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Research Article

Impact of Encapsulation on Gamma Oryzanol Content and Physicochemical Properties of Jasmine Rice Bran Oil Powder Derived from Rice Dough Stage

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Abstract

Background and Objective: Rice bran oil is renowned for its nutritional richness and significant health benefits, but it is highly susceptible to oxidation, limiting its shelf life and application. This study aimed to optimize the encapsulation process of jasmine rice bran oil extracted at the dough stage to improve its stability and preserve its bioactive properties. **Materials and Methods:** Various parameters, including homogenization speed (8,000-15,000 rpm), inlet air temperature (150-180°C), types of wall materials (maltodextrin, sodium caseinate, tapioca starch and soy protein) and maltodextrin-to-sodium caseinate ratios (1:1-3.5:1), were evaluated for their effects on emulsion stability, gamma oryzanol retention and encapsulation efficiency. The characteristics of the emulsion and the resultant jasmine rice bran oil powder (DJRBOP) were also studied. The results were analyzed using Duncan's Multiple Range Test (DMRT) which was used to determine significant mean differences at the 95% confidence level. **Results:** The findings revealed that encapsulation with a homogenization speed of 13,000 rpm, an inlet air temperature of 160°C and a maltodextrin-to-sodium caseinate ratio of 2.5:1 produced optimal results. This configuration yielded a high gamma oryzanol content of 6,685.65 mg/L, encapsulation efficiency of 77.44%, low moisture content (2.0%) and low water activity (a_w = 0.14). The morphology of the encapsulated powder was nearly spherical, with uniform and fine particle sizes, indicating effective encapsulation. **Conclusion:** This study demonstrates a novel encapsulation approach for jasmine rice bran oil using spray-drying at the dough stage, providing key insights into producing stable, high-quality functional food ingredients. The methodology enhances industrial applications, supporting improved product development and extended shelf life in functional food production.

Key words: Jasmine rice bran oil, encapsulation, spray-drying process, functional food ingredients, shelf life enhancement

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Rice bran oil (RBO) is a high-value product derived from the byproduct of the rice milling process, known for its exceptional nutritional composition and health benefits. Notably, rice bran oil extracted at the dough stage which is harvested 20-30 days after flowering (DAF) or approximately 9-12 days before full maturity exhibits higher concentrations of bioactive compounds compared to oil from mature rice[1]. The RBO is rich in unsaturated fatty acids and bioactive components such as gamma oryzanol, tocopherols, tocotrienols, polyphenols, squalene and phytosterols, all of which are associated with numerous health benefits[2]. Gamma oryzanol has been shown to reduce plasma cholesterol, inhibit cholesterol absorption, lower platelet aggregation, decrease atherosclerosis, suppress tumor growth and enhance fecal bile excretion[3]. Additionally, RBO possesses a more desirable flavor profile compared to fish and flaxseed oils, making it an attractive candidate for applications in food enrichment, pharmaceuticals and cosmetics[4]. Despite its advantages, RBO is highly susceptible to lipid oxidation during storage and processing, which limits its stability and shelf life. To address these challenges, encapsulation has been proposed as an effective method to protect RBO from environmental factors while preserving its organoleptic and nutritional properties. Encapsulation involves embedding a core material within a matrix to produce microcapsules with enhanced stability and functional properties[5]. Among various encapsulation techniques, spray drying is widely utilized for oils due to its cost-effectiveness, versatility and ability to convert liquid materials into stable powders with extended shelf life[6]. Typical inlet air temperatures for spray drying range from 150-220°C; however, temperature selection is critical, as low temperatures result in powders with high moisture content and agglomeration, while excessively high temperatures can cause core degradation and membrane cracking[6].

The selection of wall materials is another crucial factor in oil encapsulation, as these materials form a protective barrier around the core, influencing emulsion stability and microcapsule characteristics[7,8]. Commonly used wall materials include carbohydrates, proteins or their combinations. Carbohydrates, such as maltodextrins, enhance drying properties by forming a dry crust around the droplets, improving oxidative stability[9,10]. Proteins, such as sodium caseinate, are ideal for encapsulation due to their amphiphilic nature, which enhances their binding ability and facilitates better distribution around the encapsulated oil[11,12]. Prior research has explored various combinations of wall materials, including whey protein and maltodextrin[13], maltodextrin with whey protein concentrates or sodium caseinate[14] and pea protein with maltodextrin[15]. Additional studies have examined the effects of starches (e.g., tapioca and jackfruit) and proteins (e.g., soy and whey protein) on the optimization of encapsulation conditions for rice bran oil[4,16,17].

However, limited research exists on the microencapsulation of jasmine rice bran oil extracted at the dough stage, particularly regarding the effects of homogenization speed, inlet air temperature and wall material types on encapsulation efficiency, gamma oryzanol retention and microcapsule characteristics. This study addresses this gap by examining these factors' effects on encapsulation efficiency, gamma oryzanol content and the microcapsules' characteristics. The findings offer valuable insights into industrial applications, promoting the utilization of rice bran oil which is a nutritious yet underutilized resource often constrained by its susceptibility to rancidity.

MATERIALS AND METHODS

Study area: The research was conducted from July, 2023 to March, 2024 at the Faculty of Agricultural Innovation and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand.

Rice harvest and oil extraction: The dough stage of Thung Kula Rong-Hai Thai organic jasmine rice (harvested 9-12 days before full maturity) was generously provided by Community Enterprise Banmao Career Promotion Group Limited Partnership (Suwannaphum District, Roi Et Province, Thailand). Rice brans were dried at 70°C for 3 hrs to inhibit enzymatic activity. Oils were extracted using a screw press extraction machine. Fine particles in the expressed oil were separated by filtration. The rice bran oils (containing 10,000 mg/L of gamma oryzanol) were collected immediately after extraction and stored in amber vials at -20°C until use. All experiments were conducted in triplicates.

Preparation of encapsulated jasmine rice bran oil: Emulsions were prepared with a 17.5% solid (w/w) content of wall materials using water as the continuous phase and immature rice bran oil as the dispersed phase. Various wall materials (maltodextrin (MD), sodium caseinate (SC), soy protein (SP) and tapioca starch (TS)) and proportions of wall materials (1:1, 1.5:1, 2:1, 2.5:1, 3:1 and 3.5:1) were tested. Rice bran oils were blended with aqueous solutions of wall materials. The mixtures were homogenized at speeds ranging from 8,000-15,000 rpm for 5 min using a high-speed homogenizer (IKA T25 digital Ultra-Turrax, Germany).

