14.12	16.11	15.08
		T (°C)	128.79	110.09	129.71	132.98
		WL (%)	39.09	34.07	37.34	36.83
		T (°C)	224.21	223.30	226.70	229.77
		WL (%)	73.29	70.72	69.88	68.57
		T (°C)	564.50	550.95	573.66	557.94

Note: F1—Control of sodium alginate; F2—5%: films with 5% of *J. palmata* extracts; F3—10%: films with 10% of *J. palmata* extracts; F4—20%: films with 20% of *J. palmata* extracts; Peak_{exo}, exothermic peak; Ton, onset temperature; Tp, peak temperature; ΔH, enthalpy variation; WL, weight loss.

compact polymer matrices. Long-term studies (45–90 days) are recommended to capture full degradation kinetics and mineralization potential.

These results demonstrate that sodium alginate combined with plant-based extracts contains biodegradable components capable of undergoing significant structural and chemical changes under specific environmental conditions, namely the loss of structural integrity and related properties [71]. Moreover, previous studies suggest that the incorporation of root extracts into alginate matrices may reduce their ionic crosslinking capacity, thereby increasing susceptibility to degradation factors such as moisture, microbial activity and enzymatic action [72]. A similar biodegradation trend has been reported with the incorporation of green tea, basil and yerba mate extracts into cassava starch-based films [67]. Figure 8 provides a visual representation of the macroscopic changes occurring in the films during soil burial. The images reveal that films containing 10% and especially 20% of *J. palmata* extract show more pronounced fragmentation and surface irregularities after 20 days, consistent with the gravimetric data in Figure 7. These visual signs support the dose-dependent degradation trend discussed above.

5.8 | Antioxidant Performance of the Films in Preventing Sunflower Oil Oxidation

Lipid oxidation is a primary degradation pathway in vegetable oils, significantly impacting their nutritional and sensory properties. The use of biodegradable films incorporated with bioactive compounds has emerged as an effective strategy to delay this process, as demonstrated in studies on active packaging systems [73].

The results consistently demonstrate the effectiveness of sodium alginate films incorporated with 20% (F4) of *J. palmata*

(Lam.) Miers root extract in protecting sunflower oil against oxidative degradation during storage. The PI (Figure 9A) clearly shows that these active films maintained peroxide values below 5.0 mEq.kg⁻¹ after 14 days, in contrast to the PET bottle (20.0 mEq.kg⁻¹) and the unpackaged (WP), which exceeded 50.0 mEq.kg⁻¹. The peroxide value (<5.0 mEq.kg⁻¹) observed in the 20%—F4 extract film after 14 days of storage represents a significant improvement compared to several reported active packaging systems in the literature. For example, reported peroxide values between 8 and 12 mEq.kg⁻¹ for edible films enriched with *T.vulgaris* or *Rosmarinus officinalis*. These findings support the superior antioxidant effect of the *J. palmata*-enriched films in protecting sunflower oil [44, 74].

Similar findings were reported by Pavli et al. [27], who developed sodium alginate films with oregano essential oil and observed enhanced oxidative stability in packaged ham slices. Likewise, Wu et al. [27] demonstrated that alginate–starch composite films effectively delayed lipid oxidation in ground beef patties. Compared to conventional PET packaging, which lacks antioxidant functionality, the 20% *J. palmata* film maintained peroxide values below 5 mEq.kg⁻¹, highlighting its effectiveness in limiting oxidation markers and its potential as a sustainable alternative for lipid-rich food packaging.

