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Multi-response evaluation of encapsulated pandan leaf powder under different drying and wall material conditions

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ABSTRACT

Pandan (*Pandanus amaryllifolius*) leaf extract contains high amounts of bioactive compounds; however, its stability is compromised during processing, limiting its broader use in functional foods. This study aimed to optimize encapsulation techniques to improve the physicochemical properties, bioactive retention, and functional efficacy of pandan extract powder. A 3×3 full-factorial experimental design was applied, involving three drying methods (spray-drying, freeze-drying, and drum-drying) and three wall materials (maltodextrin, soy protein isolate, and egg white powder). Several quality indicators were determined, such as moisture content, water activity, solubility, encapsulation efficiency, color properties, total chlorophyll, and β-carotene, as well as antioxidant activity (DPPH, FRAP, and ABTS assays). Results demonstrated that freeze-drying combined with soy protein isolate produced powders with the highest encapsulation efficiency (76.42%), accompanied by antioxidant activity (FRAP: 64.53 µM $FeSO_4$/g; ABTS: 88.81%) and a low water activity (0.337), showing improved stability. Spray-drying using egg white powder provided excellent solubility and a high level of encapsulation efficiency. Drum-drying proved to be the least effective procedure. Multi-response optimization was performed by principal component analysis (PCA) combined with the desirability function, which revealed the optimum condition of freeze-drying using soy protein isolate. These findings provide a valuable decision-making framework for selecting drying techniques and wall materials to develop high-quality, shelf-stable, and antioxidant-rich functional powders. The practical implication of this study is its potential to guide the food and nutraceutical industries in producing standardized pandan-based products with enhanced bioefficacy and market potential.

Contribution/Originality: This study contributes to the existing literature by optimizing encapsulation conditions for *Pandanus amaryllifolius* extract using multivariate analysis. It employs a novel estimation methodology that combines PCA and desirability functions. This research is among the few that have investigated the triple interaction of drying method, wall material, and antioxidant retention.

1. INTRODUCTION

Pandan leaves (*Pandanus amaryllifolius*) are esteemed for their unique pigmentation, taste, and fragrance within various Southeast Asian culinary traditions, wherein primarily fresh and powdered variants are utilized. Techniques for encapsulation have been investigated for their prospective influence on prolonging the shelf life as well as safeguarding the functional attributes of pandan powder, which are fundamentally significant for preserving both sensory and nutritional integrity throughout storage and transit (Goula & Adamopoulos, 2012; Loh, Che Man, Tan, Osman, & Hamid, 2005). This is critically significant in the encapsulation of pandan, as the flavor, color, and bioactives can be easily influenced by environmental conditions that tend to degrade them (Yaman et al., 2023).

Encapsulation through drying techniques offers a means to preserve the functionality and stability of pandan leaf extracts (Adhamatika, Murtini, & Sunarharum, 2021). Among various techniques, spray-drying is favored for its cost-effectiveness and scalability, while freeze-drying is recognized for superior bioactive retention. Drum-drying, though less explored, offers economic advantages. Equally critical is the choice of wall materials. Polysaccharides such as maltodextrin (MD) provide excellent film-forming and stabilizing properties, whereas proteins like soy protein isolate (SPI) and egg white powder (EWP) offer emulsifying, antioxidant-binding, and protective characteristics during thermal stress (Ploypetchara et al., 2021; Tang & Li, 2013). SPI, a plant-based protein, offers emulsifying and film-forming capabilities, making it a promising encapsulation agent (Tang & Li, 2013). Despite growing interest in pandan-based functional ingredients, comparative studies that systematically investigate the combined effects of different drying methods and wall materials on powder quality are limited (Zabot et al., 2022). Prior work has either focused on a single drying technique or evaluated encapsulation agents in isolation, without exploring factorial interactions that influence encapsulation efficiency, pigment retention, or antioxidant activity (Son, Luynh, & Minh, 2023).

Recent research has also investigated the encapsulation of herbal extracts beyond pandan. The effectiveness of these techniques depends on the drying methods and the choice of wall materials, which influence physicochemical stability, antioxidant activity, and retention of bioactive compounds. For instance, using maltodextrin in spray-drying enhanced secondary metabolite retention and oxidative stability of microencapsulated yerba mate extract (Fenoglio et al., 2021). Likewise, their protein-based wall materials, such as whey and SPI, increased the encapsulation efficiency and stability of green tea and other herbal extracts (Mazár et al., 2025). Studies have also reported the enhancement of antioxidant activity by the spray-dried curcumin nanocomplex with SPI (Chen, Liu, & Tang, 2020). Additionally, freeze-drying citrus by-product extracts with maltodextrin combined with soy protein or ι-carrageenan retained their antioxidant capacity better than spray-drying (Papoutsis et al., 2018). These results demonstrate that each herbal extract should be encapsulated individually, depending on the targets, to maximize the functional properties of the final powdered products. Emerging optimization approaches have enabled precise control over bioactive retention in processed systems (Chamsai & Wanyo, 2025), motivating this study's multi-response framework to reconcile quality and scalability.

This study addresses this knowledge gap by employing a full-factorial experimental design to optimize pandan leaf powder encapsulation using three drying methods (spray-drying, freeze-drying, and drum-drying) and three wall materials (MD, SPI, and EWP). The experimental analysis employed both desirability function and principal component analysis (PCA) for multi-response optimization to determine the best operating conditions for maximizing powder quality, functional compound retention, and antioxidant capacity. The research aims to create an efficient production process for pandan leaf powder as a functional food ingredient while maximizing its stability and bioactivity properties.

2. MATERIALS AND METHODS

2.1. Materials

Wall materials used for the study were maltodextrin (MD, DE 10), soy protein isolate (SPI, 90% protein), and egg white powder (EWP), which were obtained from Krungthepchemi Co., Ltd. (Bangkok, Thailand). The majority of chemicals in this study, such as 2,2-diphenyl-1-picrylhydrazyl (DPPH), modified 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), 2,4,6-tris(2-pyridyl)-s-triazine (TPTZ), Folin-Ciocalteu reagent, chlorophyll, and β-carotene, were supplied by Merck (Darmstadt, Germany). Other analytical-grade chemicals and solvents were used.

Pandan (*Pandanus amaryllifolius*) leaves were sourced from the local market of Kalasin Province, Thailand (July 2023). The pandan leaves were cleaned, drained, and then cut into small pieces of about 1 cm x 5 cm. The raw pieces of leaves were homogenized with distilled water in a mechanical blender under room temperature conditions twice, 1 min each time. The ratio of the blended leaf sample and the water was 1:2 (w/v). The mixtures were subsequently put through a 300-micron stainless steel mesh funnel. The filtrate was kept in screw-capped bottles at refrigerator temperature (4 °C) until used.

2.2. Encapsulation Procedure

Three different types of wall materials were tested: MD, SPI, and EWP. Pandan extract was mixed with each wall material (5% w/w for MD, SPI, and EWP) and processed using three drying methods.

The procedure for spray-drying involved dispersing the core material in an encapsulation material, atomizing the mixture, and then spraying the mixture into a chamber using a hot-air desiccant. A Buchi Mini spray dryer (B-290) was used to spray dry the encapsulated solutions. The spray dryer was operated with the input temperature set between 90 and 102 °C. The feeding rate was 10 mL/min, the atomization pressure was 25 psi, and the airflow was 700 L/h. The end product was powdered pandan leaf encapsulation.