Spray drying: The emulsions were spray-dried using a spray dryer (Lab Plant SD-06 Spray Dryer, UK). A 0.5 mm nozzle atomizer was used to atomize the emulsion. The drying feed rate was maintained at 5.0 mL/min. Inlet drying temperatures ranged from 150-180°C and outlet temperatures varied between 75 and 90°C.

Morphological analysis: Oil droplet and particle dispersion in the emulsion system were examined using an optical microscope (Nikon Microscope Eclipse E-400, Nikon Corporation, Japan; model BX51, Olympus, USA). A drop of emulsion was placed on a glass slide and observed under magnifications of 10x and 100x.

Moisture content and water activity: The moisture content of DJRBOP was determined using the AOAC method (2000). Water activity (a_w) was measured using a water activity meter (Aqualab 4TE, Pullman, Washington, USA)[18,19].

Color measurement: The color of DJRBOP samples was measured using a color measurement device (Hunter Lab, Color Flex 4510, USA) following the method by Anandan *et al.*[20], where, L* represents lightness, a* redness and b* yellowness.

Creaming stability: Creaming stability was measured using a modified method by Owens *et al.*[21]. Ten grams of emulsion samples were placed in test tubes, capped to prevent evaporation and left at ambient temperature for one day. The emulsions are separated into an opaque (cream) layer at the top and a turbid or transparent (serum) layer at the bottom. The creaming stability of the emulsion was characterized accordingly as follows:

$$\text{Creaming index (\%)} = \frac{HS}{HE} \times 100$$

Gamma oryzanol content determination: The gamma oryzanol content of the DJRBOP samples was quantified using the method detailed by Tuncel and Yilmaz[22], employing reverse-phase High-Performance Liquid Chromatography (HPLC). Before analysis, the DJRBOP samples were filtered through a 0.45 µm syringe filter to remove particulates. Subsequently, 20 µL of the filtered sample was injected into an HPLC column (4.6×250 mm, 5 µm particle size) for analysis. The initial mobile phase comprised 45% acetonitrile, 45% methanol, 5% isopropyl alcohol and 5% acetic acid solution, facilitating effective separation at a flow rate of 0.8 mL/min for the first 6 min. The mobile phase was then gradually transitioned to a linear gradient composed of methanol and isopropyl alcohol in a 25:70:5 (v/v/v) ratio over the next 10 min. This gradient was maintained for an additional 12 min before reverting to the initial conditions. This precise methodology ensured accurate detection and quantification of gamma oryzanol, providing key insights into the nutritional value and efficacy of the encapsulated rice bran oil.

Encapsulation efficiency determination: The encapsulation efficiency (EE) of the oil (%) was evaluated following the method outlined by Gupta *et al.*[23]. To determine the surface oil (SO), 1 g of microcapsules was mixed with 10 mL of hexane to extract the surface oil. The resulting solution was filtered using Whatman No. 1 filter paper and the retained powder was rinsed three times with 20 mL of hexane to ensure complete removal of surface oil. The hexane was evaporated at 60°C in a hot water bath until a constant weight was achieved, allowing the surface oil content to be determined gravimetrically.

For the total oil (TO) content, 1 g of microcapsules was dissolved in 10 mL of water and vigorously shaken in a separating funnel. The mixture was then combined with 25 mL of hexane/isopropanol (3:1 v/v) and shaken for 5 min. The clear organic phase was separated and the aqueous phase was re-extracted twice with the hexane/isopropanol mixture to ensure complete oil extraction. The collected organic phases were evaporated first in a boiling water bath and then dried in a hot air oven at 105°C for 30 min to achieve a constant weight. The total oil content was determined gravimetrically. Encapsulation efficiency (EE) was calculated using the following equation[9]:

$$EE = \frac{\text{TO-SO}}{\text{TO}} \times 100$$

Morphology of rice bran oil powder: The surface morphology and structural appearance of the rice bran oil powder samples were analyzed using a Scanning Electron Microscope (SEM, Quanta 250 FEG, FEI Company, USA). The powder samples were affixed to double-sided adhesive tape mounted on SEM stubs to ensure stability during imaging. Observations were conducted at an accelerating voltage of 5 kV to achieve high-resolution visualization of particle surfaces.

Data analysis: Each experimental analysis was performed in triplicate and the results were expressed as Mean±Standard Deviation to ensure reliability and reproducibility. Statistical analysis was conducted using SPSS software (version 22, SPSS Inc., Chicago, Illinois, USA), with a significance threshold set at $p<0.05$. This rigorous approach ensured accurate sample evaluation and reliable interpretation of the findings.

RESULTS AND DISCUSSION

Effect of homogenization speed on emulsion and characteristics and stability of dough stage of jasmine rice bran oil powder (DJRBOP): The impact of homogenization speed on the physicochemical properties and gamma oryzanol content of various samples was assessed (Table 1). The moisture content and water activity (a_w) of DJRBOP samples ranged from 2.44-2.61 and 0.137-0.139%, respectively. Similar results have been reported for the encapsulation of gamma oryzanol, Baru oil, soybean oil, DHA and sesame oil[13,24-26]. Generally, dried foods should maintain a moisture content below 25% and a_w below 0.60 to inhibit microbial growth[27]. In this study, the a_w of all samples was below 0.2, effectively preventing deleterious physicochemical changes and biochemical reactions, such as oxidation, which can adversely affect the color, flavor, texture and nutritional value of foods[28].

The color values (L* for lightness, a* for redness-greenness and b* for yellowness-blueness) of DJRBOP were presented in Table 1. An increase in stirring speed resulted in higher lightness, redness and yellowness values. Similarly, Samani and Naji[29] observed a significant increase in L* values in sesame vegetable cream samples with increasing homogenizer pressure, attributed to a reduction in droplet size distribution. Additionally, the observed changes in DJRBOP color with increased stirring speed may be associated with caramelization reactions occurring during the drying process.

The gamma oryzanol content significantly increased from 2,121.10 to 3,430.57 mg/L as the stirring speed was raised from 8,000 to 13,000 rpm. The emulsion prepared at 8,000 rpm exhibited a lower gamma oryzanol content, whereas the highest content was observed at 13,000 rpm. This increase can be attributed to reduced oil droplet size with higher homogenization speeds, which enhances emulsion homogeneity and stability[30], thereby improving gamma oryzanol retention. Conversely, at lower homogenization speeds, the wall materials failed to adequately form a film at the oil-water interface, leaving oil droplets poorly coated and prone to leakage during drying, resulting in reduced gamma oryzanol content. However, at 15,000 rpm, gamma oryzanol content declined. This reduction may be due to the formation of deflocculated clusters of primary fat droplets caused by excessive homogenization, which increased droplet size. Larger emulsion droplets are more susceptible to rupture during drying, leading to greater fat leakage from the microcapsules[31].

