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Microencapsulated avocado leaf extract as a source of antioxidants for food and nutraceutical applications

Extracto microencapsulado de hojas de aguacate como fuente antioxidante para aplicaciones alimentarias y nutracéuticas

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ABSTRACT

The leaves of *Persea americana* Mill. are a significant source of phenolic compounds with antioxidant potential for health and functional foods. This study evaluated the effect of spray-drying temperature (160–180 °C) on the physicochemical, technological, and bioactive properties of an extract obtained using deep eutectic solvent extraction and microencapsulated with maltodextrin. Residual moisture, flowability, yield, total polyphenols, antioxidant capacity, release kinetics, and activity in mechanically deboned chicken meat were determined. Increasing the temperature improved process yield, polyphenol retention, and powder stability, with 180 °C emerging as the optimal condition. The release of bioactive compounds followed the Korsmeyer–Peppas model with Fickian diffusion. In the meat matrix, the extract reduced lipid peroxidation in a dose-dependent manner. Overall, the microencapsulated system showed high potential as an antioxidant ingredient for food and nutraceutical applications.

Keywords: spray drying, avocado leaves, phenolic compounds, antioxidant activity, nutraceuticals.

RESUMEN

Las hojas de *Persea americana* Mill. son una fuente relevante de compuestos fenólicos con potencial antioxidante en salud y alimentos funcionales. Este estudio evaluó el efecto de la temperatura de secado por aspersión (160–180 °C) sobre las propiedades fisicoquímicas, tecnológicas y bioactivas de un extracto obtenido mediante disolvente eutéctico profundo y microencapsulado con maltodextrina. Se determinaron humedad residual, fluidez, rendimiento, polifenoles totales, capacidad antioxidante, cinética de liberación y actividad en carne de pollo mecánicamente deshuesada. El aumento de temperatura mejoró el rendimiento del proceso, la retención de polifenoles y la estabilidad del polvo, destacando 180 °C como condición óptima. La liberación de compuestos bioactivos se ajustó al modelo de Korsmeyer–Peppas con difusión fickiana. En la matriz cárnica, el extracto redujo la peroxidación lipídica de forma dosis-dependiente. En conjunto, el sistema microencapsulado mostró alto potencial como ingrediente antioxidante para aplicaciones alimentarias y nutracéuticas.

Palabras clave: secado por aspersión, hojas de aguacate, compuestos fenólicos, actividad antioxidante, nutracéuticos.

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INTRODUCTION

Oxidative stress is a key factor in the development of chronic, metabolic, and inflammatory diseases, which has sparked growing interest in natural bioactive compounds with antioxidant properties and potential applications in functional foods and nutraceuticals (Pulido et al., 2000; Forbes-Hernández et al., 2020). In this context, plant-derived phenolic metabolites represent a promising alternative for replacing synthetic antioxidants and preventing cellular oxidative damage. As highlighted by a recent review (Torres et al., 2025), microencapsulation stands as a key enabling technology for the valorization of natural bioactive compounds in the food industry.

Persea americana (Lauraceae), known as the avocado, is a tropical species widely recognized for its ethnopharmacological value and diverse biological activities (Owolabi et al., 2005). Its leaves contain high concentrations of phenolic compounds, including hydroxycinnamic acids, hydroxybenzoic acids, and flavonoids derived from quercetin, luteolin, and epicatechin, which are associated with antioxidants, antimicrobial, anti-inflammatory, and antidiabetic effects (Henríquez et al., 2013; Forbes-Hernández et al., 2020; Kupnik et al., 2023; Bongo et al., 2024). As a result, *P. americana* leaves have been proposed as a source of natural antioxidants with potential industrial applications (Pereira et al., 2016).

However, the stability of these compounds during processing and storage poses a technological challenge. In this regard, spray drying represents an efficient strategy for improving the stability and shelf life of bioactive ingredients, due to its operational simplicity, low cost, and ability to produce stable functional powders (Verma & Singh, 2015; Rojas-Molina et al., 2022; Torres et al., 2025). Likewise, deep eutectic solvents have emerged as sustainable alternatives for the efficient extraction of phenolic compounds. Therefore, the present study evaluated the effect of spray-drying temperature on the physicochemical, antioxidant, and functional properties of a *P. americana* leaf extract obtained using a deep eutectic solvent and encapsulated with maltodextrin.