The analysis of conjugated dienes (Figure 9B), an early indicator of lipid oxidation, supports these results. Samples stored WP exhibited a sharp increase from 2.5 to over 13.0 g·100g⁻¹, while the PET-packaged sample reached 6.0 g·100g⁻¹. In contrast, the film 20% extract maintained nearly constant diene levels, not exceeding 3.0 g·100g⁻¹, demonstrating efficient inhibition of unsaturated fatty acid degradation. Regarding conjugated trienes (Figure 9C), which represent secondary oxidation products, a peak was observed in the unpackaged (WP) sample on day 7 (5.0 g·100g⁻¹), followed by a decrease to 2.0 g·100g⁻¹ on day 14, likely due to decomposition into volatile compounds. The PET

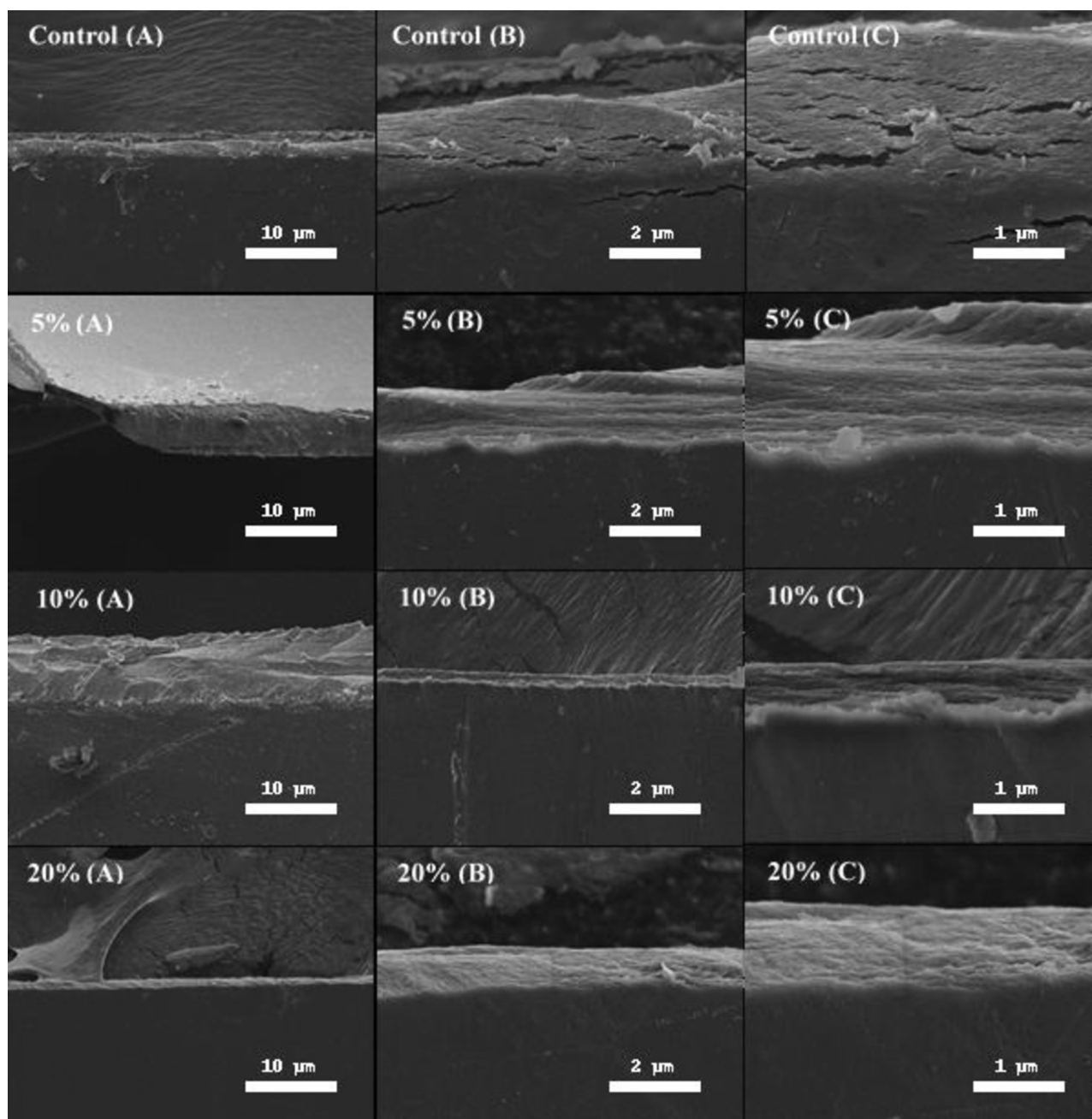


FIGURE 6 | Cross-section scanning electron microscopy of the films: F1—Control of sodium alginate; F2—5%: films with 5% of *J. palmata* extracts; F3—10%: films with 10% of *J. palmata* extracts; F4—20%: films with 20% of *J. palmata* extracts; magnifications: (A) 1000×, (B) 5000× and (C) 10000×.