A laboratory freeze dryer (Labconco FreeZone 6 L) was used to perform the freeze-drying process. Before being placed in the freeze dryer, the samples were kept at -25°C for three hours. The dryer was configured with a 20 Pa vacuum pressure, a 20°C plate temperature, and a -50°C condenser temperature. To ensure they were completely dried, they were then freeze-dried for two days. The finished product was in powdered form.

This experiment utilized a double-drum laboratory dryer, each measuring 40 cm in length and 30 cm in diameter. The input steam pressure was controlled to regulate the surface drum temperature of the double-drum dryer, which was heated using saturated steam. The steam pressure was set to 2 bar, the drum gap was set to 0.4 mm, and the drum dryer was set to rotate at 2 rpm. The temperature of the drum's surface was 130 ± 5 °C. The blades on each drum scraped and dried three separate solutions containing encapsulating agents, namely MD, SPI, and EWP, until a powder was formed. Due to the general similarity in appearance and moisture content, the dried product obtained from the two drums was taken together for examination.

All drying processes yielded powder, which was stored in airtight containers for further characterization.

2.3. Characterization of Powders

2.3.1. Powder Stability Metrics

The Association of Official Analytical Chemists' official procedures were followed in determining the moisture content of dried powders (Association of Official Analytical Chemists, 2005). A water activity meter (AquaLab 3TE, Decagon Devices, USA) was used to measure the water activity (a_w). The water solubility test was carried out repeatedly using the procedures outlined by De Marcoa, Vieiraa, Ugrib, Monteiro, and Bergamasco (2013). Distilled water was mixed with pandan powder to create a 1% w/v solution. The mixture was centrifuged for 5 minutes at 3000 rpm. After being deposited on Petri plates, the supernatant was heated to 105 °C for 5 hours in a circulating air oven. The following formula was used to determine the solubility.

$$\text{Solubility (\%)} = \frac{m_s\,(g)}{m_p\,(g)} \times 100 \quad (1)$$

Where m_s is the mass (g) of powdered extract obtained by drying the supernatant to constant weight, and m_p is the mass (g) of powdered extract taken for analysis.

2.3.2. Process Yield

For industrial food processing, process yield is a critical performance indicator reflecting the efficiency of the encapsulation system, directly influencing production economics and sustainability. The process yield of pandan leaf extract powders was quantitatively assessed to determine the operational performance of the encapsulation method under various drying methods and wall material compositions. In this study, the process yield was calculated gravimetrically as follows (Fang & Bhandari, 2010):

$$\text{Process Yield (\%)} = \frac{\text{Powder after drying (g)}}{\text{Solid in the feed solution (g)}} \times 100 \qquad (2)$$

2.3.3. Encapsulation Efficiency

Encapsulation efficiency (EE) measures how well the process retains active compounds. High EE values (>70%) indicate minimal degradation during drying, ensuring consistent product quality and reduced waste critical for industrial scale-up. Additionally, EE was used to evaluate the process robustness of pandan leaf extract microencapsulation using various wall materials under different drying methods, as shown by Equation 3 modified from Alvim, Stein, Koury, Dantas, and Cruz (2016), with chlorophyll as the marker compound.

$$\text{EE (\%)} = \frac{A_a}{A_b} \times 100 \qquad (3)$$

Where A_a is the total active compound (chlorophyll) in powder after drying, and A_b is the total active compound in the feed solution before drying. A higher encapsulation efficiency implies a more stable and efficient encapsulation system with less degradation of bioactive compounds during drying.

2.3.4. Colorimetric Analysis

In the context of industrial quality specifications, colorimetric analysis serves as a crucial quality control parameter, not only reflecting the aesthetic acceptability of powdered products but also serving as an indirect indicator of pigment stability and process uniformity. Therefore, in this study, the color of the encapsulated pandan powders was assessed using an UltraScan PRO D65 UV/VIS Spectrophotometer. It was used to measure the samples' color in the L*, a*, and b* color scales. A white standard was used for calibration of the device. Ten samples were measured separately for each treatment, and the average of the ten measurements was computed. The Hunter-Scofield equation was utilized to calculate the color difference (ΔE) based on the L*, a*, and b* parameters.

$$\Delta E = \sqrt{(\Delta a)^2 + (\Delta b)^2 + (\Delta L)^2} \qquad (4)$$

Additionally, from an industrial processing perspective, ΔE provides a quantifiable performance index to evaluate color deviation from desired specifications. This is especially important for batch-to-batch consistency, visual appeal, and downstream processing, where powders may be integrated into final consumer products.

2.3.5. Morphological Characterization

Scanning electron microscopy (SEM) was used to examine the materials' external structures. An ion coater (Eiko Engineering, model IB-2, Japan) was used to coat dried powders (20 nm thickness) on aluminum stubs. The gold-coated specimens' morphology was examined using 5 kV acceleration voltages. Software for image processing (ImageJ, NIST) was used to identify encapsulated samples, and automatic image-capturing software was used to record the images.

2.3.6. Assessment of Antioxidant Activity

The ferric reducing antioxidant power (FRAP) assay was determined by the protocol described by Wanyo, Chamsai, and Chomnawang (2025). Three components were combined in test tubes for the FRAP assay: 1.8 mL of FRAP reagent, 180 µL of Milli-Q water, and 60 µL of extract. Incubation of the mixture lasted for 4 minutes at 37 ºC. Then, absorbance was measured at 593 nm using the FRAP working solution as a reference. The units of measurement for FRAP readings are millimoles of ferrous sulfate per gram of dried weight (µM $FeSO_4$/g) based on a standard curve.

The scavenging activity of the stable DPPH free radical was determined by the method following Wanyo, Kaewseejan, Meeso, and Siriamornpun (2016). Briefly, 0.1 mL of the extract was combined with 0.1 mM DPPH in 2.9 mL of ethanol, and then vortexed for one minute. The mixture's absorbance was measured at 517 nm after it was allowed to settle undisturbed for 30 minutes. Trolox equivalent milligrams per gram dry weight (mg TE/g) was used to express the content based on a standard curve.

The ABTS assay was adapted from Re et al. (1999). For an initial absorbance close to 0.75 at 734 nm, the ABTS solution was freshly diluted with water. After thoroughly mixing 1.8 mL of ABTS solution with 200 µL of extract, the tubes were allowed to stand at ambient temperature in the dark for 30 minutes. An equation was used to determine the % inhibitory activity after the absorbances were measured at 734 nm.

$$\text{ABTS (\% inhibition)} = \frac{(A_0 - A_1)}{A_0} \times 100 \quad (5)$$

Where A_0 is the absorbance of the ABTS solution without the sample (the blank or control), and A_1 is the absorbance of the ABTS solution with the sample.

2.3.7. Determination of Total Chlorophyll Content

With minor modifications, Senklang and Anprung (2010) methodology for measuring the total chlorophyll content (TCC) of all encapsulated samples was followed. In the supernatant, the absorbance values of the isolated chlorophylls were measured at 662 nm and 645 nm. Then, using the equation, the total chlorophyll content was determined using the Costache, Campeanu, and Neata (2012) method, which is given as milligrams per gram dry weight (mg/g).

$$\text{TCC (mg g}^{-1}) = (16.26 \times A_{645}) + (7.99 \times A_{662}) \times \frac{DF}{1000} \quad (6)$$

In calculating the activity, A_{662} and A_{645} are absorbances at respective wavelengths, and DF is the dilution factor.

