Food Bioscience 75 (2026) 108093



Contents lists available at ScienceDirect

Food Bioscience

journal homepage: www.elsevier.com/locate/fbio





Evaluation of chitosan-coated liposome drying methods using freeze-drying, vacuum microwave drying, and spray drying: Physicochemical properties, energy efficiency, and CO_2 emissions

Erick Jara-Quijada [a,b,*], Paulina Muñoz-Muñoz [b], Mario Pérez-Won [c], Carla Vidal-San Martín [c], Horacio Fraguela-Meissimilly [c], Marcia Cabrera-Pérez [c], Luis González-Cavieres [d], Tatiana Beldarrain-Iznaga [e], Mario Gonzales-Santos [f]

[a] Nutrition and Dietetics, Faculty of Health Sciences, Universidad Adventista de Chile, Camino a Las Mariposas #11771, Chillán, Chile
[b] Chemistry and Pharmacy, Faculty of Health Sciences, Universidad Adventista de Chile, Camino a Las Mariposas #11771, Chillán, Chile
[c] Department of Food Engineering, Faculty of Health and Food Science, Universidad del Bío-Bío, Av. Andrés Bello 720, Box 447, Chillán, Chile
[d] School of Nutrition and Dietetics, Faculty of Health and Food Science, Universidad Catolica del Maule, Merced 333, Curicó, Chile
[e] Department of Animal Sciences, Faculty of Agronomy, and Department of Veterinary Medicine, Faculty of Veterinary Sciences, University of Concepción, Avenida Vicente Méndez 595, Chillán, Chile
[f] Faculty of Technological Sciences, Universidad Nacional de Agricultura, Carretera a Dulce Nombre de Culmí, km 215, Barrio El Espino, Catacamas, Honduras

ARTICLE INFO

Keywords:
Liposomes
Chitosan
Freeze drying
Vacuum microwave drying
Spray drying
Carbon footprint

ABSTRACT

The stability of liposomes is fundamental for incorporating polyphenols into foods, but their applicability depends on the drying method. Drying can modify particle properties, bioactive retention, and the economic-environmental impact. Therefore, comparing different drying methods is key to selecting the most suitable alternative. This study evaluated freeze-drying, microwave vacuum drying, and spray drying to determine their effects on particle properties, energy, and environmental performance. Liposomes were formulated using chitosan concentrations of 0.1 %–1 % and homogenized at 13,500 rpm for 2–10 min. Response Surface Methodology was applied to optimize particle size and encapsulation efficiency, identifying 0.1 % chitosan and 10 min of homogenization as the optimal conditions. Freeze-drying provided the highest polyphenol retention (517.83 mg/g GAE) and antioxidant activity (40.64 %) but resulted in powders with a relatively high moisture content. Vacuum microwave drying significantly reduced CO_2 emissions (8.06 kg CO_2/kg) and processing time, offering a more sustainable alternative. Spray drying produced the smallest particle size (593 nm), the lowest moisture content (1.26 %), and the highest solubility (87.36 %), yielding powders with superior technological performance and stability. While spray drying required more energy than vacuum microwave drying, it demonstrated the best balance between quality, scalability, and environmental sustainability. This study highlights, for the first time, the application of microwave drying to liposome drying, as well as the study of energy efficiency and CO_2 emissions in liposome drying technologies. Overall, spray drying has the potential for a viable industrial stage in the production of chitosan-coated liposomal powders intended for functional food applications.

1. Introduction

Developing innovative foods that offer health benefits is a top priority for the food industry. Consumers are showing increasing interest in foods that promote health and contribute to the prevention of chronic non-communicable diseases such as obesity, diabetes, and cancer (Banu & Lunghar, 2023; Misra et al., 2021). Polyphenols are plant metabolites with recognized antioxidant, anti-inflammatory, cardioprotective, antimicrobial, neuroprotective, and immune-modulating activities (Bolat et al., 2024). However, their direct application in food matrices is limited due to their instability in the presence of factors such as light, oxygen, temperature, and pH (Kasapoğlu, Gültekin-Özgüven, et al., 2024). Encapsulation has emerged as an effective strategy to improve the stability, bioaccessibility, and protection of polyphenols (Esposto et al., 2021). Among encapsulation systems, liposomes stand out for their biocompatibility, their ability to incorporate hydrophilic and

* Corresponding author. Nutrition and Dietetics, Faculty of Health Sciences, Universidad Adventista de Chile, Camino a Las Mariposas #11771, Chillán, Chile.
E-mail address: erick.jara@unach.cl (E. Jara-Quijada).

https://doi.org/10.1016/j.fbio.2025.108093
Received 30 October 2025; Received in revised form 1 December 2025; Accepted 11 December 2025
Available online 16 December 2025
2212-4292/© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

lipophilic compounds, and their potential to improve cellular absorption associated with cellular biocompatibility (Mohammadi et al., 2021; Nsairat et al., 2022). These phospholipid vesicles offer advantages such as high cargo capacity and control over the release of the active ingredient (Jara-Quijada et al., 2022; Joy et al., 2023), which has driven their incorporation into various food matrices, including chocolate (Gültekin-Özgüven et al., 2016), yogurt (Akgün et al., 2020; Ghorbanzade et al., 2017), mayonnaise (Savaghebi et al., 2021), and fruit juices (Ang et al., 2024; Jara-Quijada et al., 2025). However, their stability in aqueous suspension is limited, which hinders their storage and industrial use. Therefore, transforming liposomes into powders through drying processes has become a key step to extending their shelf life and facilitating their incorporation into food without compromising their functionality (Kasapoğlu, Sus, et al., 2024). Among the most used techniques are freeze-drying (FD) and spray-drying (SD). FD allows for the preservation of the structural integrity and biological activity of heat-sensitive compounds (Kandasamy & Naveen, 2022; Ma et al., 2022; Zhang et al., 2022), while SD offers industrial advantages due to its low operating cost, reproducibility, and production of stable powders with low moisture content (Ang et al., 2024a, 2024b; Banožić et al., 2023; Chen et al., 2020; Kasapoğlu, Sus, et al., 2024). Vacuum microwave drying (VMD) has emerged as a fast and efficient alternative that combines volumetric heating and low pressures, reducing oxidation and preserving sensory qualities (González-Cavieres et al., 2021). However, their application in liposomes is still nonexistent. The evaluation of these technologies must consider sustainability criteria, aligning with the Sustainable Development Goals through the efficient use of energy and the reduction of carbon emissions (Alara & Abdurahman, 2019). Quantifying energy consumption and carbon footprint has become a key tool for comparing technological alternatives in the food industry (Jara-Quijada, Pérez-Won, Tabilo-Munizaga, González-Cavieres, et al., 2024; Vega et al., 2021). However, no studies simultaneously compare powder quality, energy efficiency, and emissions associated with FD, SD, and VMD applied to liposomes. Therefore, this study aims to evaluate the quality of liposomal powders obtained through different drying methods, analyzing their physicochemical properties, energy efficiency, and carbon emissions, to identify viable and sustainable technological alternatives for the production of liposome-based functional ingredients.

2. Materials and methods

2.1. Materials

Soy lecithin, Tween 80, low molecular weight chitosan, ethanol, gallic acid, Folin-Ciocalteu reagent, anhydrous sodium carbonate, and 2,2-diphenyl-1-picrylhydrazyl (DPPH) reagent were analytical grades obtained from Sigma-Aldrich (Santiago, Chile).

2.2. Obtaining the polynomial extract

A polyphenol concentrate was produced using the pulsed electric field (PEF) extraction method, as outlined by Jara-Quijada, Pérez-Won, Tabilo-Munizaga, González-Cavieres, et al. (2024). The green tea extract used in the formulation was obtained from dried leaves previously ground to a particle size of 2 mm. For each extraction, 2 g of sample were weighed and suspended in 100 mL of a hydroalcoholic ethanol/water solution (1:1 v/v), with an electrical conductivity of 0.0015 S/m. Pulse-assisted extractions (PEF) were performed in a PEF system (Energy Pulse Systems, Lisbon, Portugal) equipped with a Marx Epulsus-PM110 energy modulator and a stainless steel parallel-plate treatment cell (electrode area: 58.81 cm^2; electrode spacing: 1.7 cm; useable volume: 100 mL). The treatment was applied at room temperature, using an electric field strength of 5.88 kV/cm, a frequency of 200 Hz, a pulse width of 100 μs, and a total of 10 pulses. The total polyphenols were measured, and the solution was adjusted to a concentration of 1000 ppm.