packaging showed a moderate increase, while both the control and 20% extract maintained stable or slightly reduced triene levels throughout storage (from 3.0 to 2.6 g·100 g⁻¹).

The strong antioxidant performance of the films is likely attributed to the presence of phenolic compounds and isoquinoline alkaloids, such as palmatine, which have demonstrated radical scavenging capacity and lipid peroxidation inhibition [75, 76]. Although most commonly studied for pharmacological effects, isoquinoline alkaloids such as palmatine have demonstrated strong antioxidant activity that is also relevant to food applications. Several studies report that plant-derived alkaloids and phenolics, when incorporated into biopolymer-based films, provide effective protection against lipid oxidation in food systems without compromising safety or sensory quality. Furthermore, recent

toxicological and migration studies confirm that such compounds, when used in appropriate concentrations and encapsulated in film matrices, do not pose risks of chemical migration or residual toxicity, thereby aligning with food safety standards for active packaging systems [35, 65, 77, 78]. Additionally, the polysaccharide matrix of alginate provides a partial physical barrier to oxygen diffusion, which, when combined with bioactive compounds, results in a synergistic protective effect. Given the high susceptibility of lipid-rich foods to oxidative degradation, the development of biodegradable films with inherent antioxidant activity presents a valuable solution to preserve sensory, nutritional and safety attributes during storage.

It is well established that phenolic compounds act through various antioxidant mechanisms, including hydrogen atom

donation, free radical scavenging and metal ion chelation, thereby stabilizing reactive intermediates and interrupting oxidative chain reactions in lipid-rich food systems [34, 79]. In biopolymer matrices such as alginate, these compounds are embedded in a three-dimensional network that allows sustained release and direct interaction with oxidizing species, enhancing their effectiveness [77]. Isoquinoline alkaloids like palmatine, also present in *J. palmata* root extract, may further contribute to antioxidant activity via redox modulation

and radical scavenging, as demonstrated by their electron-donating ability and resonance-stabilized structures [65]. The combination of these compounds within the film matrix likely enables synergistic effects, with phenolics providing immediate radical scavenging at the surface and alkaloids contributing to longer-term stabilization [35, 78]. The integration of these natural antioxidants into alginate-based films not only provides physical protection but also actively delays lipid oxidation, as observed in the peroxide value and conjugated diene/triene data.

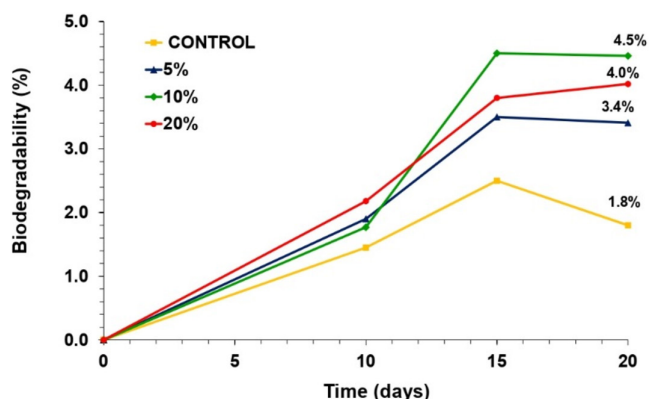


FIGURE 7 | Biodegradability of the sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