2.3.8. Determination of β-Carotene

A mixture of methanol and chloroform (2:1 v/v) was used to extract 2 g of dry particles. Samples weighing approximately 1 g were extracted using 20 mL of solvent, kept at room temperature, and then evaporated at 25°C under reduced pressure. Based on Nhung, Bung, Ha, and Phong (2010), the oil extracts were modified to measure the amount of β-carotene. A mixture of 15 mL tetrahydrofuran (THF) and methanol (MeOH) (4:1) was also used to dissolve the sample oils (0.5 g). After filtering, the liquid phase underwent three rounds of washing with a saturated sodium chloride solution. Anhydrous sodium sulfate was used to dehydrate the organic layer, which was then evaporated at 25 °C under reduced pressure. Dichloromethane (DCM) and MeOH (6:4) were mixed in 10 mL to dissolve the residue. Reversed-phase high-performance liquid chromatography (RP-HPLC) was utilized to quantify the amount of β-carotene, with a method described by Nhung et al. (2010). Eluent A and B in the RP-HPLC system (Shimadzu) were MeOH and DCM/acetonitrile (6:4, v/v, with 0.05% BHA as antioxidant) in a mobile phase. The autosampler and column oven were equipped with Inertsil ODS (4.6 mm×250 mm, 5 µm). This gradient was applied: 70% (A) and 30% (B) for 5 min as the starting condition. After that, it was 80% (A) and 20% (B) for 5 min. There was a flow rate of 1.5 mL/min. For the measurement of β-carotene, an injection volume of 20 µL and a photodiode array detector at 472 nm were used. External standards were used in the construction of calibration curves.

2.4. Optimization and Statistical Analysis

A multi-response optimization was performed using Design-Expert software version 13 (Stat-Ease Inc., USA) to determine the optimal encapsulation conditions for pandan leaf extract. Optimization focused on identifying the best combination of drying method and wall material to achieve superior powder stability metrics, encapsulation performance, and bioactive retention. The experimental design was based on a full factorial structure (3×3) under the

Design of Experiments (DOE) framework. Two categorical factors drying method (spray-drying, freeze-drying, and drum-drying) and wall material (MD, SPI, and EWP) were used to define nine treatment combinations.

Fourteen response variables, each selected based on its relevance to encapsulation performance, powder stability, and product functionality. These included process yield, EE, moisture content, a_w, water solubility, colorimetric properties (L*, a*, b*, ΔE), antioxidant activities (DPPH, FRAP, ABTS), and bioactive retention (β-carotene and chlorophyll). Each response was assigned a specific goal (maximize or minimize), along with its respective upper and lower limits, weights, and importance scores based on prior literature and preliminary experimental results. Five key responses were selected based on the balance between encapsulation quality and antioxidant activity. The overall desirability of encapsulation conditions was calculated as the geometric mean of individual desirability functions for critical responses.

The principal component analysis (PCA) was further conducted to supplement the desirability function and provide a visual representation of multi-response optimization. Five critical response variables (process yield, EE, DPPH, FRAP, and ABTS) were normalized using a Min-Max scaler before applying PCA.

At least three duplicate measurements were performed, and the results were reported as a mean ± standard deviation. The significance of treatment effects was evaluated using analysis of variance (ANOVA), followed by Duncan's multiple range test at a 95% confidence level ($p < 0.05$). This statistical validation, performed using SPSS software (Version 19.0, SPSS Inc., USA), ensured the reliability and reproducibility of the findings across the factorial conditions.

3. RESULTS AND DISCUSSION

3.1. Process Efficiency

The effects of wall materials and drying techniques on process yield and encapsulation efficiency (EE) are presented in Table 1. Freeze-drying with maltodextrin (MD-FD) yielded the highest powder recovery at 85.81%, significantly outperforming spray-drying (MD-SD: 73.87%) and drum-drying (MD-DD: 68.82%) ($p < 0.05$). Notably, soy protein isolates with freeze-drying (SPI-FD) maintained a 74.94% yield despite the protein's lower thermal stability. Drum-drying showed the lowest yields, ranging from 52.55% to 68.82%, due to thermal degradation.

The trends of encapsulation efficiency (EE) were observed: SPI-FD was better in bioactive compound protection (76.42%), whereas egg white powder with freeze-drying (EWP-FD) had low results (26.83%). Due to the flexible structure of SPI (Tang & Li, 2013), it retained more than hard EWP.

Table 1. Process yield, encapsulation efficiency (EE), moisture content, water activity, and water solubility index of encapsulated pandan leaf extract powders.

Samples	Process yield (%)	EE (%)	MC (%)	a_w value	Water solubility (%)
MD-SD	73.87±3.64^{bc}	72.70±2.44^{a}	5.78±0.20^{c}	0.36±0.02^{c}	98.32±0.13^{c}
SPI-SD	65.08±2.86^{d}	73.17±1.63^{a}	10.73±0.08^{a}	0.48±0.03^{a}	98.49±0.09^{bc}
EWP-SD	65.16±4.02^{d}	75.61±2.04^{a}	10.18±0.17^{a}	0.42±0.02^{b}	99.23±0.05^{a}
MD-FD	85.81±1.98^{a}	57.72±6.50^{b}	4.65±0.83^{d}	0.16±0.05^{e}	98.84±0.36^{abc}
SPI-FD	74.94±2.01^{b}	76.42±5.69^{a}	6.41±0.11^{c}	0.33±0.01^{cd}	98.47±0.09^{bc}
EWP-FD	69.93±1.21^{bcd}	26.83±2.44^{d}	7.24±0.13^{b}	0.33±0.01^{cd}	95.36±0.16^{d}
MD-DD	68.82±3.85^{cd}	34.15±3.25^{c}	4.79±0.50^{d}	0.27±0.04^{d}	98.29±0.18^{c}
SPI-DD	57.78±3.16^{e}	54.47±2.62^{b}	5.86±0.58^{c}	0.38±0.06^{bc}	98.96±0.77^{ab}
EWP-DD	52.55±4.14^{e}	52.03±4.18^{b}	6.08±0.42^{c}	0.27±0.02^{d}	98.73±0.22^{abc}

Note: Encapsulation efficiency (EE) was determined using Equation 3, with chlorophyll as the marker compound. A_b was measured from the feed solution pre-drying; A_a from reconstituted powder post-drying. All extractions used 80% acetone (v/v) under dim light to prevent photodegradation. Values are expressed as mean ± standard deviation (n = 3). Means with different letters in the same column were significantly different at $p < 0.05$.

Drum-drying had 40-50% lower yield and EE relative to other drying methods because surface temperatures were high (130 ± 5°C) during the processing, destroyed heat-sensitive compounds (Khoshnoudi-Nia, Forghani, & Jafari, 2020), and mechanical shear forces interfered with the integrity of wall materials. To contextualize these findings for industrial applications, Table 2 presents the drying methods trade-offs. The best encapsulation performance was achieved using freeze-drying, although at an increased operational cost, and the middle option was provided by spray-drying as a mass-produced mixture. Drum-drying, although energy-efficient, was found not applicable in drying heat-sensitive bioactives because many of the compounds could be lost through decomposition ($p < 0.05$ vs. freeze-drying/spray-drying). These results are consistent with those of Khoshnoudi-Nia et al. (2020) about thermal sensitivity in plant extracts.

Table 2. Performance comparison of drying methods for pandan leaf encapsulation.