2.3. Preparation and drying of liposomes

Liposomes were prepared following the methods proposed by Jara-Quijada, Pérez-Won, Tabilo-Munizaga, Lemus-Mondaca, et al. (2024), with modifications (Fig. 1). Polyphenol extract, soy lecithin, and Tween 80 were dissolved and mixed in a 0.1:1:1 ratio on a magnetic stirrer (500 rpm) at 60 °C until thoroughly combined. The solution was quickly injected into a phosphate buffer (pH 6.0, 0.05 M) at a 1:1 ratio, with stirring maintained at the same temperature for 30 min. Separately, chitosan solutions (0.1 %, 0.5 %, and 1 %) were prepared by dissolving the appropriate amount of chitosan in distilled water containing 0.5 % (v/v) acetic acid. The pre-liposomal solution was added to the chitosan solution at a 1:2 ratio and mixed using a shaker. To reduce particle size, a high-speed homogenizer (T25 digital Ultra-Turrax, Selangor, Malaysia) was used at 13,500 rpm for 2, 5, and 10 min. The resulting solutions were analyzed in triplicate. From the optimal sample, three drying treatments were performed. Freeze drying involved using a sample previously frozen at −80 °C, which was sublimated at a pressure of 500 mTorr for 24 h until it reached a temperature of 20 °C in a Liofilizador-3kg freeze dryer (Friologic, Santiago, Chile). Vacuum microwave drying was conducted at a power of 590 W and a vacuum of 50 kPa for 30 min using self-made equipment. Spray drying was performed at an inlet temperature of 190 °C and an outlet temperature of 90 °C for 10 s using an OLT-1500-1.5L device (Shanghai, China).

2.4. Encapsulation efficiency (EE %)

Encapsulation efficiency was determined indirectly, considering that the supernatant contains the extract that was not incorporated into the liposomes. Following the procedure described by Katouzian and Taheri (2021), 2 mL of the liposomal suspension were placed in an Amicon ultracentrifuge filter (molecular cutoff limit = 30 kDa; Millipore, UK) and centrifuged for 10 min at 2500×g to separate and quantify the unencapsulated phenolic extract. The EE % was calculated from the total polyphenol content present in the supernatant using equation (1).

$$EE\,\% = ((\text{Encapsulated extract}) \;/\; (\text{Initial extract})) \cdot 100 \quad (1)$$

where the difference between total extract and non-encapsulated extract is calculated as encapsulated extract, the non-encapsulated extract was quantified by the Folin-Ciocalteu method for total polyphenol content. The total polyphenol content was determined using the Folin-Ciocalteu method (Waterhouse, 2002). First, 100 μL of sample were mixed with 7900 μL of water. Then, 500 μL of Folin-Ciocalteu reagent was added, and the mixture was allowed to react for 5 min. Next, 1500 μL of 20 % anhydrous sodium carbonate solution was incorporated, stirring gently to homogenize. The resulting mixture was incubated in the dark for 2 h. Finally, the absorbance was measured at 760 nm using a UV/Vis spectrophotometer (BK-UV 1800 PC UV/VIS spectrophotometer, BIOBASE). A standard curve of gallic acid (100–900 ppm) was used to generate the linear equation ($y = 0.0013x - 0.0368$; $R^2 = 0.9991$).

2.5. Particle size (PZ) and polydispersity index (PDI)

The particle size and polydispersity index of liposomes were measured using a Zetasizer Nano ZS (Malvern Instruments Ltd., Worcestershire, UK) in triplicate at 20 °C. Liposomes were diluted 1/1000 in phosphate buffer (0.05 M, pH 6.0) using a Zeta DTS1070 cuvette to ensure colloidal stability and avoid artefactual aggregation during analysis (Jara-Quijada, Pérez-Won, Tabilo-Munizaga, Lemus-Mondaca, et al., 2024). The stability of liposomes during storage was evaluated by monitoring changes in particle size over a 45-day period, with samples maintained at 20 °C in sealed metallic foil bags to prevent light exposure and ensure consistent environmental conditions.

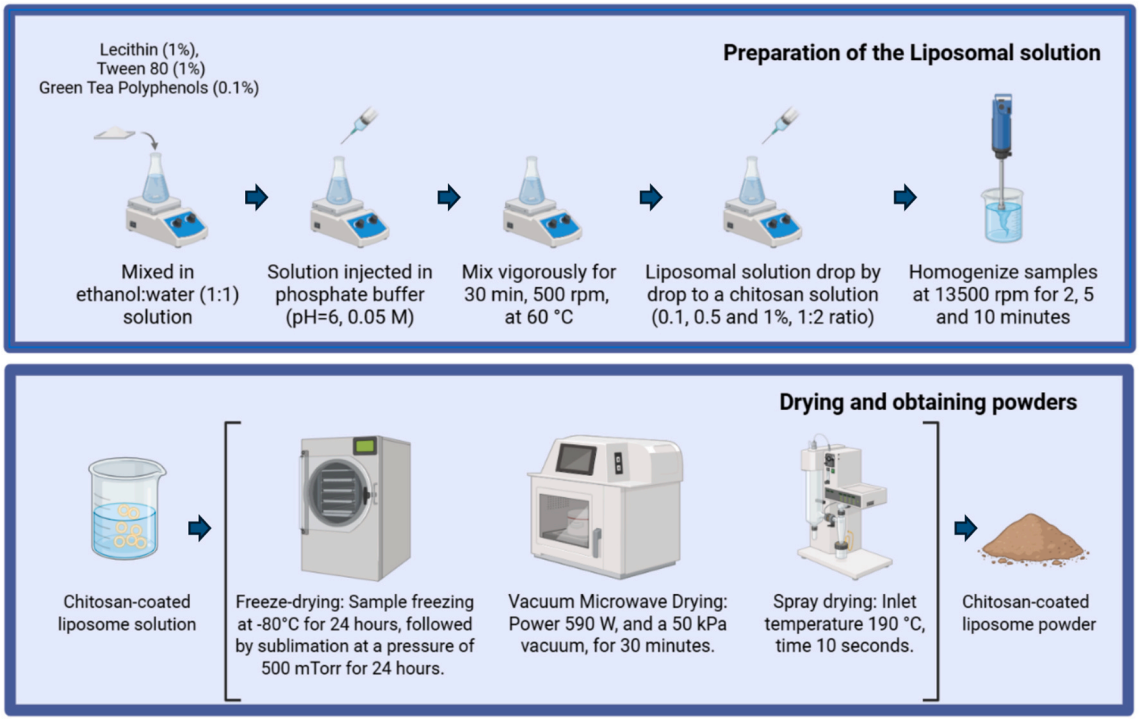


Fig. 1. Schematic representation of the preparation of chitosan-coated liposomes.

2.6. Response surface methodology

The experiments were evaluated using the response surface methodology (RSM). Chitosan (0.1 %, 0.5 %, and 1 %) and homogenization time (2 min, 5 min, and 10 min) were identified as A and B, respectively (Sumathi et al., 2021). The relationship between factors and levels was used to identify the optimal conditions that maximize EE % and minimal size (Response variables) using the model represented by equation (2):

$$\text{Response variable} = \beta_0 + \beta_1 \times A + \beta_2 \times B + \beta_{11} \times A^2 + \beta_{22} \times B^2 + \beta_{12} \times A \times B + \varepsilon \quad (2)$$

where β_0 is a constant, β_1 and β_2 are linear coefficients, β_{11} and β_{22} are quadratic coefficients, β_{12} is a cross-product coefficient, and ε is a residual.

2.7. Determination of moisture and solubility in powders

Samples of 0.1 g were taken from each drying treatment and placed in a thermobalance (Sartorius, MA37-1). The results obtained, based on the weight difference due to moisture loss, were expressed as a percentage of moisture (%). Solubility was measured by diluting the sample in distilled water (1 % w/v) at 20 °C for 150 min, with magnetic stirring, followed by centrifugation at 5000*g* for 5 min at 4 °C. The supernatant was dried at 105 °C, and the water solubility, expressed as a percentage, was calculated based on the weight difference relative to the initial sample weight, following equation (3) (Marín et al., 2018).

$$\text{Solubility (\%)} = (\text{Weight of dry supernatant} \ / \ \text{Weight of initial sample}) \times 100 \quad (3)$$

2.8. Determining energy efficiency and CO_2 emission

The environmental impact of the experimental drying conditions by the three technologies was compared under the conditions previously indicated.