According to Codex Alimentarius [80] guidelines and studies by Shahidi and Zhong [31], peroxide values above 10–20 mEq·kg⁻¹ indicate significant lipid deterioration, potentially compromising the nutritional and sensory quality of edible oils. Therefore, the application of bioactive films containing *J. palmata* extract not only preserved the chemical integrity of sunflower oil but also maintained oxidative stability within acceptable quality standards over the 14-day storage period. The antioxidant performance observed in the films is corroborated by the phytochemical and functional composition of *J. palmata* extract, which was characterized in a complementary study. In this study, 22 bioactive compounds, including isoquinoline alkaloids (palmatine, berberine), phenolic acids (gallic acid) and triterpenes (oleanolic acid), were identified, and the extract exhibited high antioxidant activity in ORAC-FL assays, reaching up to 18 225 μmol TE/g.

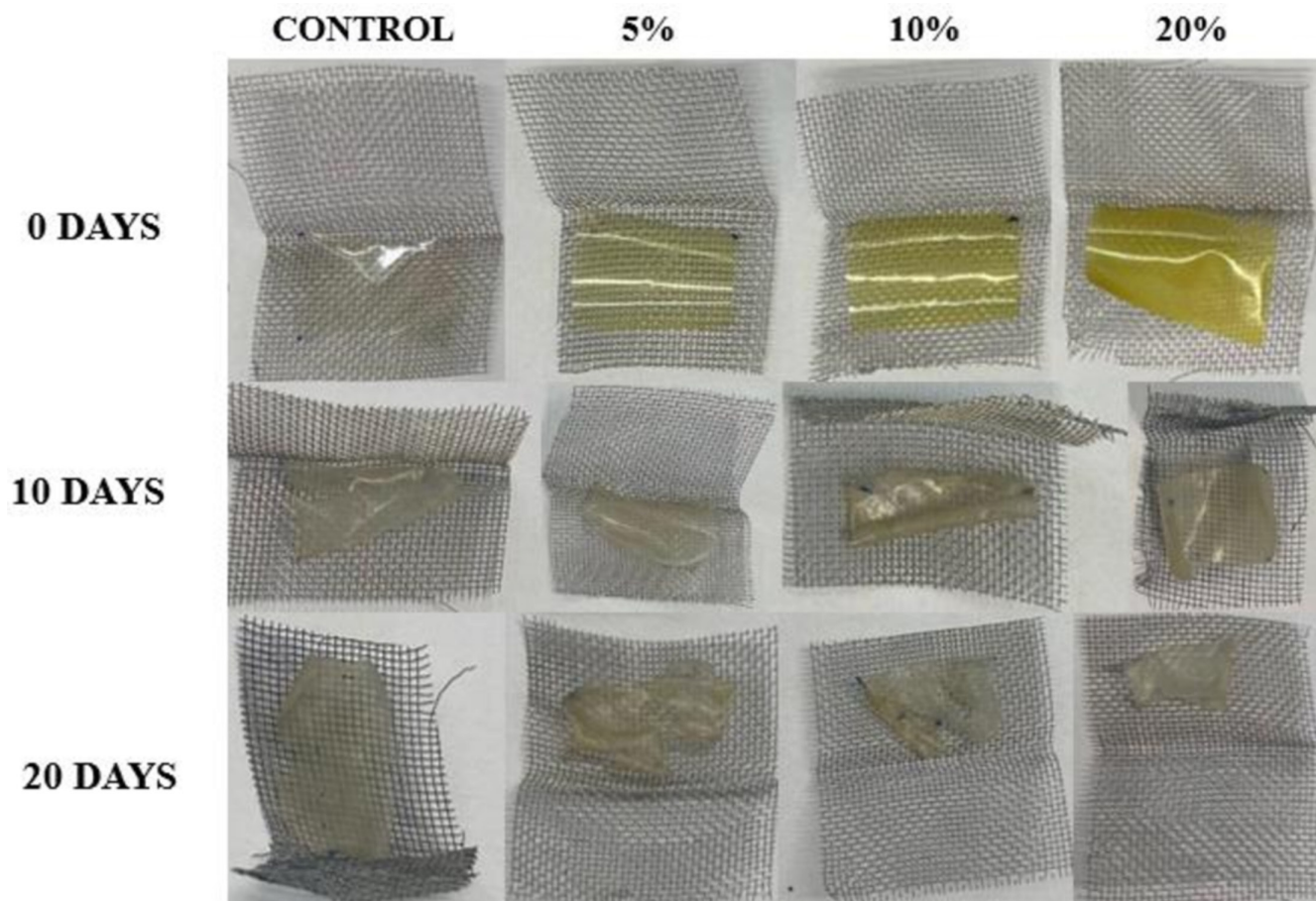


FIGURE 8 | The appearance of 10 and 20-day degradation of the sodium alginate films incorporated with 5%, 10% and 20% of *Jateorhiza palmata* (Lam.) Miers root extracts.

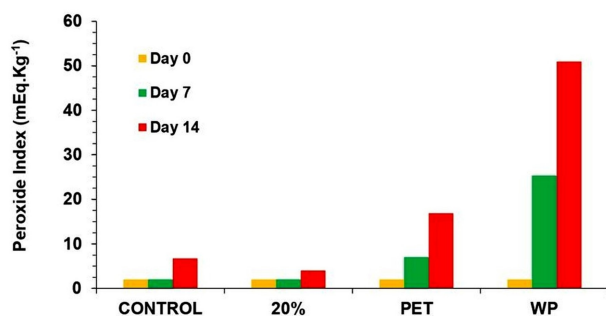
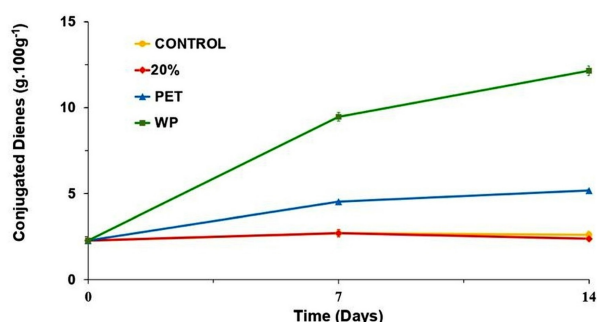
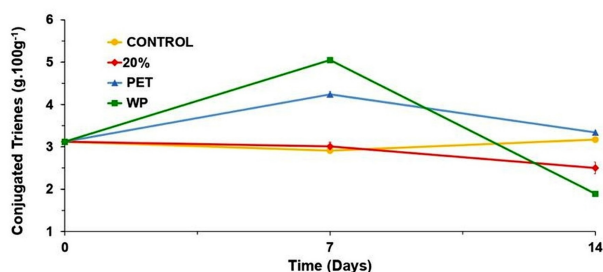
(A)**(B)****(C)**

FIGURE 9 | Peroxide index (A), conjugated dienes (B), and conjugated trienes (C) of sunflower oil stored in different packaging. 20%: sodium alginate films incorporated with 20% of *Jateorhiza palmata* (Lam.) Miers root extracts; PET: polyethylene terephthalate bottle; WP: without packaging.

These findings reinforce the technological feasibility of using *J. palmata*-based films in the food packaging industry, offering a sustainable and natural alternative to synthetic antioxidants and petroleum-derived packaging materials, thereby contributing to the extension of shelf life in lipid-rich food systems.

6 | Conclusion

The present work demonstrated the development and characterization of sodium alginate films enriched with *J. palmata* (Lam.) Miers root extract as active and biodegradable packaging materials. The incorporation of the extract improved film elasticity, thermal

stability and antioxidant activity, while maintaining barrier properties and biodegradability. In particular, the 20% formulation exhibited remarkable antioxidant effectiveness, protecting sunflower oil from lipid oxidation and showing early biodegradation potential. These outcomes highlight the potential of *J. palmata*-based alginate films as sustainable alternatives to conventional plastic packaging, particularly for applications in lipid-rich food preservation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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