Oil droplet morphology and stability of emulsion: Emulsification is a critical step in the encapsulation process, as it directly impacts encapsulation efficiency and the stability of the final product. The microscopic images of initial emulsions processed at different homogenization speeds (8,000-15,000 rpm) (Fig. 1). All emulsions displayed spherical droplets, with higher stirring speeds yielding smaller droplet sizes compared to lower speeds (Fig. 1a-h). Smaller droplets enhance emulsion stability, contributing to improved encapsulation efficiency and reduced surface oil content[32]. Among the tested conditions, the emulsion produced at 13,000 rpm exhibited the highest stability, characterized by uniformly sized and evenly distributed oil droplets (Fig. 1e). This aligns with findings reported by Namira *et al.*[33], which suggest that higher stirring speeds facilitate the reduction of droplet size to the submicron scale, achieving a narrower size distribution. The creaming index, a measure of emulsion stability, further supported these findings. A low creaming index (0-20%) indicates minimal serum separation and greater emulsion stability[34], whereas, higher values suggest faster droplet movement and increased aggregation, resulting in less stable emulsions[35]. As shown in Table 1, the creaming index decreased significantly from 42.50 to 20.61% as the homogenization speed increased from 8,000 to 13,000 rpm. This enhanced stability at 13,000 rpm underscores the critical role of stirring speed in achieving optimal emulsion formation and stability[36].

Table 1: Properties of 20% DJRBO with 17.5% maltodextrin at varying homogenization speeds

	Homogenization speed (rpm)			
Powder characteristic	8,000	11,000	13,000	15,000
Moisture content (%)	2.44±0.03^b	2.61±0.03^a	2.51±0.02^a	2.55±0.01^a
a_w	0.137±0.01^a	0.139±0.01^a	0.138±0.01^a	0.138±0.01^a
Color				
L*	61.74±0.05^b	61.81±0.03^b	61.78±0.02^b	62.06±0.03^a
a*	0.10±0.01^d	0.28±0.01^a	0.14±0.01^c	0.17±0.02^b
b*	5.41±0.01^c	5.52±0.02^b	5.47±0.01^c	5.61±0.01^a
Gamma oryzanol content (mg/L)	2121.10±19.00^c	3119.13±106.54^b	3430.57±77.90^a	3409.38±85.90^a
Creaming index (%)	42.50±0.01^a	28.82±0.01^b	20.61±0.94^c	25.88±0.52^d

Different letters in the same row indicate significant differences ($p<0.05$), L*: Lightness, a*: Redness and b*: Yellowness, water activity (a_w)

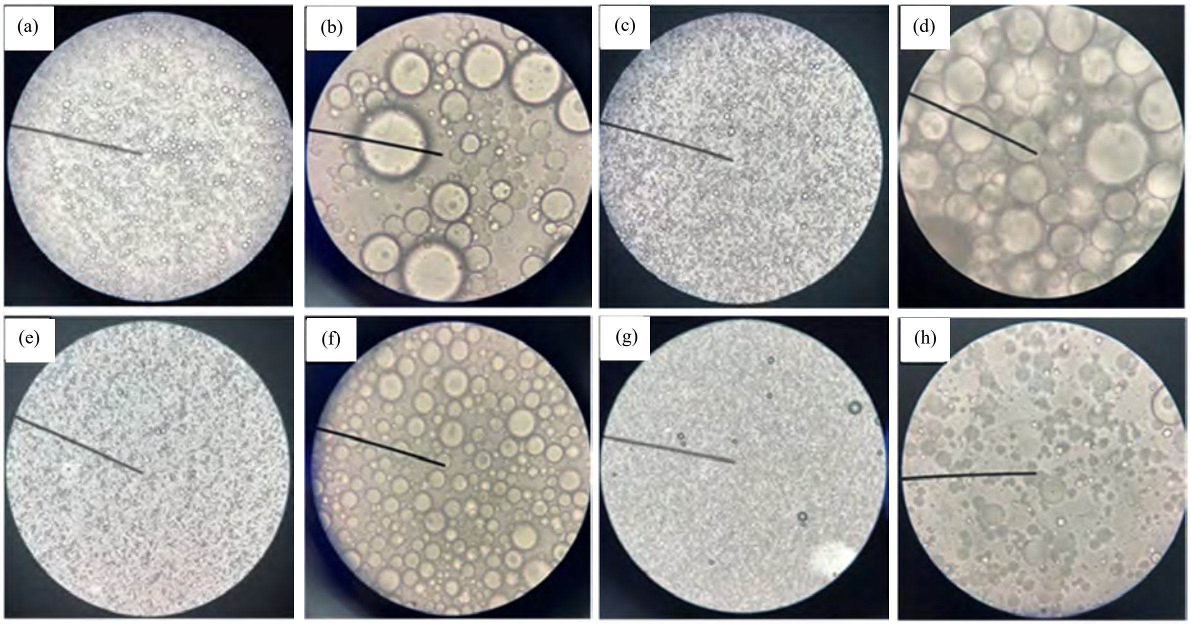

Fig. 1(a-h): Microscopic images of emulsion containing 20% rice bran oil stabilized with 12.5% maltodextrin prepared with different homogenization speeds, (a) 8,000 rpm at 10x, (b) 8,000 rpm at 100x, (c) 11,000 rpm at 10x, (d) 11,000 rpm at 100x, (e) 13,000 rpm at 10x, (f) 13,000 rpm at 100x, (g) 15,000 rpm at 10x and (h) 15,000 rpm at 100x

The observed results were consistent with the theory that higher stirring speeds promote increased homogeneity, leading to enhanced emulsion stability[37]. These findings highlight the importance of optimizing homogenization speed in the encapsulation process to produce stable and efficient emulsions.