(a) Freeze-drying: Sample freezing at −80 °C for 24 h, followed by sublimation at a pressure of 500 mTorr for 24 h.
(b) Vacuum Microwave Drying: Power 590 W, and a 50 kPa vacuum, for 30 min.
(c) Spray drying: Inlet temperature 190 °C, time 10 s.

The energy consumption of the drying processes was determined using the methodology described by Pérez-Won et al. (2023). The specific energy consumption (SEC) values were calculated using equation (4), as described by Torki-Harchegani et al. (2016), which defines them as the energy required to remove 1 kg of water from the samples during the drying process. Where Et is equivalent to the energy consumption of the drying process and mw is the mass of water removed, equation (4).

$$SEC = E_t \ / \ m_w \quad (4)$$

The energy efficiency (η_e) was determined using the equation employed by Motevali et al. (2016), which relates the energy used for water evaporation (Q_w) to the total drying consumption (E_t), as shown in equation (5).

$$\eta_e = Q_w \ / \ E_t \quad (5)$$

where Q_w is the energy consumed for moisture evaporation (kJ). It was calculated using equation (6),

$$Q_w = h_{fg} \times m_{w,ev} \quad (6)$$

where h_{fg} is the latent heat of vaporization (kJ/kg) and T_{abs} is the absolute temperature of the medium $h_{fg} = 2.503 \times 10^6 - 2.386 \times 10^3 (T_{abs}$-273.16) (273.16 ≤ T_{abs} (°K) ≤ 338.72).

Thermal efficiency (η_{th}) defines how well an energy conversion or transfer process is achieved by the ratio of the heat required for moisture evaporation to the energy consumed to evaporate free water from the food matrix; and is calculated as equation (7) (Kaveh et al., 2021).

$$\eta_{th} = (F \times A \times h_{fg}\ (M_0 - M_f\ ))\ /\ (Z \times t(100 - M_f\ )) \quad (7)$$

where F is the sample charge density (kg/m^2), A is the area of the sample (m^2), h_{fg} is the latent heat of vaporization (kJ/kg), and Z is the utilized capacity of the heat source (kW). In addition, M_i y M_f are the initial and final moisture contents (wb %) of the food matrix, respectively.

The emission factor, which reflects the intensity of pollutants generated during electricity production, is determined to assess the environmental impact of different energy sources (Pérez-Won et al., 2023). CO_2, CH_4, and N_2O emissions per kWh were calculated using the IPCC (2006) coefficients, expressed in kilograms of gas per kilowatt-hour, depending on the type of fuel used. CO_2 emissions were estimated using the method of Kaveh et al. (2021), while total greenhouse gas (GHG) emissions are expressed as CO_2 equivalent (CO_2eq), considering the global warming potentials (GWP) of each gas, according to equation (8). Finally, GHG emissions from electricity generation were calculated according to equation (9) proposed by Calvo and Domingo (2017).

$$CO_{2(eq)}kg = E(kgCO_2) + E(kgN_2O) \times PCG_{N20} + E(kgCH_2) \times PCG_{CH4} \quad (8)$$

$$E(kg) = Ad \times Ef \times Of \quad (9)$$

where in the GWP of GHGs, PCG_{N2O} is 296, PCG_{CH4} is equal to 21 (IPCC, 2006), E is the amount of pollutant emissions (CO_2, CH_4, and N_2O), *Ad* (activity data) relates to the energy used (kWh) in the process, *Ef* is the emission, factor and *Of* is the oxidation factor equal to 1.

2.9. Statistical analysis

Results were analysis of variance (ANOVA) and the least significant difference (Tukey) test using Statgraphics Centurion XVI software (Statpoint Technologies Inc., Warrenton, VA, USA) to obtain statistical insights from the study data. All experiments were conducted in triplicate, and the results are presented as the mean ± standard deviation.

3. Results and discussions

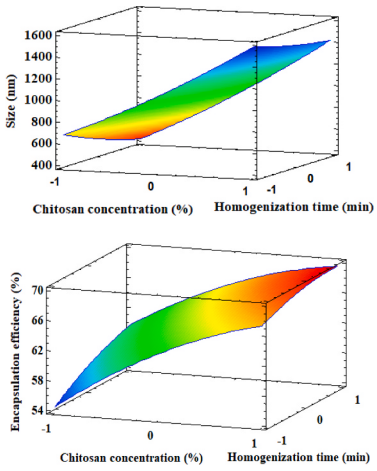
3.1. Determination of optimal conditions for liposomes

Liposome formulations were optimized using RSM. equations (10) and (11) describe the empirical relationship between the factors and both particle size (PZ) and encapsulation efficiency (EE %), considering the significant linear and quadratic effects ($p < 0.05$) to achieve the highest performance for the variable. When analyzing the second-order multiple regression model with the experimental data, it was determined that the regression model had a correlation coefficient of 98.58 % for particle size and 99.48 % for encapsulation efficiency.

$$PZ = 958.7 + 475.3 \times A - 102.7 \times B + 24.8 \times A \times B + 49.0 \times A^2 + 20.0 \times B^2 \quad (10)$$

$$EE\ \% = 50.0 + 27.4 \times A + 1.6 \times B - 11.5 \times A^2 - 0.38 \times A \times B - 0.08 \times B^2 \quad (11)$$

Table 1
Analysis of Variance (ANOVA) for Size and Encapsulation efficiency (EE %).



Analysis of Variance for Size					
Source	Ss.	Df.	Ms.	*F*-value	*p*-value
A: Chitosan	1.4•10^6	1	1.4•10^6	196.4	0.0008
B: Homogenization time	63242.7	1	63242.7	9.2	0.0565
AA	4802.0	1	4802.0	0.7	0.4655
AB	2450.3	1	2450.3	0.4	0.593
BB	800.0	1	800.0	0.1	0.756
Total error	20710.4	3	6903.5		
Total	1.5•10^6	8			

Analysis of Variance for Encapsulation efficiency (%)					
Source	Ss.	Df.	Ms.	*F*-value	*p*-value
A: Chitosan	39.7	1	39.7	100.3	0.002
B: Homogenization time	7.1	1	7.1	18.0	0.024
AA	10.5	1	10.5	26.5	0.014
AB	1.9	1	1.9	4.9	0.115
BB	2.7	1	2.7	6.7	0.081
Total error	1.2	3	0.4		
Total	226.2	8			

SS: Sum of squares; Df.: Degrees of freedom, Ms: Mean square

From the presented models, it was determined that the optimal particle size achieved was 424.9 nm. Likewise, an optimal value of 70.0 % encapsulation efficiency was obtained. The statistical analysis of variance (ANOVA) revealed that, in relation to encapsulation efficiency, the factors of chitosan concentration and homogenization time had a significant influence. In contrast, only the concentration of chitosan had a significant effect on particle size.

Table 1 show the analysis of variance to optimize particle size and encapsulation efficiency of the liposomal formulations. In the case of particle size, the results show that the main effect of chitosan concentration is highly dominant (F = 196.4; p = 0.0008), representing virtually all of the variance explained in the model (1.4 × 10^6 sum of squares). In contrast, both the A × B interaction (F = 0.4; p = 0.593) and the quadratic terms (AA and BB) have very low sums of squares compared to the error (2450.3, 4802.0, and 800.0 vs. 20710.4), indicating that their effects are marginal within the selected experimental space. This suggests that the system's response to particle size is primarily controlled by the increasing thickness of the polymer layer, and that this response does not depend on the homogenization time in a combined manner. Similarly, for encapsulation efficiency, the main effects again account for most of the explained variability: chitosan concentration is highly significant (F = 100.3; p = 0.002), and homogenization time also contributes significantly (F = 18.0; p = 0.024). However, the A × B interaction (F = 4.9; p = 0.115) and the quadratic term B^2 (F = 6.7; p = 0.081) do not reach statistical significance. This is attributed to the fact that the mechanism for increasing EE

% is primarily associated with the direct increase in polymer coating thickness (main effect A), while homogenization time modifies efficiency through an independent mechanism associated with dispersion and mechanical stabilization. Since both processes act additively and not synergistically, the interaction does not emerge as significant within the evaluated experimental range.