Parameter	Freeze-drying	Spray-drying	Drum-drying
Best yield	85.81% (MD-FD)	73.87% (MD-SD)	68.82% (MD-DD)
Best EE	76.42% (SPI-FD)	75.61% (EWP-SD)	54.47% (SPI-DD)
Recommended use	Premium products	Mass production	Bulk ingredients

Note: Process yield, encapsulation efficiency (EE), and recommended applications of freeze-drying (FD), spray-drying (SD), and drum-drying (DD) with optimal wall materials. Data shown as mean values from triplicate experiments (n=3). MD: maltodextrin; SPI: soy protein isolate; EWP: egg white powder. Significantly, drum-drying has tolerable yields in MD (68.82%), however, its low EE (34–54%) degrades heat-sensitive ingredients. Industrial factors, drum-drying only applies with ingredients that are not sensitive and the cost justifies quality loss.

3.2. Powder Stability Metrics

The encapsulated pandan leaf powder was analyzed in terms of stability using moisture content, water activity (a_w), solubility, and morphology. These measures are important determinants of shelf life and industrial functionality in food applications.

3.2.1. Moisture Content and Water Activity

Freeze-dried powders exhibited superior moisture control (Table 1). Maltodextrin-based freeze-dried powder (MD-FD) showed the lowest moisture content (4.65%), significantly outperforming spray-dried counterparts (SPI-SD: 10.73%; $p < 0.05$). This aligns with Sarabandi and Jafari (2020) findings on the moisture-barrier properties of polysaccharide matrices.

An a_w value followed similar trends (Table 1), MD-FD showing the lowest a_w value of 0.16 (microbiologically stable per Association of Official Analytical Chemists (2005)). In contrast, SPI-SD recorded 0.48 (requires auxiliary drying agents). The inverse correlation between drying temperature and moisture retention ($R^2 = 0.89$) confirms freeze-drying's advantage for humidity-sensitive regions.

3.2.2. Water Solubility

The solubility of all encapsulated powders was more than 95% with the highest dissolution (99.23%) obtainable with egg white protein spray-dried powder (EWP-SD), as presented in Table 1.

This demonstrates the usefulness of the protein-based wall materials in producing highly soluble powders through a process of spray-drying (Botrel, De Barros Fernandes, Borges, & Maria Irene Yoshida, 2014). This approach usually provides higher and quicker solubility, and phenomena were similar to Fenoglio et al. (2021) who observed high solubility enhancement and improved physical stability in spray-dried powders across various food applications.

Notably, freeze-dried samples exhibited slightly reduced solubility (MD-FD: 98.84%) because the porous structures slow wetting.

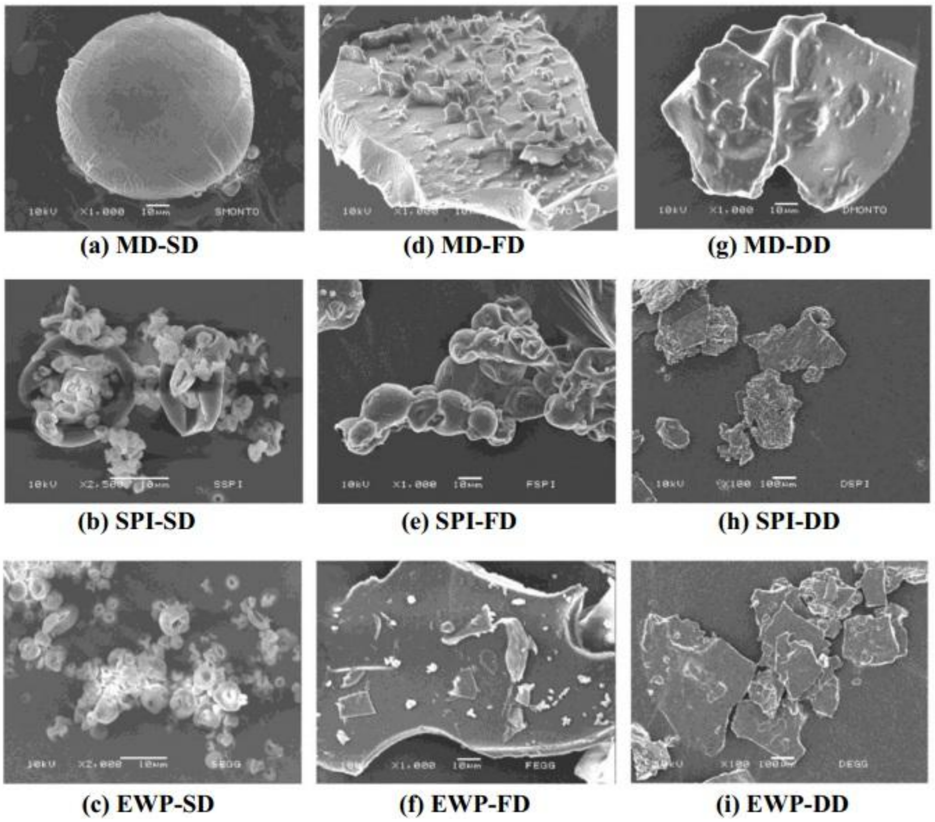

Figure 1. Scanning electron micrographs of encapsulated powders showing surface morphology: (a–c) Spray-dried particles with spherical shapes, (d–f) Freeze-dried matrices with porous structures, and (g–i) Drum-dried flakes with irregular surfaces. Images were captured at 5 kV acceleration voltage with 5000× magnification. Scale bars: 10 µm.

3.2.3. Morphological Stability

Particle morphology, significantly influenced by drying method and wall material, is critical for powder performance, impacting encapsulation, stability, and functional properties. The scanning electron microscopic (SEM) analysis revealed that spray-dried particles were smooth and spherical (5–20 µm) with significantly greater bulk density (12% more than freeze-dried) and enhanced flowability that was essential to industrial packaging. On the other hand, freeze-dried powders were obtained as porous, larger flakes (50–200 µm), whereas drum-dried samples were irregular agglomerates (Figure 1). Higher encapsulation efficiency and superior stability are generally associated with smoother spray-dried particles, whereas rougher, porous freeze-dried particles, although they might provide less protection, may improve rehydration (Castro-López et al., 2021). In addition to the drying method, the choice of wall material significantly impacts the microcapsule's structural integrity, including the release mechanisms and the protection of core materials (Pudziuvelyte et al., 2019).

These morphological differences have significant industrial implications. For instance, MD-FD suits long-term storage (low a_w), EWP-SD is ideal for instant products (high solubility), and SPI-SD provides a compromise between retention and yield to make the product cost-effective. Based on the results, the type of wall material affects product stability more than the type of drying process itself ($p < 0.01$). This appreciation of the influence of drying method and wall material on morphology and functionality is essential in the design of optimum encapsulation processes in food, pharmaceutical, and nutraceutical applications.

3.3. Color Quality

3.3.1. Color Parameter Analysis

The color parameters changes (L*, a*, and b* values) of the encapsulated pandan leaf powder due to various encapsulation conditions are provided in Table 3, reflecting the visual change observed in Figure 2. The drying method and wall material significantly affected the color of the encapsulated powders ($p < 0.05$), as did the degradation patterns in other plant extracts (Castro-López et al., 2021). Lightness was markedly preserved during spray-drying, with MD-SD as the brightest (L* = 79.58) and SPI-DD as the darkest (L* = 49.06) compared to each other, in line with the findings on the chlorophyll content in spray-dried powders (Niu, Feng, Xuan, & Shao, 2021). Greenness was also different, with SPI-DD exhibiting the most intense green (a* = -7.69), possibly because of the polyphenol-binding capacity of soy protein (Ploypetchara et al., 2021), while EWP-SD showed weaker pigment stabilization (a* = -6.73), the yellowness (b* = 28.55) was highest in SPI-SD powders. The underlying mechanistic causes of these color differences were different; for example, the amorphous nature of maltodextrin reduced the browning process of Maillard during spray-drying, resulting in a lighter color (Zhang et al., 2022), whereas protein-polyphenol interactions enhanced the formation of green pigmentation in SPI (Ploypetchara et al., 2021).