Effects of inlet air temperature on gamma oryzanol content and powder characteristics: The effect of inlet air temperature on the physical and chemical properties, as well as the gamma oryzanol content of spray-dried powder, is presented in Table 2. As the drying temperature increased from 150 to 180°C, the moisture content decreased from 2.87 to 2.31% and the water activity (a_w) declined from 0.34 to 0.18. These findings align with those of Ren *et al.*[38], who reported reductions in the moisture content and a_w of citrus oil microcapsule powder (from 3.6 to 1.7% and 0.11 to 0.14%, respectively) as the drying temperature increased from 110 to 150°C. Similarly, Li *et al.*[25] observed that increasing the inlet air temperature from 127 to 187°C decreased the moisture content of oil powder from 5.54 to 2.33% and the a_w from 0.635 to 0.188%. These results can be attributed to the higher inlet air temperature, which enhances the drying process by providing a greater driving force for moisture evaporation, leading to a more complete drying process[39]. Low moisture content and a_w (below 0.6) are desirable characteristics for spray-dried powders, as they contribute to improved storage stability[40].

The effect of drying temperature on the color properties of DJRBOP is presented. While the overall appearance of the samples remained visually consistent, significant changes in color values (L*, a* and b*) were observed with increasing inlet air temperature. The lightness (L*) and yellowness (b*) increased significantly, from 51.55 to 64.30 and 1.44 to 8.70, respectively, as the inlet temperature rose from 150 to 180°C (Table 2). These findings are consistent with the studies of Chong and Wong[41], as well as Yang *et al.*[42], on spray-dried sapodilla and *Panax notoginseng* saponin (PNS) powder, respectively. The darker and yellower appearance of the powder at higher temperatures can be attributed to caramelization reactions triggered by elevated heat.

The gamma oryzanol content, a key quality parameter of DJRBOP, is also shown in Table 2. A significant impact on gamma oryzanol content was observed with varying inlet air temperatures. The content increased from 2,959.30 to 3,430.57 mg/L as the inlet temperature rose from 150 to 160°C, indicating that lower temperatures promote encapsulation efficiency by minimizing degradation. At lower inlet temperatures, particles were less likely to adhere, facilitating effective encapsulation and preserving gamma oryzanol content. These findings align with Ren *et al.*[38], who reported that citrus oil was well preserved at an inlet air temperature of 150°C.

Table 2: Characteristics of rice bran oil powder containing 20% dough stage of rice bran oil stabilized with 17.5% solid of maltodextrin

	Inlet air temperature (°C)			
Powder characteristics	150	160	170	180
Moisture content (%)	2.87±0.32^{a}	2.71±0.10^{b}	2.44±0.05^{c}	2.31±0.03^{d}
a_w	0.34±0.02^{a}	0.23±0.02^{b}	0.19±0.01^{c}	0.18±0.04^{c}
Color				
L*	64.30±0.01^{a}	61.90±0.04^{b}	55.71±0.01^{c}	51.55±0.04^{d}
a*	0.32±0.01^{a}	0.37±0.01^{a}	0.17±0.01^{b}	0.01±0.01^{c}
b*	1.44±0.01^{c}	1.74±0.01^{b}	8.56±0.01^{a}	8.70±0.01^{a}
Gamma oryzanol content (mg/L)	2,959.30±0.37^{b}	3,430.57±23.67^{e}	2,385.97±0.01^{c}	1,863.54±0.03^{d}

Different letters in each row mean statistically significant differences at a 95% confidence level

Table 3: Properties of RBOP with 20% dough-stage RBO stabilized by various wall materials

					Color		
Type of wall material	Gamma oryzanol content (mg/L)	Encapsulation efficiency (%)	Moisture content (%)	a_w	L*	a*	b*
MD	3,433.73±32.26^{e}	37.33±0.64^{cd}	2.43±0.02^{c}	0.22±0.02^{e}	61.90±0.04^{bc}	0.37±0.01^{b}	1.74±0.01^{f}
MD:SP	5,491.01±116.30^{b}	72.05±0.42^{b}	2.80±0.30^{a}	0.38±0.01^{a}	59.71±0.06^{e}	0.02±0.01^{g}	8.10±0.01^{b}
MD:SC	6,674.39±79.33^{a}	77.44±1.08^{a}	2.54±0.21^{b}	0.14±0.01^{f}	61.82±0.03^{c}	0.16±0.01^{d}	5.45±0.02^{e}
MD:TS	3,302.99±44.61^{f}	35.08±0.18^{d}	2.34±0.08^{d}	0.32±0.01^{b}	63.41±0.01^{a}	0.48±0.01^{a}	1.75±0.01^{c}
SC:SP	5,338.07±68.76^{c}	70.53±2.51^{b}	2.16±0.09^{e}	0.28±0.03^{c}	62.22±0.01^{b}	0.11±0.01^{f}	6.10±0.01^{d}
TS:SP	3,618.74±14.80^{d}	37.94±0.17^{c}	2.47±0.32^{c}	0.24±0.01^{d}	54.30±0.01^{g}	0.32±0.01^{c}	8.44±0.01^{a}
SC:MD	3,322.73±32.26^{ef}	35.34±0.18^{cd}	2.67±0.37^{b}	0.14±0.01^{f}	61.17±0.01^{cd}	0.19±0.01^{e}	6.70±0.01^{c}

Different letters in each column mean statistically significant differences at 95% confidence level, MD: Maltodextrin, SP: Soy protein, SC: Sodium caseinate and TS: Tapioca starch and the ratio of each sample (MD:SP, MD:SC and MD:TS) were 2.5:1

However, as the inlet temperature increased from 170 to 180°C, gamma oryzanol content significantly decreased from 2,385.97 to 1,863.54 mg/L, suggesting thermal degradation during spray drying. This observation is supported by studies from Abdullah *et al.*[43], on spray-dried coconut milk, Lai *et al.*[14], on microencapsulation of rice bran oil and Li *et al.*[25], on encapsulation of vitamin A palmitate, β-carotene and DHA via spray drying. Additionally, Kelly *et al.*[44] found that high drying temperatures reduce fat encapsulation efficiency across various oil types.

The degradation and loss of encapsulated gamma oryzanol at higher temperatures can be attributed to excessive evaporation, leading to membrane cracking and premature release of the core material[7]. These results suggested that lower drying temperatures are more favorable for achieving higher encapsulation efficiency and preserving the quality of microcapsules in DJRBOP.