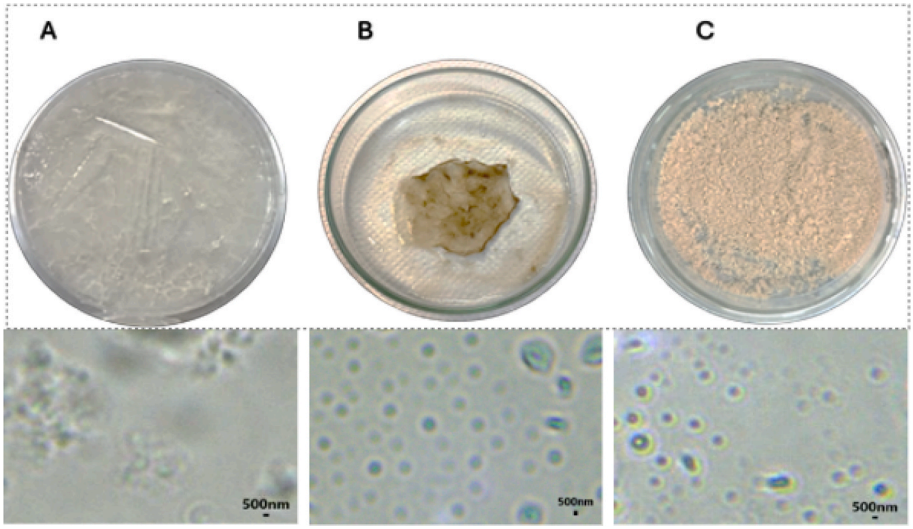
Statistical analysis indicated that the optimal conditions for obtaining the smallest particle size along with high encapsulation efficiency corresponded to 0.1 % chitosan and 10 min of homogenization. Both particle size and encapsulation efficiency are determining properties for the stability, half-life, and bioaccessibility of liposomes (Shaker et al., 2017). At this concentration, chitosan increased the particle size to values between 479.94 and 696.81 nm and increased the encapsulation efficiency from 54.03 % to 61.31 %, demonstrating that the polymeric layer reduces the permeability of the lipid bilayer and promotes the retention of the bioactive compound. At higher concentrations (0.5 % and 1 %), a more marked increase in particle size was observed, reaching up to 1654.96 nm, while encapsulation efficiency continued to increase, reaching 69.62 % under the highest concentration and homogenization time conditions. These results confirm that increasing the chitosan concentration generates larger particles due to the thickening of the polymer layer, but also significantly improves the retention of the encapsulated active ingredient. Similar trends have been previously reported. Li et al. (2024) observed an increase in both particle size (217.27 ± 1.18 to 379.60 ± 9.23 nm) and encapsulation efficiency (66.60 ± 2.19 to 68.07 ± 1.76) when the chitosan concentration was increased to 4.5 mg/mL. Similarly, Kasapoğlu, Gültekin-Özgüven, et al. (2024) reported an increase from 95.4 ± 0.8 nm to 124.7 ± 1.6 nm when chitosan was increased from 0.1 % to 0.5 %. Consistently, Ma et al. (2022) demonstrated that increasing chitosan can raise the particle size from 97 nm to over 500 nm, while encapsulation efficiency increases from 74.66 % to 87.21 %, reaffirming its role in stabilizing and protecting the active compound. Although higher chitosan concentrations showed further improvements in encapsulation efficiency, the selection of 0.1 % as the optimal formulation was not based solely on maximizing encapsulation efficiency (EE %), but rather on achieving a balance between particle size, efficiency, colloidal stability, and applicability in food matrices. Particles larger than 1 μm, such as those generated with 0.5–1 % chitosan, can be advantageous in systems whose primary objective is to maximize the protection of the bioactive ingredient; however, they present disadvantages in applications where diffusion, colloidal stability, bioavailability, or gastrointestinal behavior are critical. Therefore, the RSM model determined that 0.1 % chitosan and 10 min of homogenization represent the best compromise within the evaluated experimental range. For this reason, the optimal formulation is the most suitable for applications requiring moderate particle sizes and good stability, such as functional beverages (Jara-Quijada et al., 2025).

The increase in particle size with higher chitosan concentrations can be mechanistically explained by the progressive formation of a thicker polymeric shell around the liposomal bilayer. Chitosan, being a cationic polysaccharide, interacts electrostatically with the negatively charged phospholipid head groups, promoting multilayer deposition (Sebaaly et al., 2021). This results in larger hydrodynamic diameters and reduced bilayer permeability. Additionally, encapsulation efficiency increases because the denser chitosan network decreases diffusion losses and stabilizes the vesicle structure (Esposto et al., 2021). In contrast, homogenization time affects EE % through a mechanical mechanism, improving droplet breakdown and facilitating the distribution of chitosan over the vesicle surface, but without substantially altering the polymer–lipid interactions that determine particle size (Mankan et al., 2025).

3.2. *Physicochemical and antioxidants properties of powder obtained by drying*

Table 2 compares liposomal powders obtained by different drying methods, both at the macroscopic and microscopic levels, based on the optimized formulation. The macrostructure of FD resembles a fibrous mesh, whereas the VMD dried product presents morphology more like

Table 2
Morphology of liposomes subjected to A) Freeze-Drying, B) *Vacuum Microwave Drying, and C)* Spray Drying Properties of liposomal (0.1 % chitosan) powders obtained by drying.



Drying technology	Size (nm)	PDI	Moisture	Solubility	TPC (mg/g GAE)	AC (%)
FD	606.40 ± 30.15^{a}	0.26 ± 0.05^{a}	1.43 ± 0.18^{a}	74.46 ± 1.70^{a}	517.83 + 6.97^{a}	40.64 + 0.65^{a}
VMD	1128.83 ± 99.55^{b}	0.18 ± 0.07^{a}	1.92 ± 0.00^{b}	92.33 ± 1.20^{b}	417.31 + 3.9^{b}	37.77 + 0.64^{b}
SD	593.15 ± 39.86^{a}	0.22 ± 0.05^{a}	1.26 ± 0.04^{a}	87.36 ± 2.15 ^{b}	432.75 + 2.1^{c}	37.06 + 1.20^{b}

Samples were performed in triplicate. Results are presented as mean ± standard deviation. Different letters indicate significance ($p < 0.05$).

that of a biofilm. In contrast, SD resulted in a granular powder, as expected. For VMD drying, a longer processing time was tested; however, powder formation was not achieved. Morphologically, upon reconstitution, the FD products presented aggregates, whereas those from vacuum microwave drying and spray drying showed better distribution and dispersion of liposomes in water. This analysis highlights the differences in the physical and structural properties of the products obtained by the various drying methods studied. Particle size and PDI are important in the characterization of liposomes, this factor affects the stability and bioactivity of nanoparticles (Nsairat et al., 2022). However, it can change during sample drying and rehydration. Other quality parameters of liposome powders include moisture and solubility, which are crucial for their use in food applications and their stability.

The results obtained indicated that liposomes dried by FD and SD had a smaller particle size compared to those obtained by VMD. Ma et al. (2022) reported that the FD process caused an increase in the particle size of liposomes with chitosan at low concentrations (0.25 % and 0.5 %). This aligns with our findings, where the size changed from 389.9 ± 181.0 nm to 606.40 ± 30.15 nm when applying FD. This behavior can be attributed to the fusion and aggregation of liposomes during FD, as well as the expansion of bilayers during reconstitution (Marín et al., 2018). Regarding SD, Kasapoğlu, Gültekin-Özgüven, et al. (2024) observed an increase in particle size for *Rosa pimpinellifolia* extract encapsulated in SD chitosan-loaded liposomes, from 107.8 ± 2.2 nm to 406.7 ± 47.6 nm after reconstruction. These results agree with our data. Concerning VMD, no previous studies in this application have been identified. A review by Franzé et al. (2018) explains the relationship between humidity and solubility in freeze-dried liposomes. They noted that FD helps control residual humidity, which is crucial for maintaining the stability of bioactive materials, but residual humidity can negatively impact solubility and stability. Misra et al. (2009) suggested that freeze-drying can influence liposome solubility, with the phase transition temperature (Tm) of lipid membranes being adjustable to enhance the penetration of protective agents, often by pre-cooling the formulation to Tm. Jensen (2017) mentioned that a lower drying temperature can benefit solubility by reducing crystal formation and improving rehydration, a concept also supported by Chen et al. (2010), regarding vacuum pressure. All samples showed significant differences, with vacuum microwave dehydration exhibiting the highest solubility. Pashazadeh et al. (2021) compared nanoparticle drying methods; FD, conventional microwave (MW), and SD end found humidity levels under 2 % in all three, which is like our results (FD: 1.43 ± 0.18, VMD: 1.92 ± 0.00, and SD: 1.26 ± 0.04). They achieved solubility greater than 90 % (MW: 99.95 ± 0.070, FD: 90.45 ± 0.91, and SD: 99.95 ± 0.070). Our results were somewhat lower: FD, 74.46 ± 1.70; MW, 92.33 ± 1.20; and SD, 87.36 ± 2.15. FD showed the highest total polyphenol content (517.83 ± 6.97 mg GAE/g), followed by MW (432.75 ± 2.10 mg GAE/g) and SD (417.31 ± 3.94 mg GAE/g). Regarding antioxidant capacity, FD had the highest value (40.64 ± 0.65 %), followed by VMD (37.77 ± 0.64 %) and SD (37.06 ± 1.20 %).