Table 3. Color parameter of encapsulated pandan leaf extract powders.

Samples	**L***	**a***	**b***	**ΔE**
MD-SD	79.58 ± 0.10^{a}	-7.31 ± 0.17^{cd}	23.01 ± 0.27^{c}	65.11 ± 0.08^{a}
SPI-SD	53.98 ± 0.43^{d}	-6.36 ± 0.08^{a}	28.55 ± 0.11^{a}	40.95 ± 0.44^{e}
EWP-SD	57.43 ± 0.33^{c}	-6.73 ± 0.11^{ab}	26.76 ± 0.72^{b}	43.83 ± 0.48^{c}
MD-FD	64.50 ± 0.07^{b}	-7.16 ± 0.49^{bc}	19.44 ± 0.45^{ef}	49.81 ± 0.08^{b}
SPI-FD	53.99 ± 0.45^{d}	-6.38 ± 0.02^{a}	21.60 ± 0.06^{d}	39.50 ± 0.43^{f}
EWP-FD	57.13 ± 0.23^{c}	-6.73 ± 0.10^{ab}	20.13 ± 0.39^{e}	42.49 ± 0.26^{d}
MD-DD	53.63 ± 0.20^{d}	-6.42 ± 0.30^{a}	22.50 ± 0.31^{c}	39.28 ± 0.24^{f}
SPI-DD	49.06 ± 0.29^{e}	-7.69 ± 0.08^{d}	19.28 ± 0.34^{f}	34.44±0.31g
EWP-DD	46.07 ± 0.18^{f}	-6.89 ± 0.34^{bc}	15.27 ± 0.71^{g}	31.34 ± 0.13^{h}

Note: Values are expressed as mean ± standard deviation (n = 10). Means with different letters in the same column were significantly different at $p < 0.05$.

Figure 2. Visual appearance of encapsulated pandan leaf powders produced by (a–c) Spray-drying (SD), (d–f) Freeze-drying (FD), and (g–i) Drum-drying (DD) with different wall materials: maltodextrin (MD), Soy protein isolate (SPI), and egg white powder (EWP). Samples were photographed under standardized lighting conditions (D65 illuminant) immediately after processing. Scale bar: 1 cm.

3.3.2. Color Stability Mechanisms

The total color difference (ΔE) in the encapsulated powders varied significantly, ranging from 31.34 (EWP-DD) to 65.11 (MD-SD). Spray-drying was effective at protecting color, with a relatively low ΔE value of 65.11 for MD-SD, which was due to the rapid drying process that diminished thermal exposure (Zhang et al., 2022). Important protein-pigment interactions were also involved, as amino acids in SPI created protective complexes with chlorophyll (Tang & Li, 2013). On the other hand, drum-drying exhibited limitations, with EWP-DD's high ΔE of 31.34 (Table 3) reflecting cumulative heat damage during the process (Adhamatika et al., 2021).

3.3.3. Industrial Implications

Color stability can be a key criterion in consumer acceptance, and all formulations can be adapted to suit various product requirements. For a vibrant green hue, consider SPI-SD (ΔE = 40.95) (Botrel et al., 2014). In the case of neutral tones, MD-FD (ΔE = 49.81) would be an appropriate option (Mahdavi, Jafari, Assadpour, & Ghorbaniet, 2016). For cost-effective solutions, MD-DD (ΔE = 39.28) could be recommended to produce more economically friendly options, although there may be quality trade-offs associated with them (Nambiar, Sellamuthu, & Perumal, 2017). The results confirm the importance of both the wall materials and the drying methods in dictating the quality of the powder. SPI with freeze-drying produced the best retention of antioxidants and EE, the lowest moisture, and high solubility (98.47%). The overall solubility was highest with spray-drying (99.23%). Drum-drying was cheaper but also resulted in consistently poor-quality powders, representing a trade-off between cost and functional performance.

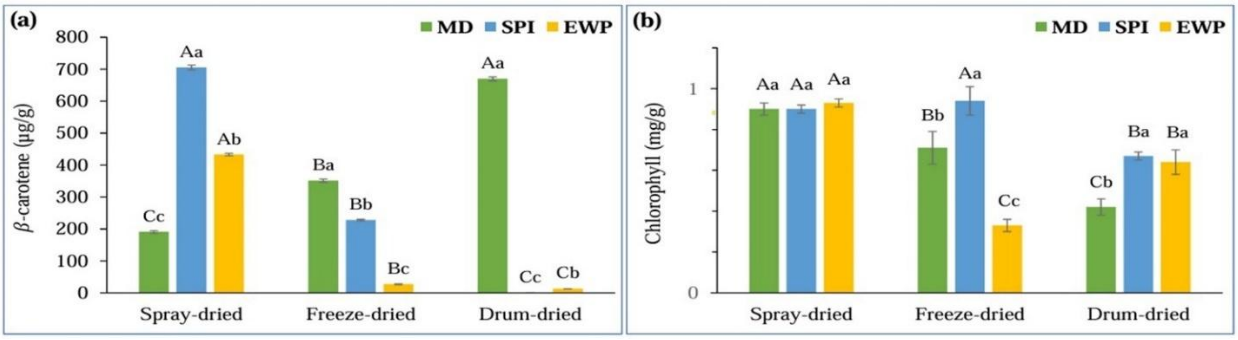

Figure 3. Bioactive compound retention: (a) β-carotene content (μg/g dry weight) and (b) total chlorophyll content (mg/g dry weight) in encapsulated powders. Bars represent mean ± SD (n=3).

Note: Different uppercase letters indicate significant differences among wall materials within each drying method, while lowercase letters compare drying methods within each wall material ($p < 0.05$, Duncan's test).

3.4. Bioactive Compound Retention

3.4.1. β-Carotene Stability

The importance of nutritional value and antioxidant capacity indicator β-carotene highly relies on the nature of the encapsulation method and wall material selected in the process, as illustrated in Figure 3a. The highest retention (705 μg/g) was revealed by SPI-SD, which may be caused by the antioxidant-skewing power of SPI (Tang & Li, 2013). On the other hand, SPI-DD also caused complete degradation (100% degraded), which validated the thermal sensitivity of β-carotene (Nhung et al., 2010). The MD-FD provided moderate protection (351 μg/g), and this can be explained by maltodextrin's ability to form an oxygen barrier (Fang & Bhandari, 2010).

3.4.2. Chlorophyll Preservation

The experimental findings indicate that chlorophyll preservation depends notably on both wall substance choice and drying application, as presented in Figure 3b. The freeze-drying method exhibited stronger chlorophyll retention ($p < 0.05$), with MD-FD retaining 94% of the initial content (0.94 mg/g), which is comparable to findings related to low-temperature drying (Silva-Espinoza, Ayed, Foster, Camacho, & Martínez-Navarrete, 2020). Good retention was also observed with spray-dried samples, which retained 85-90% of the chlorophyll (e.g., MD-SD: 0.90 mg/g). Conversely, drum-dried powders were highly degraded, and 40% of chlorophyll was lost (MD-DD: 0.56 mg/g) because of excessive heat exposure (Adhamatika et al., 2021). Mechanistically, because the chlorophyll magnesium center is stable at temperatures below 60 °C, it is easily broken down under the higher temperatures (130 °C) of drum-drying (Costache et al., 2012).