Effect of wall material types and proportions on DJRBOP characteristics and gamma oryzanol content: The gamma oryzanol content of DJRBOP encapsulated with various wall materials, demonstrating that wall material types significantly influenced gamma oryzanol content ($p \leq 0.05$). The highest gamma oryzanol content (6,674.39 mg/L) was achieved using a maltodextrin/sodium caseinate blend, while the lowest (3,302.99 mg/L) was obtained with a maltodextrin/tapioca starch blend (Table 3). This outcome highlights the superior encapsulation properties of proteins, particularly sodium caseinate, due to their high solubility, excellent emulsifying properties, rapid interfacial film formation and surface activity[45]. Conversely, starch lacks sufficient interfacial properties for high encapsulation efficiency when used alone[8]. However, maltodextrin provides effective thermal protection and acts as a strong barrier against oxidation, safeguarding the core material from external factors[8]. The combination of maltodextrin and sodium caseinate leverages the protein's emulsifying abilities and the carbohydrate's matrix-forming properties, resulting in superior encapsulation efficiency and higher gamma oryzanol content[46]. This finding aligns with prior research by Munin and Edwards-Lévy[47], who reported high encapsulation efficiency using maltodextrin and sodium caseinate blends and Lai *et al.*[14], who found that sodium caseinate outperformed whey protein concentrate for rice bran oil encapsulation. The encapsulation efficiency (EE) of DJRBOP using various wall materials is also shown in Table 3, ranging from 35.08 to 77.44%. The maltodextrin/sodium caseinate blend exhibited the highest EE (77.44%), underscoring its effectiveness in entrapping jasmine rice bran oil during the spray drying process. This result corresponds with the blend's highest gamma oryzanol content. Previous studies have similarly reported that wall material types significantly affect the EE of encapsulated oil products[24,48].

Table 4: Properties of RBOP with 20% immature RBO stabilized by maltodextrin-sodium caseinate ratios

Wall material ratio (MD:SC)	Gamma oryzanol content (mg/L)	a_w	Moisture content (%)	Color		
				L*	a*	b*
1:1	4,710.39±29.91[f]	0.13±0.01[bc]	2.080±0.12[d]	61.79±0.02[bc]	0.11±0.01[b]	5.40±0.01[d]
1.5:1	5,286.48±37.25[e]	0.14±0.01[b]	2.150±0.13[d]	62.18±0.02[a]	0.09±0.01[c]	5.41±0.02[d]
2:1	5,920.24±36.50[d]	0.14±0.01[b]	2.613±0.15[b]	61.75±0.04[c]	0.13±0.01[b]	5.31±0.01[e]
2.5:1	6,685.65±69.93[a]	0.14±0.01[b]	2.007±0.02[e]	61.79±0.03[d]	0.25±0.02[a]	5.53±0.03[c]
3:1	5,985.35±184.79[b]	0.33±0.01[a]	2.367±0.04[c]	58.16±0.04[d]	0.07±0.01[c]	10.07±0.04[a]
3.5:1	5,248.28±78.93[c]	0.32±0.01[a]	3.890±0.12[a]	58.41±0.01[d]	0.09±0.01[c]	9.99±0.02[b]

Different letters in each column mean statistically significant differences at 95% confidence level, MD: Maltodextrin and SC: Sodium caseinate

Moisture content and water activity (a_w) of DJRBOP prepared with different wall materials are also presented in Table 3, showing values ranging from 2.16 to 2.80 and 0.14 to 0.38%, respectively. The maltodextrin/soy protein blend exhibited the highest moisture content and a_w, whereas the maltodextrin/sodium caseinate blend had the lowest. These variations, statistically significant ($p \leq 0.05$), likely reflect differences in the chemical structures of the wall materials. Similar trends were reported by Selim *et al.*[48] and Zahran *et al.*[49], who observed significant differences in the moisture content of spray-dried microcapsules (hazelnut oil and fish oil) based on wall material type. The low moisture content and a_w values across all powders in this study indicate reduced free water, minimizing chemical and physical damage and microbial degradation, thereby enhancing stability and quality[50].

Color values (L*, a* and b*) of DJRBOP are also provided in Table 3, with significant differences observed among samples. The maltodextrin/tapioca starch blend had the highest lightness (L*) value of 63.41, consistent with Xiao *et al.*[51] findings that starch improves color and other physicochemical properties of microcapsules. The tapioca starch/soy protein blend exhibited the lowest lightness value (54.30), while the highest yellowness (b* = 8.44) was attributed to the Maillard reaction during spray drying. Overall, these results suggest that a maltodextrin/sodium caseinate blend is the most suitable wall material for spray-drying and microencapsulating jasmine rice bran oil at the dough stage.

The optimal ratio of maltodextrin to sodium caseinate was investigated to achieve favorable characteristics and maximize gamma oryzanol content in DJRBOP. The gamma oryzanol content varied significantly among different ratios, ranging from 4,710.39 to 6,685.65 mg/L (Table 4). The content increased substantially as the maltodextrin/sodium caseinate ratio increased from 1:1 to 2.5:1, with the highest value of 6,319.13 mg/L observed at a ratio of 2.5:1. However, further increasing the ratio to 3:1 and 3.5:1 led to a decline in gamma oryzanol content, likely due to the higher maltodextrin concentration increasing the total solid content and diluting the nutrient concentration of the product[52]. This observation aligns with findings by Murali *et al.*[17], who reported a decrease in gamma oryzanol content with increasing starch-to-protein ratios in encapsulated powders.

The all DJRBOP samples produced at different maltodextrin/sodium caseinate ratios exhibited low moisture content (below 4%) and water activity (a_w <0.6), which are favorable for product stability. Additionally, as shown in Table 4, the whiteness of the samples slightly decreased with increasing maltodextrin ratios (1:1 to 3.5:1). This reduction in whiteness may be attributed to non-enzymatic browning reactions occurring during the drying process. These results highlight that a maltodextrin/sodium caseinate ratio of 2.5:1 provides the most desirable balance between gamma oryzanol content and physical properties in DJRBOP.

Morphology of DJRBOP: The SEM images of microcapsules of dough stage jasmine rice bran oil (DJRBOP) produced with different wall materials. All samples (Fig. 2a-g) exhibited a nearly spherical morphology with minor appendages. Some particle surfaces displayed roughness or depressions, likely caused by particle shrinkage due to water loss during the spray drying process (Fig. 2). Microcapsules produced using a maltodextrin and sodium caseinate blend were smaller, exhibited greater particle homogeneity and had smoother surfaces compared to those produced with other wall materials.

In contrast, larger particles and agglomerates were observed in samples with less stable emulsions, which may have resulted from partial flocculation of the feed emulsion and subsequent agglomerate formation during spray drying. The SEM images confirm that DJRBOP produced with maltodextrin and sodium caseinate provided superior particle morphology and uniformity, consistent with the high encapsulation efficiency (77.44%) reported earlier. This indicates that the microparticles effectively protected the core material and were less susceptible to oxidative degradation.