The observed differences between drying technologies can be explained by the distinct physical and thermal mechanisms involved. In freeze-drying, freezing induces ice crystal formation that disrupts liposomal packing, while sublimation creates porous matrices that promote aggregation upon rehydration (Rahim et al., 2025). In VMD, rapid volumetric heating by microwaves causes localized pressure gradients and accelerated water removal, which can destabilize bilayer integrity and promote vesicle fusion (Sajini & Joseph, 2025). Spray drying, in contrast, forms a rigid protective matrix during rapid droplet drying, limiting vesicle movement and preventing aggregation, which explains the smaller reconstituted particle size (Dattani et al., 2025).

These findings demonstrate how drying method significantly influences the structural integrity, solubility, and bioactive compound retention of chitosan-coated liposomes, highlighting freeze-drying as the most effective technique for preserving polyphenolic content and antioxidant capacity.

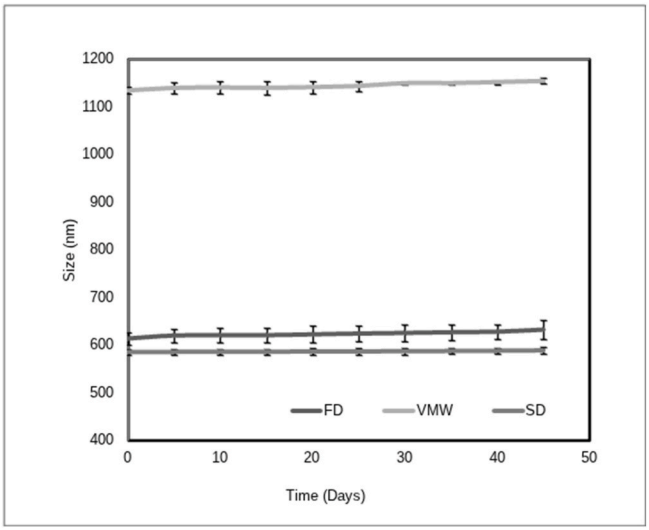


Fig. 2. Evolution of the particle size of liposomes obtained by freeze-drying (FD), vacuum microwave drying (VMD), and spray drying (SD) during 45 days of storage.

3.3. Stability of liposomes in storage

Fig. 2 shows the variation in liposome particle size as a function of storage time for the three drying techniques evaluated. In all cases, a general trend towards increased size over time is observed, suggesting processes of aggregation or partial fusion of vesicles associated with structural relaxation phenomena of the lipid bilayer (Jovanović et al., 2025). The liposomes obtained by FD had an initial size of 613.7 nm, increasing slightly to 632.3 nm on day 45. This change, close to 3 %, indicates good physical stability of the system, although the freezing and sublimation process can induce some reorganization of the phospholipid bilayer after rehydration. In the case of drying by VMD, the particle size showed higher values from the beginning (1133.9 nm) and a moderate increase to 1153.8 nm. This behavior could be attributed to the thermal and pressure stresses generated during the rapid elimination of water, which favor coalescence or the formation of multilamellar structures (Zhong et al., 2024). In contrast, liposomes obtained by SD remained practically stable over time, ranging from 585.2 to 588.8 nm. The increase in size during storage is consistent with classical mechanisms of colloidal instability, including reduced electrostatic repulsion, bilayer relaxation after rehydration, and van der Waals-induced aggregation. FD liposomes show moderate growth due to partial bilayer reorganization caused by freezing stress (Mankan et al., 2025). VMD liposomes experience greater instability due to structural imperfections generated by microwave-induced thermal gradients. SD liposomes remain the most stable because the dried matrix restricts molecular mobility and prevents vesicle–vesicle contact (Dattani et al., 2025).The minimal variation observed (<1 %) evidence high stability, attributed to the formation of a solid protective matrix that limits molecular mobility and prevents aggregation during storage.

3.4. Energy consumption and GHG emission factors of drying processes

The environmental impact of food processing methods, such as drying, is gaining increasing attention due to their energy consumption and resource use (Pérez-Won et al., 2024). New drying technologies are expected to offer advantages, including improved energy efficiency, enhanced product quality, reduced costs, and a lower environmental footprint (Dattani et al., 2025). However, the adoption of these methods in the food industry depends on a delicate balance between performance, implementation cost, and the emissions associated with each technology.

Table 3
Energy parameters and of drying treatments of Liposome.

Treatment	Consumption (kWh)	SEC (kWh/kg)	MER (kg/h)
SD	1.88 ± 0.00[b]	122.18 ± 0.04[b]	5.54 ± 0.00[a]
FD	22.34 ± 0.00[a]	1451.38 ± 0.57[a]	0.01 ± 0.00[c]
VMD	0.18 ± 0.00[c]	11.37 ± 0.00[c]	0.03 ± 0.00[b]

Treatment	CO_2 emissions (kg/h)	CO_2 emissions (kg/kg)	η_{th} (%)	η_e (%)
SD	1.33 ± 0.00[b]	86.63 ± 0.03[b]	60.61 ± 0.00[b]	9.44 ± 0.05[b]
FD	15.84 ± 0.00[a]	1029 ± 0.40[a]	21.79 ± 0.10[c]	3.12 ± 0.02[c]
VMD	0.12 ± 0.00[c]	8.06 ± 0.68[c]	69.20 ± 0.42[a]	39.11 ± 0.22[a]

Different letters in the same showed significant differences ($p < 0.05$). FD freeze-drying, VMD vacuum microwave drying, SD spray dry, SEC specific energy consumption, MER moisture extraction rate.

Table 3 shows the energy consumption of the three drying technologies, with significant differences between the samples ($p < 0.05$). FD treatment had the highest consumption for liposome drying, at 22.34 kWh, which is 99.19 % more than the lowest drying process (VMD). The SD drying process had an intermediate value of 1.88 kWh. SEC relates the energy consumption value per kg of water removed during the drying process. There were significant differences ($p < 0.05$) between the drying technologies, with values showing similar trends to energy consumption, where FD > SD > VMD, with FD being the highest value. Boateng et al. (2021) mentioned that FD technology requires high energy consumption to generate sublimation during the drying process. The samples treated by VMD had the lowest SEC value (11.37 kWh/kg). On the other hand, the SEC value obtained by SD is within the range of values reported by Bimbenet et al. (2002), who dried skim milk under similar treatment conditions (≈190 °C).

The MER measures the amount of moisture (kg) removed during the drying time (Boateng et al., 2021). The MER results described in Table 3 show that SD treatment has a significantly higher value than other drying technologies. SD is a significantly faster drying process, capable of processing materials in minutes or seconds (Ledri et al., 2024). It is more energy efficient than the FD process, but less so than VMD. According to Laina et al. (2024), it has a lower cost than other drying methods (FD) and produces consistently with acceptable quality (Ledri et al., 2024; Laina et al., 2024).