METHODOLOGY

Healthy leaves of *P. americana* Mill. were collected in Havana, Cuba, and homogeneous specimens were selected. After washing and cutting into 1-cm pieces, the material was dried at 40 °C for 48 h, ground, and sieved (0.5 mm), yielding a fine powder that was stored in amber bottles at room temperature.

Residual moisture was determined gravimetrically in a drying oven (Model YLD-6000, AISET, China) at 105 °C until a constant weight was reached. Particle size distribution was assessed by sieving (0.07–0.45 mm) for 15 min. For analytical extraction, 1 g of sample was mixed with 25 mL of 50% (v/v) ethanol under orbital agitation (250 rpm, 1 h), followed by centrifugation (10,000 rpm, 15 min) and re-extraction in triplicate. Total polyphenol content (TPC) was determined using the Folin-Ciocalteu method (Slinkard & Singleton, 1977), and antioxidant capacity (AC) was determined by FRAP according to Benzie and Strain (1996), modified by Pulido et al. (2000). The results were expressed as mg EAG/g and μmol EAA/g of dry extract, respectively.

The extract was obtained by solid-liquid extraction using a deep eutectic solvent consisting of glucose, citric acid, and water (1:2:7.5 molar), prepared at 60 °C (Tejero, 2021). Extraction was performed with 70% (v/v) DES, a solid-liquid ratio of 1:15 (w/w), at 60 °C for 3 h under mechanical agitation (Iglesias-Guevara et al., 2024). Subsequently, the extract was vacuum-filtered and stored at -20 °C.

Spray drying was performed in a Mini Spray Dryer B-191 (BÜCHI, Switzerland), evaluating inlet temperatures of 160, 170, and 180 °C. For each trial, 50 mL of extract and DE 12 maltodextrin (25% w/v) were used as the encapsulant. Operating conditions included a 0.5 mm nozzle, 6 bar pressure, 100% suction, and 35% feed flow, with outlet temperatures ranging from 70–75 °C. The yield, residual moisture, flow properties, TPC, phenolic retention, and AC of the resulting powders were determined.

The residual moisture content of the powder was determined gravimetrically at 105 °C until a constant mass was reached. The flow properties were expressed using the Carr index and the Hausner index (Jinapong et al., 2008). To quantify TPC and FRAP, 0.1 g of powder was dispersed in 1 mL of distilled water, followed by vortexing for 3 min (IKA® Vortex 3) and centrifugation (10 min) to recover the analytical supernatant. Polyphenol retention was calculated based on the ratio of the powder's phenolic content to the initial concentration of the feed suspension.

The drying yield was calculated by considering the total solids present in the feed and those recovered in the dry product (Equation 1):

$$Rendimiento(\%) = \frac{(MC+MPE)-MC}{MT} \times 100 \quad \text{(Eq. 1)}$$

Where: MC: mass of the collector; MPE: mass of the dry-basis powder extract; MT: total mass of solids in the feed.

The release kinetics were evaluated in water and ethanol (50% v/v) as hydrophilic and lipophilic simulants (Estévez-Areco et al., 2018). Two hundred milligrams of powder were dispersed in 20 mL of medium, and 50 µL aliquots were collected at 24-hour intervals with volume replacement. The data were fitted by nonlinear regression to the Korsmeyer-Peppas (Equation 2; ⩽60 – 65% release) and Weibull (Equation 3; full range) models.

$$\frac{M_t}{M_\infty} = k \times t^n \quad \text{(Eq. 2)} \qquad \frac{M_t}{M_\infty} = 1 - e^{-\left(\frac{t}{\alpha}\right)^\beta} \quad \text{(Eq. 3)}$$

Where: Mt/M∞ represents the fraction released at time t; k, the kinetic constant; n, the release mechanism; α, the time scale; and β, the shape of the kinetic profile.