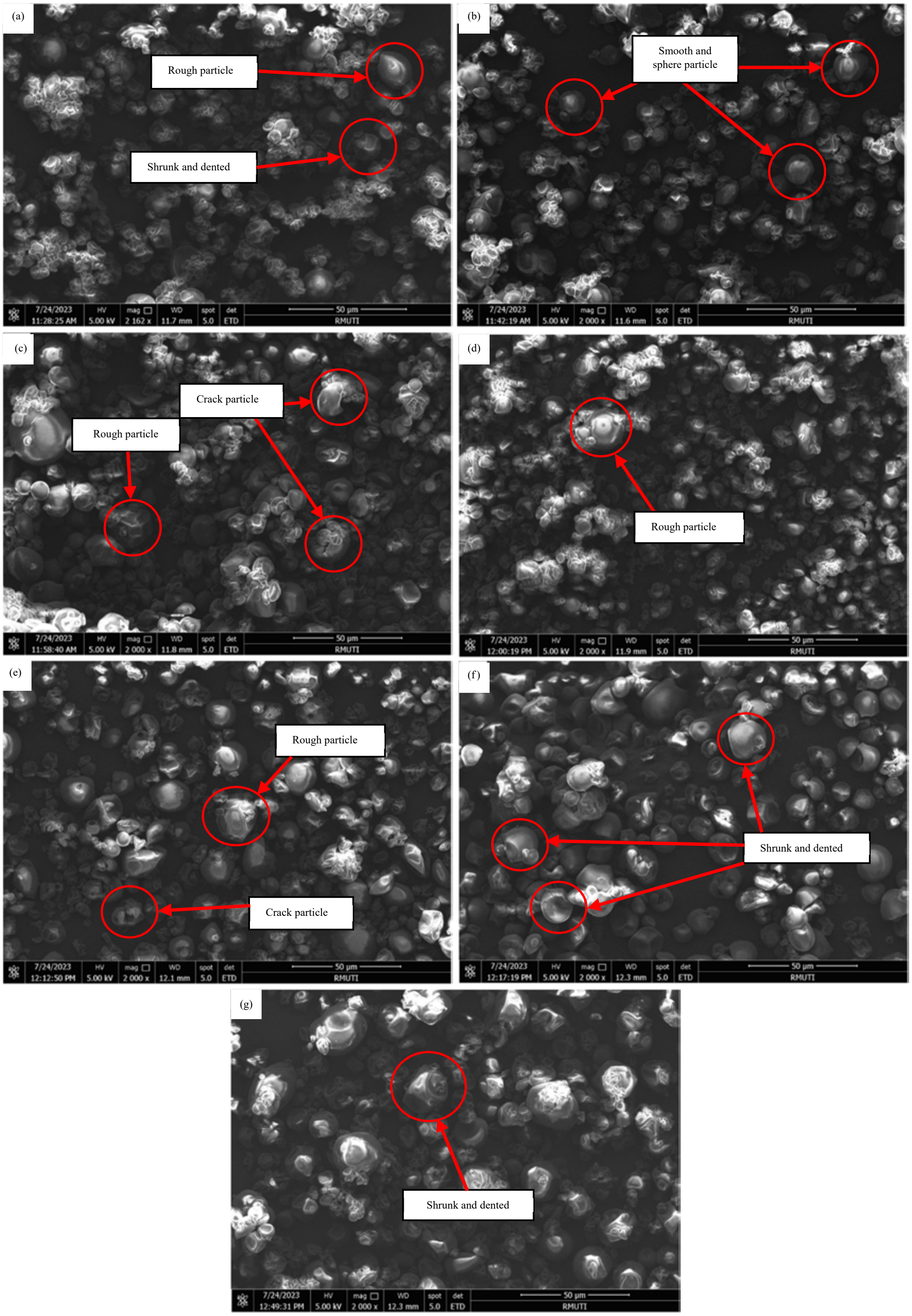

Fig. 2(a-g): SEM images of microcapsules of dough stage jasmine rice bran oil (DJRBOP) produced with different wall materials at ×2,000 magnification, (a) MD (maltodextrin), (b) MD/SC (maltodextrin/sodium caseinate), (c) MD/SP (maltodextrin/soy protein), (d) MD/TS (maltodextrin/tapioca starch), (e) SC/SP (sodium caseinate/soy protein), (f) TS/SP (tapioca starch/soy protein) and (g) SC/MD (sodium caseinate/maltodextrin)

Similar findings have been reported by Lima *et al.*[24], for Baru oil and by Li *et al.*[25], for soy oil, further supporting the effectiveness of maltodextrin and sodium caseinate as wall materials for microencapsulation. These results emphasize the importance of wall material selection in achieving high-quality microcapsules with desirable characteristics.

CONCLUSION

This study investigated the effects of encapsulation parameters, including homogenization speed, air inlet temperature and wall material composition, on the characteristics and gamma oryzanol content of immature rice bran oil powder (DJRBOP). The findings demonstrated that these parameters significantly influenced gamma oryzanol content, encapsulation efficiency and powder properties. Optimized conditions, homogenization speed of 13,000 rpm, spray drying inlet temperature of 160°C and a maltodextrin/sodium caseinate ratio of 2.5:1 which resulted in emulsions with enhanced stability and smaller oil particles. The resulting microcapsules exhibited high encapsulation efficiency, elevated gamma oryzanol content and superior powder quality with low water activity (a_w) and moisture content. The characteristic properties of rice bran oil powder, including its antioxidant activity in both *in vitro* and human cell-based studies, as well as its toxicity in human cell models, will be evaluated to determine its potential as a future dietary supplement.

SIGNIFICANCE STATEMENT

This study provides critical insights into optimizing encapsulation processes for immature rice bran oil, a valuable functional ingredient known for its high gamma oryzanol content and health-promoting properties. By identifying the ideal combination of homogenization speed, spray drying temperature and wall material composition, this research advances the development of stable, high-quality microcapsules with superior encapsulation efficiency and product characteristics. The findings contribute to enhancing the industrial application of immature rice bran oil, offering a viable approach to preserving its bioactive components, extending shelf life and expanding its use in functional foods, pharmaceuticals and nutraceuticals. This work lays a foundation for further exploration of encapsulation technologies to improve the stability and functionality of bioactive-rich oils.