The drying processes can consume much energy and, as a result, emit a large volume of CO_2 into the environment (Pérez-Won et al., 2023). Table 3 shows the results of CO_2 emissions during the drying time and the amount of CO_2 emitted per volume of water removed. The results show that FD generated the highest CO_2 emissions compared to VMD and SD, achieving 99.24 % more than the lowest emission value (0.12 $kgCO_2/h$). VMD technology had the lowest value for both CO_2 emissions during the drying time and the amount of CO_2 emitted per volume of water removed.

Finally, the results show that FD generated the highest carbon emissions compared to vacuum microwave drying and spray drying, particularly when carbon-based electricity was used. Each technology exhibits distinct characteristics in nanoparticle production: FD is the slowest method, taking several hours to days, and involves high energy consumption due to freezing (not included in this study) and sublimation stages. This results in elevated implementation and operational costs. VMD is a faster method and, although it requires significant power for both the microwave and vacuum pump, it substantially reduces processing time. However, limitations in sample volume and drying uniformity persist. SD, by contrast, is significantly quicker capable of processing materials in minutes or even seconds. It is more energy-efficient, has a lower implementation cost, and consistently produces powders of acceptable quality, as previously reported (Drosou & Krokida, 2024; Laina et al., 2024; Ledri et al., 2024).

3.5. Thermodynamic parameters

Table 3 also shows the η_e and η_{th} values of the drying treatments. For both η_e and η_{th}, the samples showed significant differences between them ($p < 0.05$). The η_e values for VMD were >30 %, significantly higher than other treatments. The Authors report similar η_e values during the VMD drying process for onion slices: 14.3–51.9 % (Taner, 2023), tomato slices 14–26 % (Alvi et al., 2023), and cranberries (Sunjka et al., 2004). The samples treated by SD had a mean η_e value, which was 75.86 % lower than the value obtained by VMD and 66.94 % higher than the FD treatment. Sim et al. (2023) mentioned in their research that the major problem with SD technology is the η_{th} and η_e values, as they are typically low compared to other drying methods (HAD and VMD). On the other hand, the samples dried by FD had the lowest value (3.12 %) compared to the other drying methods. For η_{th} the values show similar behavior to η_e Values ranging from 21.79 to 69 % were obtained, with the following order: VMD > SD > FD, showing significant differences between them ($p < 0.05$). Mousa and Farid (2002) mentioned in their research that high moisture extraction in a food matrix is the result of good heat transfer, achieving good η_{th} values: Samples treated with VMD achieved a η_{th} value > 60 %, with similar values obtained for samples treated with SD. Bimbenet et al. (2002) highlighted that the SD process can present low η_e values but high η_{th} values. Samples treated with FD have the lowest η_{th} value, corresponding to 21.79 %. Martynenko and Vieira (2023) relate SEC and η_{th} values, which are inversely proportional indicators in the case of the FD process, where a high SEC value is shown: 1451.38 kWh/kg, but with low η_e and η_{th} reflecting that of the SEC value, only 316.25 kWh/kg were used for the heat transfer process, and the difference in value (1135.13 kWh/kg) was used to carry out the process operation (freezing, vacuum, etc.) (Martynenko & Vieira, 2023).

4. Conclusion

The study identified the optimal formulation of chitosan-coated liposomes for polyphenol encapsulation, which was obtained using a chitosan concentration of 0.1 % and a homogenization time of 10 min. These conditions maximize encapsulation efficiency and minimize particle size. Regarding drying methods, FD showed greater polyphenol retention, although it resulted in a relatively high moisture content. On the other hand, VMD allowed for a significant reduction in processing time and lower CO_2 emissions, in addition to decreasing particle size and achieving a low moisture content; however, macroscopically, it did not behave like a powder. SD achieved the greatest reduction in particle size, exhibiting low moisture content, high solubility, and long-term stability, making it the most viable option for industrial applications. Morphologically, it behaved like a powder, despite its higher energy consumption compared to VMD. In terms of environmental impact, spray drying has a lower carbon footprint than FD. Although spray drying may be slightly more energy-intensive, it is more practical and scalable for industrial use. Therefore, the choice of drying method will depend on the balance between sustainability, efficiency, and scalability sought in the production of liposomal functional ingredients. It is recommended that future studies optimize each technology separately using an experimental design that considers other variables such as temperature, vacuum pressure, and microwave power, depending on the specific technology.

CRediT authorship contribution statement

Erick Jara-Quijada: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Paulina Muñoz-Muñoz:** Investigation. **Mario Pérez-Won:** Writing – review & editing, Writing – original draft. **Carla Vidal-San Martín:** Investigation. **Horacio Fraguela-Meissimilly:** Investigation. **Marcia Cabrera-Pérez:**

Investigation. **Luis González-Cavieres:** Writing – original draft, Investigation. **Tatiana Beldarrain-Iznaga:** Investigation. **Mario Gonzales-Santos:** Writing – review & editing.

Funding

The study was funded by the National Agency for Research and Development of the Ministry of Science, Technology, Knowledge and Innovation of Chile (Project VIU23P0038).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

All authors thank God and the National Research and Development Agency, through the Subdirectorate of Applied Research, University Research Valorization Program, Project VIU23P0038, Chile.

Data availability

Data will be made available on request.

References

Akgün, D., Gültekin-Özgüven, M., Yücetepe, A., Altin, G., Gibis, M., Weiss, J., & Özçelik, B. (2020). Stirred-type yoghurt incorporated with sour cherry extract in chitosan-coated liposomes. *Food Hydrocolloids, 101*, Article 105532. https://doi.org/10.1016/j.foodhyd.2019.105532

Alara, O. R., & Abdurahman, N. H. (2019). Kinetics studies on the effects of extraction techniques on bioactive compounds from Vernonia cinerea leaf. *Journal of Food Science and Technology, 56*(2), 580–588. https://doi.org/10.1007/s13197-018-3512-4

Alvi, T., Khan, M. K. I., Maan, A. A., Rizwan, M., Aamir, M., Saeed, F., Ateeq, H., Raza, M. Q., Afzaal, M., & Shah, M. A. (2023). Microwave–vacuum extraction cum drying of tomato slices: Optimization and functional characterization. *Food Science and Nutrition, 11*(7), 4263–4274. https://doi.org/10.1002/fsn3.3352

Ang, S. S., Devkota, L., Dhital, S., Thoo, Y. Y., & Siow, L. F. (2024). Functional mango juice with apigenin encapsulated in spray-dried chitosan-coated liposomes: Characterisation, in-vitro gastrointestinal release, sensory acceptance, and storage stability. *LWT.* , Article 116361. https://doi.org/10.1016/j.lwt.2024.11636

Ang, S. S., Thoo, Y. Y., & Siow, L. F. (2024). Encapsulation of hydrophobic apigenin into small unilamellar liposomes coated with chitosan through ethanol injection and spray drying. *Food and Bioprocess Technology, 17*(2), 424–439. https://doi.org/10.1007/s11947-023-03140-y

Banožić, M., Vladić, J., Banjari, I., Velić, D., Aladić, K., & Jokić, S. (2023). Spray drying as a method of choice for obtaining high quality products from food wastes–A review. *Food Reviews International, 39*(4), 1953–1985. https://doi.org/10.1080/87559129.2021.1938601

Banu, A. T., & Lunghar, J. (2023). Cinnamon as a potential nutraceutical and functional foodingredient. *Herbs, Spices and their Roles in Nutraceuticals and Functional Foods, 257*, 278. https://doi.org/10.1016/B9780323907941.000211

Bimbenet, J., Schuck, P., Roignant, M., Brulé, G., & Méjean, S. (2002). Article. *Dairy Science & Technology, 82*(4), 541–551. https://doi.org/10.1051/lait:2002031

Boateng, I. D., Soetanto, D. A., Yang, X., Zhou, C., Saalia, F. K., & Li, F. (2021). Effect of pulsed-vacuum, hot-air, infrared, and freeze-drying on drying kinetics, energy efficiency, and physicochemical properties of Ginkgo biloba L. seed. *Journal of Food Process Engineering, 44*(4). https://doi.org/10.1111/jfpe.13655

Bolat, E., Sarıtaş, S., Duman, H., Eker, F., Akdaşçi, E., Karav, S., & Witkowska, A. M. (2024). Polyphenols: Secondary metabolites with a biological impression. *Nutrients, 16*(15). https://doi.org/10.3390/nu16152550

Calvo, L., & Domingo, R. (2017). CO2 emissions reduction and energy efficiency improvements in paper-making drying process control using sensors. *Sustainability, 9*(4), 514. https://doi.org/10.3390/su9040514