The antioxidant activity of the powdered extract was evaluated in mechanically deboned (MDB) chicken meat using the TBARS assay (Equation 4). Four concentrations of ESEA-180 °C (0.25–1.00% w/w) and a control were analyzed over 72 h at 10 ± 2 °C. The samples (50 g; n = 3) were evaluated at 0, 24, and 72 h. The TBARS index was determined according to Song et al. (2024) using trichloroacetic acid and thiobarbituric acid, with a reading at 532 nm on a UV-VIS spectrophotometer (Rayleigh UV-1601, Beijing).

$$TBARS\left(\frac{mg}{kg}\right) = A_{532} \times 9{,}45 \quad \text{(Eq. 4)}$$

For statistical analysis, the data (mean ± SD) were analyzed using one-way ANOVA and Duncan's test ($p < 0.05$) in SPSS v.26.0. Kinetic fitting was performed using nonlinear regression (SciPy, Python 3.11), with Matplotlib and Scikit-learn used for plotting and calculating R^2.

RESULTS AND DISCUSSION

Characterization of *P. americana* revealed a particle size of 0.27 mm (Table 1). This particle size optimizes the effective surface area, which facilitates solvent penetration and improves the mass transfer of polyphenols and polysaccharides from the matrix to the medium, thereby increasing their bioaccessibility (Shu et al., 2019). The powder had a moisture content of

9.18%, which is higher than the technical threshold of 8% recommended for the stability of plant matrices. However, the moisture content (9.18%) complies with the limits (10–12%) of the European Pharmacopoeia (European Pharmacopoeia Commission, 2020), ensuring physicochemical and microbiological stability.

Table 1. Characterization of the plant material

Parameters	Mean (standard deviation)
Average particle size (mm)	0,27 (0,03)
Residual moisture (%)	9,18 (0,08)
Total polyphenols (mg GAE/g)	7,1 (0,13)
Total antioxidant capacity (µmol AAE/g)	536 (149)

GAE: Gallic acid equivalents; AAE: Ascorbic acid equivalents.

The TCP (7.1 mg GAE/g) exceeds the value reported by Oliveira et al. (2022) of 5 mg GAE/g. From a functional perspective, TPC in dried plant materials exceeding 5 mg GAE/g is considered significant for exerting beneficial effects in food matrices, both as a natural preservative and due to its potential bioactivity in the body (Balasundram et al., 2006). The AC (536 µmol AAE/g) is competitive compared to defatted avocado peel extracts (673.89 µmol AAE/g) (Petrantonaki et al., 2025). Values above 300 µmol AAE/g are associated with a significant reduction in lipid oxidation (Kähkönen et al., 1999). This bioactive profile confirms the extract's suitability for integration into complex food systems prone to oxidative deterioration.

Figure 1 shows that the drying efficiency depended critically on the inlet temperature. When the temperature was increased from 160 to 180 °C, the solids recovery increased from 49–51% to 80%. This increase suggests that higher temperatures optimize heat and mass transfer by minimizing adhesion in the chamber and maximizing efficiency at 180 °C.

For avocado leaf extract, temperatures of 160–170 °C may have been insufficient for immediate complete drying, resulting in sticky particles and losses due to deposition. Tonon et al. (2008) reported a positive correlation between temperature and yield in açai pulp, with peaks in the 150–180 °C range depending on the matrix and additives, reaching 86%. The observed increase up to 180 °C suggests an optimal condition close to this value. The 80% yield is significant and

demonstrates the effectiveness of maltodextrin in reducing viscosity and stickiness by forming a protective glassy matrix (Augustin & Sanguansri, 2015).