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REFERENCES

1. Li, D., C. Zhang, H.M. Zhang, D.J. Zhang and F. Zuo, 2022. Separation of γ-oryzanol from immature rice seeds by nanofiltration membrane. Food Sci. Technol., Vol. 42. 10.1590/fst.12922.
2. Liu, R., Y. Xu, M. Chang, L. Tang and M. Lu *et al.*, 2021. Antioxidant interaction of α-tocopherol, γ-oryzanol and phytosterol in rice bran oil. Food Chem., Vol. 343. 10.1016/j.foodchem.2020.128431.
3. Wang, Q., P. Han, M. Zhang, M. Xia and H. Zhu *et al.*, 2007. Supplementation of black rice pigment fraction improves antioxidant and anti-inflammatory status in patients with coronary heart disease. Asia Pac. J. Clin. Nutr., 16: 295-301.
4. Murali, S., A. Kar, A.S. Patel, D. Mohapatra and P. Krishnakumar, 2017. Optimization of rice bran oil encapsulation using jackfruit seed starch-whey protein isolate blend as wall material and its characterization. Int. J. Food Eng., Vol. 13. 10.1515/ijfe-2016-0409.
5. Onsaard, E. and W. Onsaard, 2019. Microencapsulated Vegetable Oil Powder. In: Microencapsulation-Processes, Technologies and Industrial Applications, Salaün, F. (Ed.), IntechOpen, London, United Kingdom, ISBN: 978-1-83881-870-8.
6. Mohammed, N.K., C.P. Tan, Y.A. Manap, B.J. Muhialdin and A.S.M. Hussin, 2020. Spray drying for the encapsulation of oils-A review. Molecules, Vol. 25. 10.3390/molecules25173873.
7. Gharsallaoui, A., G. Roudaut, O. Chambin, A. Voilley and R. Saurel, 2007. Applications of spray-drying in microencapsulation of food ingredients: An overview. Food Res. Int., 40: 1107-1121.
8. Carneiro, H.C.F., R.V. Tonon, C.R.F. Grosso and M.D. Hubinger, 2013. Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials. J. Food Eng., 115: 443-451.
9. Hofman, D.L., V.J. van Buul and F.J.P.H. Brouns, 2016. Nutrition, health, and regulatory aspects of digestible maltodextrins. Crit. Rev. Food Sci. Nutr., 56: 2091-2100.

10. Vidović, S.S., J.Z. Vladić, Ž.G. Vaštag, Z.P. Zeković and L.M. Popović, 2014. Maltodextrin as a carrier of health benefit compounds in *Satureja montana* dry powder extract obtained by spray drying technique. Powder Technol., 258: 209-215.
11. Hogan, S.A., B.F. McNamee, E.D. O'Riordan and M. O'Sullivan, 2001. Emulsification and microencapsulation properties of sodium caseinate/carbohydrate blends. Int. Dairy J., 11: 137-144.
12. Shi, L., S.K. Beamer, H. Yang and J. Jaczynski, 2018. Micro-emulsification/encapsulation of krill oil by complex coacervation with krill protein isolated using isoelectric solubilization/precipitation. Food Chem., 244: 284-291.
13. Wangdee, K., E.A. Decker and E. Onsaard, 2022. Characterization of encapsulated γ-oryzanol powder by spray drying using whey protein and maltodextrin as wall materials. J. Food Sci. Technol., 59: 355-365.
14. Lai, Q.D., N.T.T. Doan and T.T.T. Nguyen, 2021. Influence of wall materials and homogenization pressure on microencapsulation of rice bran oil. Food Bioprocess Technol., 14: 1885-1896.
15. Benito-Román, Ó., T. Sanz and S. Beltrán, 2020. Microencapsulation of rice bran oil using pea protein and maltodextrin mixtures as wall material. Heliyon, Vol. 6. 10.1016/j.heliyon.2020.e03615.
16. Murali, S., A. Kar, A.S. Patel, J. Kumar, D. Mohapatra and S.K. Dash, 2023. Encapsulation of rice bran oil in tapioca starch-soya protein isolate complex using spray drying. Indian J. Agric. Sci., 86: 984-991.
17. Murali, S., A. Kar and A.S. Patel, 2020. Protein-polysaccharide matrix as novel wall material for rice bran oil encapsulation. J. Agric. Eng., 57: 329-340.
18. Stone, M.C. and G. Carta, 2007. Patterns of protein adsorption in chromatographic particles visualized by optical microscopy. J. Chromatogr. A, 1160: 206-214.
19. Zhang, L., D.W. Sun and Z. Zhang, 2017. Methods for measuring water activity (a_w) of foods and its applications to moisture sorption isotherm studies. Crit. Rev. Food Sci. Nutr., 57: 1052-1058.
20. Anandan, R., N.S. Chatterjee, R. Sivakumar, S. Mathew, K.K. Asha and B. Ganesan, 2015. Dietary chitosan supplementation ameliorates isoproterenol-induced aberrations in membrane-bound ATpases and mineral status of rat myocardium. Biol. Trace Elem. Res., 167: 103-109.
21. Owens, C., K. Griffin, H. Khouryieh and K. Williams, 2018. Creaming and oxidative stability of fish oil-in-water emulsions stabilized by whey protein-xanthan-locust bean complexes: Impact of pH. Food Chem., 239: 314-322.
22. Tuncel, N.B. and N. Yılmaz, 2011. Gamma-oryzanol content, phenolic acid profiles and antioxidant activity of rice milling fractions. Eur. Food Res. Technol., 233: 577-585.
23. Gupta, P.K., S.B. Jadhav and R.S. Singhal, 2015. Development of *shrikhand* premix using microencapsulated rice bran oil as fat alternative and hydrocolloids as texture modifier. Food Hydrocolloids, 48: 220-227.
24. Lima, D.C., N.H. Noguera, A. del Pilar Flores Granados and R.A.F. Rodrigues, 2023. Hydrocolloids and partially defatted cake on encapsulation of Baru oil (*Dipteryx alata* Vogel): A study on emulsion, particle, and oxidative stability. Food Bioprocess Technol., 16: 2598-2610.
25. Li, X., Y. Feng, S. Ting, J. Jiang and Y. Liu, 2019. Effect of processing conditions on the physiochemical properties and nutrients retention of spray-dried microcapsules using mixed protein system. CyTA-J. Food, 17: 25-35.
26. Fajriah, F., A. Mustafa, M. Rais, L. Anadi and K.T. Isamu *et al*., 2022. UFLPlus: An underwater fish lamp technology as an innovation of fish-luring aids on boat lift net. J. Ilmiah Perikanan Kelautan, 14: 93-104.
27. Jay, J.M., M.J. Loessner and D.A. Golden, 2005. Protection of Foods by Drying. In: Modern Food Microbiology, Jay, J.M., M.J. Loessner and D.A. Golden (Eds.), Springer, Boston, MA, ISBN: 978-0-387-23413-7, pp: 443-456.
28. Mujumdar, A.S., 2014. Handbook of Industrial Drying. 4th Edn., CRC Press, Boca Raton, Florida, ISBN: 9781466596658, Pages: 1348.
29. Samani, S.A. and M.H. Naji, 2019. Effect of homogenizer pressure and temperature on physicochemical, oxidative stability, viscosity, droplet size, and sensory properties of Sesame vegetable cream. Food Sci. Nutr., 7: 899-906.
30. Juttulapa, M., S. Piriyaprasarth, H. Takeuchi and P. Sriamornsak, 2017. Effect of high-pressure homogenization on stability of emulsions containing zein and pectin. Asian J. Pharm. Sci., 12: 21-27.
31. Ochoa, A.A., J.A. Hernández-Becerra, A. Cavazos-Garduño, E.J. Vernon-Carter and H.S. García, 2016. Preparation and characterization of curcumin nanoemulsions obtained by thin-film hydration emulsification and ultrasonication methods. Rev. Mex. Ing. Quim., 15: 79-90.
32. Noguera, N.H., D.C. Lima, J.C.K.M. Filho and R.A.F. Rodrigues, 2022. Production of rice bran oil (*Oryza sativa* L.) microparticles by spray drying taking advantage of the technological properties of cereal co-products. J. Microencapsulation, 39: 314-326.
33. Namira, Z.R., V. Paramita and H. Kusumayanti, 2021. The effect of rotational speed of homogenization on emulsion results obtained using soy lecithin emulsifier. J. Vocational Stud. Appl. Res., 3: 14-17.
34. Zungur, A., M. Koç and F.K. Ertekin, 2015. Physical properties of olive oil in water model emulsion: Effect of aqueous and oil phase concentration and homogenization types. Akademik Gıda, 13: 22-34.