Chen, C., Han, D., Cai, C., & Tang, X. (2010). An overview of liposome Freeze-drying and its future potential. *Journal of Controlled Release, 142*(3), 299–311. https://doi.org/10.1016/j.jconrel.2009.10.024

Chen, F. P., Liu, L. L., & Tang, C. H. (2020). Spray-drying microencapsulation of curcumin nanocomplexes with soy protein isolate: Encapsulation, water dispersion, bioaccessibility and bioactivities of curcumin. *Food Hydrocolloids, 105*, Article 105821. https://doi.org/10.1016/j.foodhyd.2020.105821

Dattani, S., Li, X., Lampa, C., Barriscale, A., Damadzadeh, B., Lechuga-Ballesteros, D., & Jasti, B. R. (2025). Development of spray-dried micelles, liposomes, and solid lipid nanoparticles for enhanced stability. *Pharmaceutics, 17*(1), 122. https://doi.org/10.3390/pharmaceutics17010122

Drosou, C., & Krokida, M. (2024). A comparative study of encapsulation of β-Carotene via spray-drying and freeze-drying techniques using pullulan and Whey protein isolate as wall material. *Foods, 13*(12), 1933. https://doi.org/10.3390/foods13121933

Esposto, B. S., Jauregi, P., Tapia-Blacido, D. R., & Martelli-Tosi, M. (2021). Liposomes vs. chitosomes: Encapsulating food bioactives. *Trends in Food Science & Technology, 108*, 40–48. https://doi.org/10.1016/j.tifs.2020.12.003

Franzé, S., Selmin, F., Samaritani, E., Minghetti, P., & Cilurzo, F. (2018). Freeze-drying of liposomal formulations: Still necessary, still challenging. *Pharmaceutics, 10*(3), 139. https://doi.org/10.3390/pharmaceutics10030139

Ghorbanzade, T., Jafari, S. M., Akhavan, S., & Hadavi, R. (2017). Nano-encapsulation of fish oil in nano-liposomes and its application in fortification of yogurt. *Food Chemistry, 216*, 146–152. https://doi.org/10.1016/j.foodchem.2016.08.022

González-Cavieres, L., Pérez-Won, M., Tabilo-Munizaga, G., Jara-Quijada, E., Díaz-Álvarez, R., & Lemus-Mondaca, R. (2021). Advances in vacuum microwave drying (VMD) systems for food products. *Trends in Food Science & Technology, 116*, 626–638. https://doi.org/10.1016/j.tifs.2021.08.005

Gültekin-Özgüven, M., Karadağ, A., Duman, Ş., Özkal, B., & Özçelik, B. (2016). Fortification of dark chocolate with spray dried Black mulberry (*Morus nigra)* waste extract encapsulated in chitosan-coated liposomes and bioaccessability studies. *Food Chemistry, 201*, 205–212. https://doi.org/10.1016/j.foodchem.2016.01.091

IPCC. (2006). THE IPCC. *Guidelines for national greenhouse gas inventories, prepared by the national green-house gas inventories programme*.

Jara-Quijada, E., Muñoz-Muñoz, P., Pérez-Won, M., González-Cavieres, L., & Rivera-Tobar, D. (2025). Chitosan-coated liposomes loaded with green tea polyphenols incorporated into Apple juice: Characterization, stability, in vitro digestion, and sensory analysis. *Food and Bioprocess Technology*, 1–12. https://doi.org/10.1007/s11947-025-03918-2

Jara-Quijada, E., Pérez-Won, M., Tabilo-Munizaga, G., González-Cavieres, L., & Lemus-Mondaca, R. (2022). An overview focusing on food liposomes and their stability to electric fields. *Food Engineering Reviews, 14*(2), 292–306. https://doi.org/10.1007/s12393-022-09306-2

Jara-Quijada, E., Pérez-Won, M., Tabilo-Munizaga, G., González-Cavieres, L., Palma-Acevedo, A., Herrera-Lavados, C., & Lemus-Mondaca, R. (2024). Polyphenol extraction of green tea through pulsed electric field: Yield improvement and environmental assessment. *Food and Bioprocess Technology, 17*(9), 2718–2734.

Jara-Quijada, E., Pérez-Won, M., Tabilo-Munizaga, G., Lemus-Mondaca, R., González-Cavieres, L., Palma-Acevedo, A., & Herrera-Lavados, C. (2024). Liposomes loaded with green tea polyphenols—optimization, characterization, and release kinetics under conventional heating and pulsed electric fields. *Food and Bioprocess Technology, 17*(2), 396–408. https://doi.org/10.1007/s11947-023-03136-8

Jensen, G. M. (2017). The care and feeding of a commercial liposomal product:liposomal amphotericin B (AmBisome®). *Journal of Liposome Research, 27*(3), 173–179. https://doi.org/10.1080/08982104.2017.1380664

Jovanović, A. A., Petrović, P., Pirković, A., Mitić, N., Giampieri, F., Battino, M., & Dekanski, D. (2025). Ergosterol-enriched liposomes with post-processing modifications for Serpylli Herba polyphenol delivery: Physicochemical, stability and antioxidant assessment. *Pharmaceutics, 17*(11), 1362. https://doi.org/10.3390/pharmaceutics17111362

Joy, J. M., Amruth, P., Dara, P. K., Renuka, V., & Anandan, R. (2023). Liposome mediated encapsulation and role of chitosan on modulating liposomal stability to deliver potential bioactives-A review. *Food Hydrocolloids for Health.* , Article 100142. https://doi.org/10.1016/j.fhfh.2023.100142

Kandasamy, S., & Naveen, R. (2022). A review on the encapsulation of bioactive components using spray-drying and freeze-drying techniques. *Journal of Food Process Engineering, 45*(8), Article e14059. https://doi.org/10.1111/jfpe.14059

Kasapoğlu, K. N., Gültekin-Özgüven, M., Kruger, J., Frank, J., Bayramoğlu, P., Barla-Demirkoz, A., & Özçelik, B. (2024). Effect of spray drying on physicochemical stability and antioxidant capacity of *Rosa pimpinellifolia* fruit extract-loaded liposomes conjugated with Chitosan or whey protein during in vitro digestion. *Food and Bioprocess Technology*, 1–15. https://doi.org/10.1007/s11947-024-03317-z

Kasapoğlu, K. N., Sus, N., Kruger, J., Frank, J., & Özçelik, B. (2024). Fabrication of phenolic loaded spray-dried nanoliposomes stabilized by chitosan and whey protein: Digestive stability, transepithelial transport and bioactivity retention of phenolics. *International Journal of Biological Macromolecules.* , Article 132676. https://doi.org/10.1016/j.ijbiomac.2024.132676

Katouzian, I., & Taheri, R. A. (2021). Preparation, characterization and release behavior of chitosan-coated nanoliposomes (chitosomes) containing olive leaf extract optimized by response surface methodology. *Journal of Food Science and Technology, 58*, 3430–3443. https://doi.org/10.1007/s13197-021-04972-2

Kaveh, M., Abbaspour-Gilandeh, Y., & Nowacka, M. (2021). Comparison of different drying techniques and their carbon emissions in green peas. *Chemical Engineering and Processing: Process Intensification, 160*, Article 108274. https://doi.org/10.1016/j.cep.2020.108274

Laina, K. T., Drosou, C., & Krokida, M. (2024). Comparative assessment of encapsulated essential oils through the innovative electrohydrodynamic processing and the conventional spray drying, and freeze-drying techniques. *Innovative Food Science & Emerging Technologies.* , Article 103720. https://doi.org/10.1016/j.ifset.2024.103720

Ledri, S. A., Milani, J. M., Shahidi, S. A., & Golkar, A. (2024). Comparative analysis of freeze drying and spray drying methods for encapsulation of chlorophyll with maltodextrin and whey protein isolate. *Food Chemistry X, 21*, Article 101156. https://doi.org/10.1016/j.fochx.2024.101156

Li, Q., Ran, C., Chen, J., Jin, J., He, J., Li, Y., & Wang, Q. (2024). Chitosan-coated double-loaded liposomes as a promising delivery system for clove essential oil. *Journal of Food Engineering, 376*, Article 112084. https://doi.org/10.1016/j.jfoodeng.2024.112084