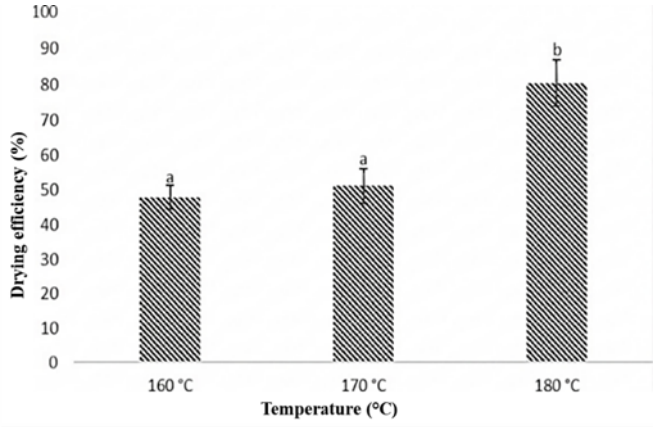

Figure 1. Effect of drying temperature on process yield. Different letters indicate significant differences ($p < 0.05$).

Table 2 shows the influence of drying temperature on the moisture content and flowability of the powders. In the *P. americana* extract, moisture decreased as the inlet temperature increased. Despite an anomaly (6.70%) at 170 °C, the minimum was reached at 180 °C, consistent with mass transfer. Moisture levels below 6% are essential to ensure product stability during storage, limiting both the growth of microorganisms and chemical degradation reactions (Nguyen et al., 2021).

Table 2. Effect of drying temperature on the moisture content and flow properties of the powders

Parameters	Mean (standard deviation)		
	160 °C	170 °C	180 °C
Moisture (%)	6,07 (0,13) a	6,70 (0,05) b	5,80 (0,18) c
Carr index (%)	35,0 (0,54) a	34, 0 (1,32) a	24,9 (1,65) b
Hausner index	1,53 (0,01) a	1,54 (0,02) a	1,33 (0,01) b

Different letters indicate significant differences ($p \leq 0.05$).

The Carr index showed that flowability improved as the temperature increased; however, the powder obtained at 180 °C still exhibited limited flow, likely due to residual moisture and interparticle cohesion. According to Aulton and Taylor (2017), values of 18–20% indicate “good” flowability, while >23% correspond to “poor” flow. The Hausner index showed similar behavior,

indicating better handling properties at 180 °C. Buljeta et al. (2022) attribute this effect to the formation of more spherical and less adhesive particles, which are facilitated by the encapsulant.

Figure 2A shows that increasing the spray-drying temperature (160–180 °C) significantly increased ($p < 0.05$) the TCP and its retention in the ESEA powders, reaching a maximum at 180 °C, with values exceeding 100%. This effect is attributed to the fact that high spray-drying temperatures can trigger the release of phenolic compounds from their forms bound to cell wall components, thereby increasing their extractability and measured concentration (Dayoob et al., 2025) without necessarily involving degradation. Furthermore, maltodextrin (DE 12, 25% w/v) promotes stabilization through a glassy matrix that limits thermal and oxidative degradation (Augustin & Sanguansri, 2015).

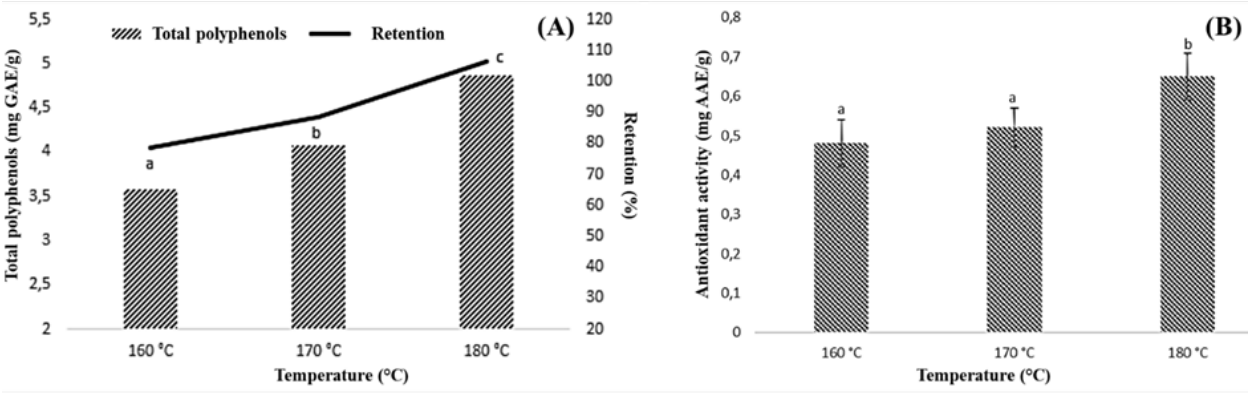

Figure 2. Effect of drying temperature on TCP and retention (A); and antioxidant capacity (B). Different letters indicate significant differences ($p < 0.05$).