3.4.3. Comparative Performance

The best preservation of bioactive compounds depended on the drying methods and wall materials. Chlorophyll favored MD-FD, preserving 94% (0.94 mg/g) of the fresh pandan leaf content (1.00 mg/g) Senklang and Anprung (2010)). In the case of β-carotene, the SPI-SD showed a maximum retention of 88% (705 µg/g) compared to 800 µg/g in fresh leaves (Nambiar et al., 2017).

3.4.4. Industrial Implications

For nutraceuticals, the preferred method of preserving heat-sensitive compounds is freeze-drying. Alternatively, spray-drying offers an excellent combination of cost-effectiveness and high retention (85-90% efficacy) of fortified foods. Nonetheless, in products where natural colorants are essential, drum-drying is not recommended as it structurally damages pigments. Regarding methods to address the demand for more novel strategies of encapsulation to retain thermostable molecules, the effectiveness of combined pretreatments (e.g., ultrasonic-assisted enzymatic hydrolysis) and fermentation in improving bioaccessibility of bioactive compounds has also been successfully tested in our recent research (Chamsai & Wanyo, 2025; Wanyo et al., 2025).

3.5. Antioxidant Activity

Antioxidant activity was evaluated using DPPH, FRAP, and ABTS assays. Figure 4 illustrates the variations in the antioxidant activity of encapsulated pandan leaf powder produced with different wall materials and drying methods. Significant differences were observed between the various encapsulation methods and wall material types ($p < 0.05$).

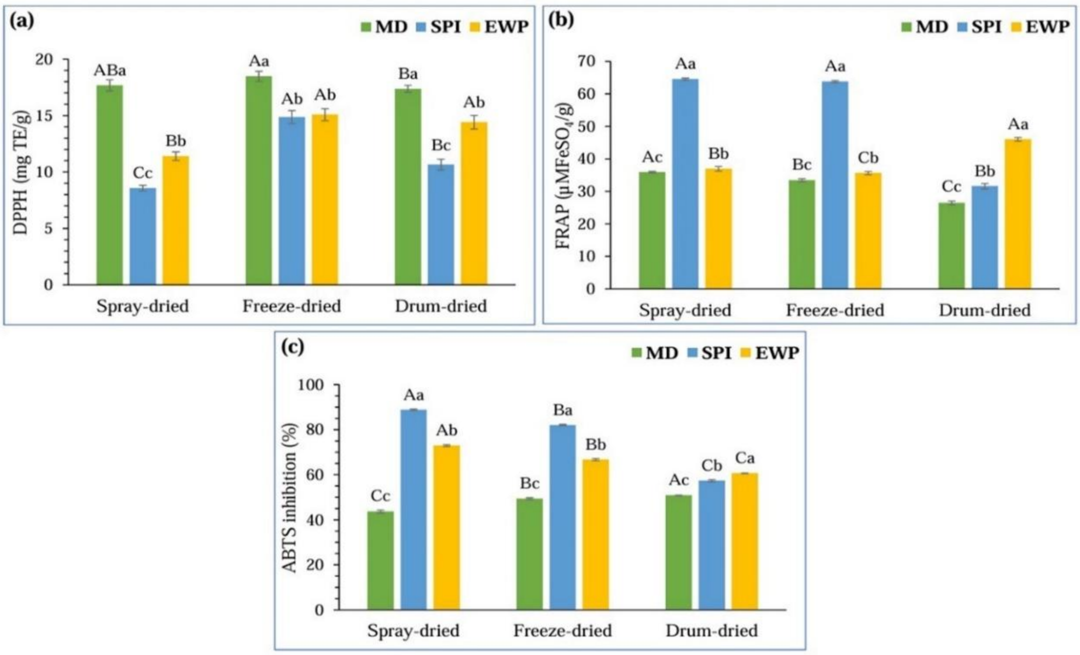

Figure 4. Antioxidant activities measured by (a) DPPH radical scavenging (mg TE/g), (b) FRAP reducing power (µM $FeSO_4$/g), and (c) ABTS inhibition (%). Error bars show standard deviation (n=3).

Note: Different uppercase letters indicate significant differences among wall materials within each drying method, while lowercase letters compare drying methods within each wall material ($p < 0.05$, Duncan's test).

3.5.1. DPPH Radical Scavenging Activity

As in Figure 4a, pandan leaf powder prepared by MD-FD demonstrated the highest DPPH inhibition (18.47 mg TE/g), significantly outperforming drum-dried samples ($p < 0.05$). This corresponds to the findings that freeze-drying is effective in preserving phenolic compounds (Silva-Espinoza et al., 2020). Although protein-based spray-dried samples exhibited moderate activities (SPI-SD: 15.2 mg TE/g; EWP-SD: 14.8 mg TE/g), drum-drying significantly reduced antioxidant capacity due to thermal degradation of SPI-DD, which had 35% lower activity compared to SPI-FD (Adhamatika et al., 2021).

3.5.2. FRAP Reducing Power

The SPI demonstrated exceptional iron-reducing ability, with SPI-SD (spray-dried) exhibiting the highest FRAP reducing power at 64.53 μM $FeSO_4$/g, closely followed by SPI-FD (freeze-dried) at 63.80 μM $FeSO_4$/g (Figure 4b). They point to the importance of sulfhydryl groups of SPI, which lose electrons easily to free radicals, hence their high activity (Tang & Li, 2013). One of the most critical conclusions concerned the surprising finding that spray-drying partially reduced SPI (11% more than freeze-drying, $p < 0.01$), which was indicative of, rather than refuting, the widely held belief that freeze-drying is always the best method to preserve antioxidant characteristics.

3.5.3. ABTS Radical Inhibition

As in Figure 4c, SPI-SD achieved the highest ABTS radical scavenging activity (88.81%), significantly outperforming all freeze-dried samples and therefore being most suitable for beverage fortification. The EWP-SD sample, with 72.93% inhibition, further confirmed that proteins provide stability to polar antioxidants (Botrel et al., 2014). In the case of shelf-stable nutraceuticals, SPI-FD was strongly inhibited, performing at 82.07%, whereas EWP-SD has potential applications in instant functional foods.

3.5.4. Multi-Assay Insights

In multiple antioxidant activities, SPI was superior to MD and EWP. Spray-drying performed better in terms of ABTS and FRAP activities, as it was able to stabilize polar antioxidants efficiently through a rapid encapsulation process (Zhang et al., 2022). On the other hand, freeze-drying was the most effective in DPPH inhibition, as non-polar compounds were best preserved (Wanyo et al., 2016). Drum-drying systematically showed the lowest antioxidant activity, with values of 50% of the freeze-drying or spray-drying values. In particular, MD-FD was the best with DPPH (18.47 mg TE/g), given the retention of polyphenols at a low temperature, whereas the SPI-SD showed the best performance on FRAP (64.53), followed by ABTS (88.81%) through effective emulsification of hydrophilic antioxidants.

Antioxidant retention profiles in the encapsulation of the pandan leaf are similar to the general conclusions regarding plant-based powders. The ABTS inhibition of SPI-SD was 88.81%, approaching that of spray-dried yerba mate extracts (86% ABTS inhibition) that were mixed with blends of maltodextrin/gum Arabic (Fenoglio et al., 2021). Nevertheless, the chlorophyll retention of the freeze-dried pandan (94%) was better than the spray-dried moringa polyphenols (78%) (Castro-López et al., 2021), presumably because the non-polar chlorophyll binds more readily to the hydrophobic bond pockets in SPI than to the polar moringa flavonoids. Remarkably, the stability of β-carotene in SPI-SD (705 μg/g) was also higher than that of spray-dried turmeric curcumin (420 μg/g), reflecting the better stability of non-polar phytochemicals in SPI (Kharat & Mc Clements, 2019). These comparisons emphasize that although the process of spray-drying systematically degrades heat-sensitive antioxidants, protein-based wall materials (particularly SPI) better avoid losses than polysaccharides with non-polar bioactive compounds such as the pigments of pandan.