35. Zarena, A.S., S. Bhattacharya and U.S. Kadimi, 2012. Mangosteen oil-in-water emulsions: Rheology, creaming, and microstructural characteristics during storage. Food Bioprocess Technol., 5: 3007-3013.
36. McClements, D.J. and J. Rao, 2011. Food-grade nanoemulsions: Formulation, fabrication, properties, performance, biological fate, and potential toxicity. Crit. Rev. Food Sci. Nutr., 51: 285-330.
37. Siregar, R.F., A. Hintono and S. Mulyani, 2012. The change of chicken egg functional properties after pasteurization [In Indonesian]. Anim. Agric. J., 1: 521-528.
38. Ren, W., G. Tian, S. Zhao, Y. Yang and W. Gao *et al*., 2020. Effects of spray-drying temperature on the physicochemical properties and polymethoxyflavone loading efficiency of citrus oil microcapsules. LWT, Vol. 133. 10.1016/j.lwt.2020.109954
39. Arya, S.S. and B.R. Thakur, 1990. Effect of water activity on vitamin A degradation in wheat flour (Atta). J. Food Process. Preserv., 14: 123-134.
40. Dantas, D., M.A. Pasquali, M. Cavalcanti-Mata, M.E. Duarte and H.M. Lisboa, 2018. Influence of spray drying conditions on the properties of avocado powder drink. Food Chem., 266: 284-291.
41. Chong, S.Y. and C.W. Wong, 2017. Effect of spray dryer inlet temperature and maltodextrin concentration on colour profile and total phenolic content of Sapodilla (*Manilkara zapota*) powder. Int. Food Res. J., 24: 2543-2548.
42. Yang, M., B. Xu, X. Wang, W. Li, J. Cao, W. Li and Y. Qiao, 2021. Effect of spray drying conditions on physical properties of *Panax notoginseng* saponin (PNS) powder and the intra-batch dissolution variability of PNS hydrophilic matrix tablet. Drug Des. Dev. Ther., 15: 1425-1440.
43. Abdullah, Z., F.S. Taip, S.M.M. Kamal and R.Z. Abdul Rahman, 2021. The effect of drying temperature and sodium caseinate concentration on the functional and physical properties of spray-dried coconut milk. J. Food Sci. Technol., 58: 3174-3182.
44. Kelly, G.M., J.A. O'Mahony, A.L. Kelly and D.J. O'Callaghan, 2014. Physical characteristics of spray-dried dairy powders containing different vegetable oils. J. Food Eng., 122: 122-129.
45. Zhang, Y., K. Pan and Q. Zhong, 2018. Eugenol nanoencapsulated by sodium caseinate: Physical, antimicrobial, and biophysical properties. Food Biophys., 13: 37-48.
46. Labuschagne, P., 2018. Impact of wall material physicochemical characteristics on the stability of encapsulated phytochemicals: A review. Food Res. Int., 107: 227-247.
47. Munin, A. and F. Edwards-Levy, 2011. Encapsulation of natural polyphenolic compounds: A review. Pharmaceutics, 3: 793-829.
48. Selim, K.A., S.S. Alharthi, A.M. Abu El-Hassan, N.A. Elneairy, L.A. Rabee and A.G. Abdel-Razek, 2021. The effect of wall material type on the encapsulation efficiency and oxidative stability of fish oils. Molecules, Vol. 26. 10.3390/molecules26206109.
49. Zahran, H., H. Bat and N. Şahin-Yeşilçubuk, 2022. Influence of wall material combination on the lipid oxidation of the hazelnut oil microcapsules. Discovery Food, Vol. 2. 10.1007/s44187-022-00018-4.
50. Inada, K.O.P., S. Nunes, J.A. Martínez-Blázquez, F.A. Tomás-Barberán, D. Perrone and M. Monteiro, 2020. Effect of high hydrostatic pressure and drying methods on phenolic compounds profile of jabuticaba (*Myrciaria jaboticaba*) peel and seed. Food Chem., Vol. 309. 10.1016/j.foodchem.2019.125794.
51. Xiao, Z., J. Xia, Q. Zhao, Y. Niu and D. Zhao, 2022. Maltodextrin as wall material for microcapsules: A review. Carbohydr. Polym., Vol. 298. 10.1016/j.carbpol.2022.120113.
52. Quek, S.Y., N.K. Chok and P. Swedlund, 2007. The physicochemical properties of spray-dried watermelon powders. Chem. Eng. Process. Process Intensif., 46: 386-392.