Figure 2B shows that increasing the drying temperature (160–180 °C) significantly increased ($p < 0.05$) the antioxidant capacity (FRAP), reaching a maximum at 180 °C. This trend is consistent with the behavior of the TPC, demonstrating a direct relationship between phenolic compounds and reducing capacity, with the hydroxycinnamic acids, flavonoids, and tannins of *P. americana* being the primary contributors. Taken together, these findings confirm that 180 °C optimizes the release and stability of phenolic compounds, maximizing the antioxidant functionality of the system.

The release profile (Figure 3A) showed a rapid initial phase, more pronounced in water (>80% in 5 h), attributed to the high solubility of maltodextrin and the desorption of surface polyphenols, followed by a plateau characteristic of hydrophilic matrices. In a hydroalcoholic solution (50%), release was more gradual (~70% at 24 h), due to the lower polarity of the medium, which restricts matrix dissolution and the diffusion of bioactive compounds.

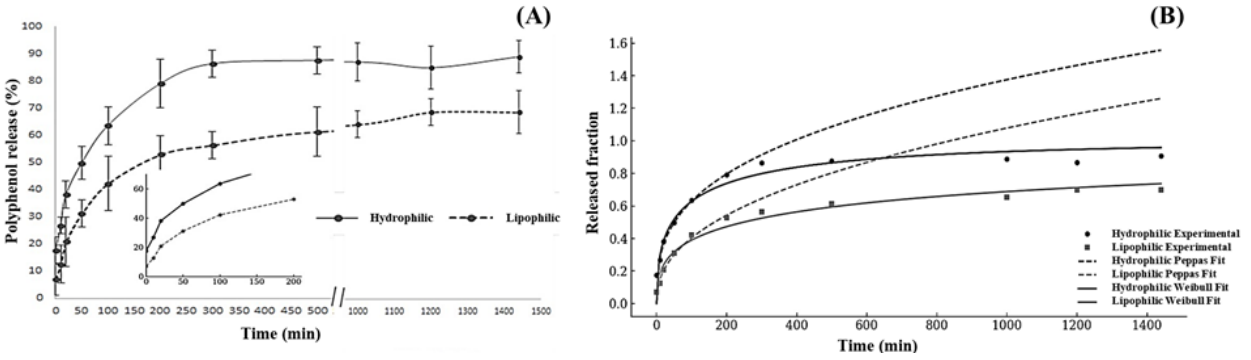

Figure 3. Release of phenolic compounds in food simulants (A). Fitted models for the release of polyphenolic compounds (B).

The polyphenol release profile varied according to the medium (Figure 3B; Table 3). The Korsmeyer–Peppas model (~0–60%) yielded n < 0.43 in both systems, confirming Fickian diffusion, likely associated with the high solubility and lack of structural barriers in maltodextrin (Kurniasari et al., 2025). Higher k values in water indicated faster release than in the hydroalcoholic medium, attributable to greater matrix polarity and solubility (Flores & Kong, 2017). The Weibull model showed the best fit; lower α values in water reflected accelerated release, whereas β < 1 evidenced decelerated kinetics characterized by an initial burst followed by gradual diffusion (Papadopoulou et al., 2006). The β range (0.2–0.6) agreed with previous spray-dried microcapsule reports (Kurniasari et al., 2025).