Encapsulation procedures, in combination with the selection of wall material, now play a very crucial role in regulating the antioxidant activity of pandan leaf powder. Nonetheless, some wall materials have exhibited superior antioxidant retention rates in their spray-drying than in freeze-drying. Conversely, freeze-drying may be helpful to others, especially regarding ABTS radical scavenging activity. The protection of antioxidative activities seems to be less suitable by drum-drying when compared to the other methods. This observation can be used to guide the process of encapsulation to maximize the health benefits of pandan leaf powder in different applications.

3.6. Multi-Response Optimization of Encapsulation Conditions

The most suitable encapsulation strategy for pandan leaf extract was determined using multi-response optimization through combined statistical modeling and multivariate analysis that incorporated a desirability function and Principal Component Analysis (PCA).

Table 4. Comparative summary of optimal (SPI-FD) and alternative (EWP-SD) encapsulation conditions for pandan leaf powder based on model-predicted responses from Design-Expert software.

Parameter	Optimal condition[a]	Alternative condition[a]
Drying method	Freeze-drying	Spray-drying
Wall material	SPI	EWP
Process yield (%)	74.611	62.368
Encapsulation efficiency (%)	63.554	67.194
Moisture content (%)	6.909	9.872
Water activity	0.337	0.427
Water solubility (%)	97.898	98.154
L*	53.614	59.944
a*	-6.703	-6.733
b*	21.696	24.989
ΔE	39.258	46.211
DPPH (mg TE/g)	13.229	11.902
FRAP (µM $FeSO_4$/g)	56.004	43.741
ABTS (% inhibition)	78.533	71.630
β-carotene content (µg/g)	222.196	309.359
Chlorophyll (mg/g)	0.781	0.828
Desirability	0.701	0.558

Note: [a] This table summarizes results from the Design-Expert optimization output.

Multi-response optimization was conducted using 14 parameters, including physicochemical properties (e.g., process yield, EE, moisture content, water solubility, and color), antioxidant activity (DPPH, FRAP, ABTS), and bioactive retention (β-carotene, chlorophyll). Each response was assigned a specific goal, weight, and importance, aiming to maximize antioxidant activity and encapsulation quality while minimizing moisture-related degradation indicators (moisture content, a_w). Among the four solutions generated, the condition combining soy protein isolate with freeze-drying (SPI-FD) showed the highest overall desirability of 0.701, with a high DPPH value (13.229 mg TE/g), FRAP value (56.004 µM $FeSO_4$/g), and ABTS inhibition (78.53%). This combination also maintained a low moisture content (6.91%) and a_w (0.337), indicating superior product stability and quality. In contrast, the alternative condition spray-drying with egg white powder (EWP) had a desirability score of only 0.558 (Table 4), indicating that the SPI-FD condition better balanced all target responses.

The SPI-FD combination provided substantial advantages in antioxidant retention, encapsulation efficiency, and low water activity, aligning with the findings of Zhang et al. (2022) and Fang and Bhandari (2010), who emphasized the role of protein carriers in improving powder performance. Additionally, freeze-drying was confirmed as the most suitable drying method for sensitive bioactives, as supported by Silva-Espinoza et al. (2020) and Castro-López et al. (2021). Comparable findings on antioxidant optimization applied to germinated brown rice reported that ultrasonic-assisted enzymatic pretreatment improved antioxidant bioaccessibility, which highlights the significance of pre-processing and structure on functional stability (Chamsai & Wanyo, 2025).

The overall desirability of encapsulation conditions, along with a corresponding desirability plot of five critical responses (process yield, EE, DPPH, FRAP, and ABTS), was analyzed. The SPI-FD condition achieved the highest overall desirability score, indicating the best balance between antioxidant activity and encapsulation quality. Principal Component Analysis (PCA) was performed to further validate the optimization based on normalized values of the five critical responses. PCA successfully reduced these five response variables into two principal components: PC1 explains 57.5% of the variance, and PC2 explains 24.0%, together accounting for 81.5% of the total variation among the encapsulation conditions. The PCA biplot of nine encapsulated combinations, based on the five key normalized responses, clearly distinguishes SPI-FD, which is positioned in a favorable quadrant of high PC1 and PC2 values, confirming it as the most balanced option for high encapsulation performance and antioxidant activity.

The visual summary of Figure 5 effectively combines PCA projection with desirability scores. PCA-Desirability map of nine encapsulation conditions, each point representing a unique combination of drying method and wall material. The position reflects PCA of normalized key responses, while the point size and color indicate overall desirability scores. The SPI-FD condition is positioned in the optimal quadrant and exhibits the highest desirability, confirming it as the most effective treatment. The SPI-SD and MD-FD combinations also showed high antioxidant activity but had lower desirability scores due to compromises in process yield or encapsulation efficiency.

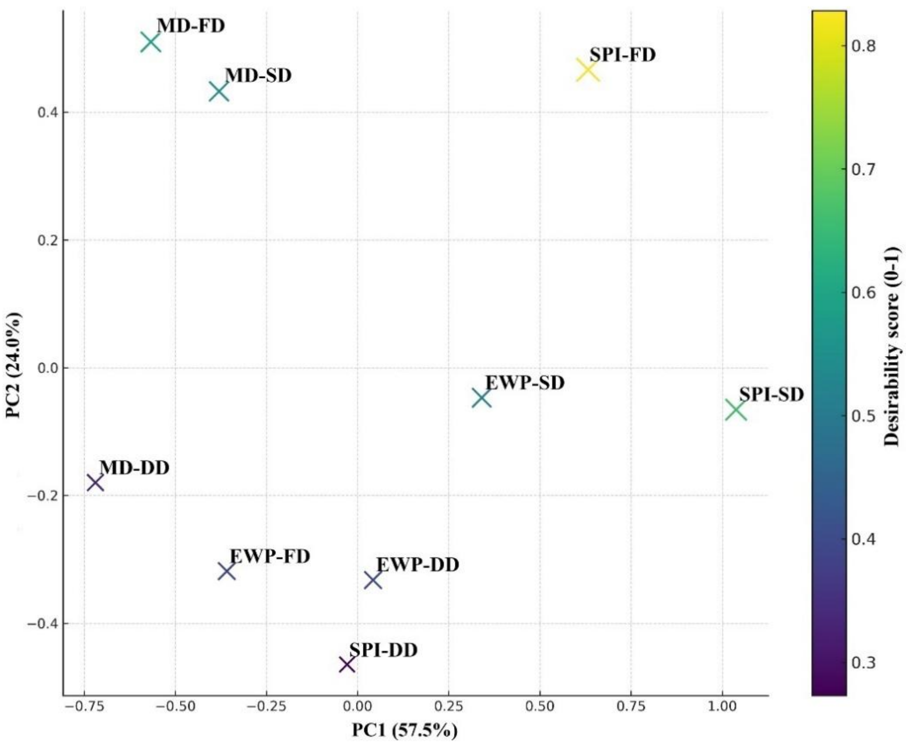

Figure 5. PCA-desirability map integrating five key response variables (yield, EE, DPPH, FRAP, ABTS) across nine encapsulation conditions. Point size and color intensity represent overall desirability scores (0–1 scale). PC1 (57.5%) and PC2 (24.0%) explain 81.5% of the total variance. SPI-FD is positioned in the optimal quadrant.