Ma, Y., Xu, J., Jiang, S., & Zeng, M. (2022). Effect of chitosan coating on the properties of nanoliposomes loaded with oyster protein hydrolysates: Stability during spray-drying and freeze-drying. *Food Chemistry, 385*, Article 132603. https://doi.org/10.1016/j.foodchem.2022.132603

Mankan, E., Karakas, C. Y., Saroglu, O., Mzoughi, M., Sagdic, O., & Karadag, A. (2025). Food-grade liposome-loaded delivery systems: Current trends and future perspectives. *Foods, 14*(17), 2978. https://doi.org/10.3390/foods14172978

Marín, D., Alemán, A., Montero, P., & Gómez-Guillén, M. C. (2018). Encapsulation of food waste compounds in soy phosphatidylcholine liposomes: Effect of freeze-drying, storage stability and functional aptitude. *Journal of Food Engineering, 223*, 132–143. https://doi.org/10.1016/j.jfoodeng.2017.12.009

Martynenko, A. A., & Vieira, G. N. A. (2023). Sustainability of drying technologies: System analysis. *Sustainable Food Technology, 1*(5), 629–640. https://doi.org/10.1039/d3fb00080j

Misra, A., Jinturkar, K., Patel, D., Lalani, J., & Chougule, M. (2009). Recent advances in liposomal dry powder formulations: Preparation and evaluation. *Expert Opinion on Drug Delivery, 6*(1), 71–89. https://doi.org/10.1517/17425240802652309

Misra, S., Pandey, P., & Mishra, H. N. (2021). Novel approaches for co-encapsulation of probiotic bacteria with bioactive compounds, their health benefits and functional food product development: A review. *Trends in Food Science & Technology, 109*, 340–351. https://doi.org/10.1016/j.tifs.2021.01.039

Mohammadi, A., Jafari, S. M., Mahoonak, A. S., & Ghorbani, M. (2021). Liposomal/nanoliposomal encapsulation of food-relevant enzymes and their application in the food industry. *Food and Bioprocess Technology, 14*, 23–38. https://doi.org/10.1007/s11947-020-02513-x

Motevali, A., Minaei, S., Banakar, A., Ghobadian, B., & Darvishi, H. (2016). Energy analyses and drying kinetics of chamomile leaves in microwave-convective dryer. *Journal of the Saudi Society of Agricultural Sciences, 15*(2), 179–187. https://doi.org/10.1016/j.jssas.2014.11.003

Mousa, N., & Farid, M. (2002). Microwave vacuum drying of banana slices. *Drying Technology, 20*(10), 2055–2066. https://doi.org/10.1081/drt-120015584

Nsairat, H., Khater, D., Sayed, U., Odeh, F., Al Bawab, A., & Alshaer, W. (2022). Liposomes: Structure, composition, types, and clinical applications. *Heliyon, 8*(5), Article e09394. https://doi.org/10.1016/j.heliyon.2022.e09394

Pashazadeh, H., Zannou, O., Ghellam, M., Koca, I., Galanakis, C. M., & Aldawoud, T. M. (2021). Optimization and encapsulation of phenolic compounds extracted from maize waste by freeze-drying, spray-drying, and microwave-drying using maltodextrin. *Foods, 10*(6), 1396. https://doi.org/10.3390/foods10061396

Pérez-Won, M., González-Cavieres, L., Palma-Acevedo, A., Jara-Quijada, E., Tabilo-Munizaga, G., & Lemus-Mondaca, R. (2024). Vacuum microwave drying of PEF-pretreated Chilean abalone (Concholepas Concholepas) slices: Drying features, sustainability parameters, and protein quality properties. *Food Production, Processing and Nutrition, 6*(1), 21. https://doi.org/10.1186/s43014-023-00202-8

Pérez-Won, M., González-Cavieres, L., Palma-Acevedo, A., Tabilo-Munizaga, G., Jara-Quijada, E., & Lemus-Mondaca, R. (2023). Pulsed electric fields as pretreatment for different drying methods in Chilean abalone (Concholepas concholepas) mollusk: Effects on product physical properties and drying methods sustainability. *Food and Bioprocess Technology, 16*(12), 2772–2788. https://doi.org/10.1007/s11947-023-03102-4

Rahim, M. A., Zahran, H. A., Jaffar, H. M., Ambreen, S., Ramadan, M. F., Al-Asmari, F., … Zongo, E. (2025). Liposomal encapsulation in food systems: A review of formulation, processing, and applications. *Food Science and Nutrition, 13*(8), Article e70587. https://doi.org/10.1002/fsn3.70587

Sajini, T., & Joseph, J. (2025). Microwave-assisted synthesis of nanomaterials: A green chemistry perspective and sustainability assessment. *RSC Sustainability, 3*(11), 4911–4935. https://doi.org/10.1039/D5SU00584A

Savaghebi, D., Ghaderi-Ghahfarokhi, M., & Barzegar, M. (2021). Encapsulation of sargassum boveanum algae extract in nano-liposomes: Application in functional mayonnaise production. *Food and Bioprocess Technology, 14*, 1311–1325. https://doi.org/10.1007/s11947-021-02638-7

Sebaaly, C., Trifan, A., Sieniawska, E., & Greige-Gerges, H. (2021). Chitosan-coating effect on the characteristics of liposomes: A focus on bioactive compounds and essential oils: A review. *Processes, 9*(3), 445. https://doi.org/10.3390/pr9030445

Shaker, S., Gardouh, A. R., & Ghorab, M. M. (2017). Factors affecting liposome particle size prepared by the ethanol injection method. *Research in pharmaceutical sciences, 12*(5), 346–352. https://doi.org/10.4103/1735-5362.213979

Sim, J. W., Lee, H., Jo, S., Oh, S., Kim, S., & Kim, D. R. (2023). Increasing energy saving of pilot-scale spray dryers with enhanced yield by low-adhesive surfaces. *Case Studies in Thermal Engineering, 49*, Article 103218. https://doi.org/10.1016/j.csite.2023.103218

Sumathi, R., Punitha, S., Tamizharasi, S., Sivakumar, T., & Jeyaprakash, R. (2021). Formulation and characterization of soya lecithin-based liposomes for encapsulating a weakly soluble naringenin. *Journal of Medical Pharmaceutical and Allied Sciences, 10*, 2018–4023. https://doi.org/10.22270/jmpas.V10I6.2560

Sunjka, P. S., Rennie, T. J., Beaudry, C., & Raghavan, G. S. V. (2004). Microwave-convective and microwave-vacuum drying of cranberries: A comparative study. *Drying Technology, 22*(5), 1217–1231. https://doi.org/10.1081/drt-120038588

Taner, O. O. (2023). Vacuum freeze dryer technology for extending the shelf life of food and protecting the environment: A scenario study of the energy efficiency. *Environmental Science and Pollution Research, 31*(27), 38573–38584. https://doi.org/10.1007/s11356-023-30398-8

Torki-Harchegani, M., Ghanbarian, D., Pirbalouti, A. G., & Sadeghi, M. (2016). Dehydration behaviour, mathematical modelling, energy efficiency and essential oil yield of peppermint leaves undergoing microwave and hot air treatments. *Renewable and Sustainable Energy Reviews, 58*, 407–418. https://doi.org/10.1016/j.rser.2015.12.078

Vega, G. C., Sohn, J., Voogt, J., Birkved, M., Olsen, S. I., & Nilsson, A. E. (2021). Perspectives on combining techno-economic and life cycle assessment: A case study of polyphenol extraction from red wine pomace. *Resources, Conservation and Recycling, 167*, Article 105318. https://doi.org/10.1016/j.resconrec.2020.105318

Waterhouse, A. L. (2002). Determination of total phenolics. *Current Protocols in Food Analytical Chemistry, 6*(1), I1–I.

Zhang, F., Cao, C., Kong, B., Sun, F., Shen, X., Yao, X., & Liu, Q. (2022). Pre-dried mealworm larvae flour could partially replace lean meat in frankfurters: Effect of pre-drying methods and replacement ratios. *Meat Science, 188*, Article 108802. https://doi.org/10.1016/j.meatsci.2022.108802

Zhong, W., Hu, D., Chen, Y., & Zhao, L. (2024). Microwave-assisted physical foaming of polymers: A review. *Polymer Reviews, 64*(4), 1136–1175. https://doi.org/10.1080/15583724.2024.2372492