Table 3. Models fitted for the release of polyphenolic compounds

Model	Medium	Parameters	R^2
Korsmeyer–Peppas	Hydrophilic	k= 0,1316 n= 0,3398	0,9955
	Lipophilic	k= 0,0566 n= 0,4268	0,9875
Weibull	Hydrophilic	α= 102,48 β= 0,4390	0,9327
	Lipophilic	α= 662,84 β= 0,3723	0,9653

The TBARS analysis (Figure 4) of MDM treated with ESEA-180 °C revealed a dose-dependent effect. At 72 h, the control exceeded 5 mg/kg, while concentrations of 0.25–1.00% significantly reduced lipid peroxidation. The addition of 1.00% showed maximum efficacy (~3.8 mg/kg), limiting oxidative rancidity in the meat matrix. These findings are consistent with Paglarini et al. (2023), who reported similar effects with grape and rosemary extracts (>0.5%) in chicken MDM. Taken together, the results reinforce the potential of natural antioxidants in meat systems (Manessis et al., 2020).

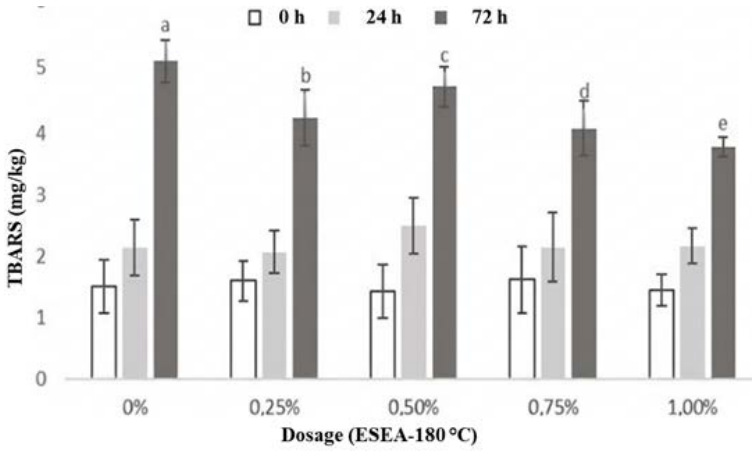

Figure 4. Inhibition of lipid oxidation in MDM by the powdered extract (ESEA-180 °C). Different letters indicate significant differences ($p < 0.05$).

CONCLUSIONS

The microencapsulated extract of *P. americana* leaves exhibited high antioxidant capacity and high phenolic content. The spray-drying temperature significantly affected the physicochemical properties of the powder, with 180 °C being the optimal condition for maximizing yield, flowability, and phenolic retention, as well as reducing residual moisture. The release of bioactive compounds followed the Korsmeyer-Peppas model, indicating Fickian diffusion modulated by the polarity of the medium. Furthermore, the extract significantly reduced lipid oxidation in chicken meat, confirming its antioxidant efficacy. These results position the microencapsulated powder as a promising functional ingredient for food, nutraceutical, and phytotherapeutic applications aimed at controlling oxidative stress.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

AUTHOR CONTRIBUTIONS

Conceptualization: Dairon Iglesias, Gabriela Ruíz, Joe Doyharzabal, and José A. Arencibia. **Data curation:** Dairon Iglesias and Gabriela Ruíz. **Formal analysis:** Dairon Iglesias, Gabriela Ruíz, Joe Doyharzabal, and José A. Arencibia. **Investigation:** Dairon Iglesias, Gabriela Ruíz, Joe Doyharzabal, and José A. Arencibia. **Methodology:** Dairon Iglesias, Gabriela Ruíz, Joe Doyharzabal, and José A. Arencibia. **Project administration:** Dairon Iglesias, Joe Doyharzabal, and José A. Arencibia. **Resources:** Dairon Iglesias, Joe Doyharzabal, and José A. Arencibia. **Software:** Dairon Iglesias. **Supervision:** Dairon Iglesias and Joe Doyharzabal. **Validation:** Dairon Iglesias and José A. Arencibia. **Visualization:** Dairon Iglesias and José A. Arencibia. **Writing – original draft:** Dairon Iglesias, Gabriela Ruíz, and José A. Arencibia. **Writing – review & editing:** José A. Arencibia.

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