The integrated analysis confirmed that SPI-FD is the optimal encapsulation strategy for developing pandan leaf powders with enhanced functional and stability characteristics. Such systematic optimization can guide future scale-up and formulation strategies for plant-based bioactive powders in functional foods and nutraceuticals.

A detailed comparison between the best-performing SPI-FD combination and an alternative EWP-SD condition is presented in Table 4. Although the EWP formulation exhibited slightly higher encapsulation efficiency and chlorophyll content, the SPI-FD sample demonstrated better overall performance across antioxidant indices and powder stability metrics, especially in terms of reduced water activity and higher ABTS inhibition. This indicates that the SPI-FD strategy is most suitable for preserving the bioactive integrity of pandan extract during encapsulation.

3.7. Industrial Relevance, Sustainability, and Scale-Up Considerations

Encapsulation methods in relation to the application of recommended encapsulation methods on pandan leaf powder should be balanced between functionality and practicality requirements. We compare in Table 5 the three drying methods (spray-drying, freeze-drying, and drum-drying) on the basis of scalability, cost, and sustainability.

3.7.1. Spray-Drying

Spray-drying can be widely extended into a large-scale, continuous mode (50–500 kg/h), fits well with current food industry infrastructure, and has lower operating costs (~2.5–3.5 kWh/kg) than freeze-drying. Though spray-drying using SPI or EWP had competitive levels of antioxidant retention (e.g., SPI-SD: 88.81% ABTS inhibition), it led to an increase in moisture content (10.73% in SPI-SD) relative to freeze-drying. Hence, spray-drying is most suitable in applications where the application parameters focus on speed of production and maximum solubility, i.e., instant beverages and fortified snacks.

3.7.2. Freeze-Drying

Even though freeze-drying, which is normally batch processed, along with the substantial capital and energy requirements (~10–15 kWh/kg), makes its scaling expensive, it is considered the gold standard for preserving heat-sensitive bioactive compounds (Silva-Espinoza et al., 2020). High encapsulation efficiency (76.42%) and low water activity (0.337) of SPI-FD justify the usage of nutraceuticals and high-value functional foods. In the future, even newer drugs such as hybrid freeze-spray drying have the potential to enhance sustainability, as they may reduce energy use by 30–40% (Zhang et al., 2022).

3.7.3. Drum-Drying

Drum-drying is energy-efficient (~1.5–2.0 kWh/kg), but it repeatedly shows poor bioactive retention, as indicated by the undetectable β-carotene in SPI-DD. Consequently, it can only be used to process low-value products where thermal degradation is acceptable, such as bulk flavor carriers, but not for applications requiring the preservation of sensitive compounds.

In order to quantitatively compare the industrial feasibility of each encapsulation technique, several main operational parameters, such as energy consumption, throughput, and encapsulation efficiency, are summarized in Table 5. These parameters are highly important in production costs and scalability, especially in functional food formulations, in which the retention of bioactive compounds and process economics must be considered. The industry-standard data combines the experimental results of this study with industry benchmarks to offer insights on how to act in the choice of technology.

Table 5. Comparative economic and performance metrics of spray-drying, freeze-drying, and drum-drying for encapsulated pandan leaf powder production.

Parameters	Spray-drying	Freeze-drying	Drum-drying
Energy use (kWh/kg)	2.5–3.5	10–15	1.5–2.0
Throughput (kg/h)	50–500	5–20 (batch)	100–300
Encapsulation efficiency (%)	72–76 (SPI/EWP)	76 (SPI-FD)	34–54

Note: Energy consumption, throughput, and encapsulation efficiency (EE) are presented as key indicators for industrial scalability. Data reflect experimental results from this study and industry benchmarks from Zhang et al. (2022) and Silva-Espinoza et al. (2020). SPI: soy protein isolate; EWP: egg white powder.

As indicated in Table 5, spray-drying presents the most desirable trade-off between throughput and energy efficiency, and it is capable of addressing high-volume production. However, freeze-drying remains unmatched for premium applications requiring maximal bioactive protection (e.g., SPI-FD's 76% EE), despite its higher energy demands. Drum-drying is a cost-effective method but has limitations in its application due to low encapsulation efficiency (34-54%). These trade-offs highlight the issue of context-dependent technology selection, which is discussed below in more detail in hybrid approaches.

3.7.4. Future Directions

In further research, hybrid drying methods that integrate the economy of spray-drying with the safety of freeze-drying to maximize commercial production should be investigated. Environmental trade-offs, including the SPI-FD energy use compared to food waste reduction due to a longer shelf life, need to be assessed using a full Lifecycle Assessment (LCA). In cost-sensitive applications that require large-scale production, SPI-SD or EWP-SD is suggested, and SPI-FD is worth the high price tag needed to deliver high-value bioactive compounds. On the other hand, drum-drying is a niche treatment as it has its inherent limitations in quality.

From an industrial perspective, while freeze-drying with SPI offers the best quality, it is costly and energy-intensive. Maltodextrin-based spray-drying offers a more practical and scalable possibility, with respectable product quality and significantly lower operational costs. Drum-drying, although economical, may not be suitable for sensitive bioactives due to thermal stress. In terms of both cost and quality, the SPI-SD and MD-SD combinations show promise for use in industrial applications. The results of this study suggest a framework for selecting encapsulation methods designed to achieve a balance between financial feasibility and performance in functional foods.

In the context of a sustainability standpoint, the SPI-FD formulation, while optimal in functionality, may be more suitable for premium product development, where bioactive concentration, low moisture content, and clean-label protein carriers justify its energy footprint. Lifecycle assessment (LCA) and techno-economic modeling are recommended for future studies to quantify trade-offs between process desirability and industrial feasibility. Our results guide manufacturers in selecting encapsulation methods: freeze-drying (SPI-FD) for premium quality, spray-drying (SPI-SD) for cost-effective scale-up, and drum-drying only for non-sensitive applications.

4. CONCLUSION

A comprehensive evaluation studied three drying methods, including spray-drying, freeze-drying, and drum-drying, along with three wall materials consisting of maltodextrin (MD), soy protein isolate (SPI), and egg white powder (EWP) in terms of pandan (*Pandanus amaryllifolius*) leaf extract encapsulation performance. Results showed that both drying approach selection and wall choice significantly affect the powder stability metrics, antioxidant activities, and bioactive compound quantities in finished dry materials. The powder from the freeze-drying and soy protein isolate (SPI-FD) combination method achieved superior performance results for multiple critical parameters during comprehensive evaluations among all evaluated samples. The drying process with SPI wall material delivered maximum compound encapsulation and maintained suitable water values while conserving β-carotene and chlorophyll antioxidants. The combination of SPI-FD encapsulation reached optimal conditions through Principal Component Analysis (PCA) identification and desirability function analysis, which produced a 0.701 desirability score and beneficial clustering results.

From an industrial engineering standpoint, freeze-drying offers better product quality, while its economic costs, along with batch processing restrictions, make spray-drying more suitable for large-scale production due to lower operational expenses and higher energy efficiency. The preservation of bioactivity during premium or functional food applications makes SPI-FD a valid solution. This research establishes critical information for food process engineers and formulators regarding suitable encapsulation approaches, which supports further investigations on techno-economic modeling of pandan functional powder stability and its industrial-scale implementation.

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