



Development of High-Stability Avocado Oil Powder via Spray Drying and Wall Material Engineering

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Abstract

Virgin avocado oil, a bioactive compound rich in monounsaturated fatty acids and antioxidants, is highly susceptible to oxidative degradation, which limits its industrial applications. This study investigated the microencapsulation of virgin avocado oil via spray drying to enhance its stability. We formulated oil-in-water (O/W) emulsions using a ternary blend of maltodextrin (MD), gum Arabic (GA), and guar gum (GG) as the wall material. The influence of the wall material composition on the physicochemical properties of the resulting avocado oil powder was evaluated. Emulsions were homogenized and then spray-dried at an inlet temperature of 150°C. An optimized wall material ratio of 59% MD, 40% GA, and 1% GG yielded a high production yield (78.72%) and an encapsulation efficiency of 51.25%. The microcapsules exhibited a low water activity (0.153) and moisture content (2.83%), which are critical for powder stability. The powder also demonstrated good solubility (68.37%) and wettability (4.71 s). Morphological analysis revealed semi-spherical microcapsules with the characteristic surface indentations of spray-dried powders. These findings demonstrate that a balanced blend of MD, GA, and GG can effectively encapsulate avocado oil, producing a stable powder with potential for use as a functional ingredient in the food industry. Future work should focus on validating the long-term oxidative stability of the powder.

Keywords: Microencapsulation, Spray Drying, Avocado Oil, Wall Materials, Gum Arabic, Maltodextrin

1. Introduction

Avocado (*Persea Americana* Mill.) is a high-value fruit cultivated worldwide with its oil being a key agricultural product. Unlike most vegetable oils derived from seeds, avocado oil is extracted from the mesocarp, the fleshy pulp of the fruit, which can have an oil content of up to 60% [1]. The 'Hass' variety is the most commercially significant cultivar, accounting for approximately 95% of avocados sold globally [2]. However, the fruit's short shelf-life and susceptibility to chilling injury and disease contribute to significant post-harvest losses, which can be as high as 30-40% in the supply chain [3, 4]. This necessitates the development of value-added processing techniques to ensure sustainable utilization of the crop, particularly for the food industry. Virgin avocado oil (VAO) is recognized for its nutritional benefits, including a high content of monounsaturated fatty acids, as well as potential cardiovascular and anti-inflammatory effects [5, 6]. Modern extraction techniques use low temperatures (<50°C) to produce VAO, preserving its natural bioactive compounds [7]. Despite this, the oil's high concentration of unsaturated fatty acids makes it prone to oxidation, and it is also susceptible to thermal degradation at temperatures above 180°C [8].

Microencapsulation is a widely used technology to protect sensitive core materials like oils from degradation, improve their handling, and control their release [9]. Spray drying is the most common microencapsulation method used in the food industry due to its cost-effectiveness and scalability. The process involves atomizing an oil-in-

water (O/W) emulsion into a hot air stream, which rapidly evaporates the water and forms a powder consisting of small microcapsules where oil droplets are entrapped within a solid matrix of wall material.

The choice of wall material is critical for the stability and functionality of the final powder. Maltodextrin (MD) is a common carrier due to its low viscosity and high solubility, forming a good protective matrix [10]. Gum Arabic (GA) is an excellent emulsifier and film-former, enhancing oil retention [11]. Guar gum (GG) is a hydrocolloid known for its ability to increase viscosity and strengthen networks, which can improve encapsulation efficiency [12]. While studies have explored these materials individually or in pairs for encapsulating various oils [13-15], a systematic investigation into the ternary combination of maltodextrin, gum Arabic, and guar gum for the microencapsulation of virgin avocado oil is lacking. The specific interactions and optimal ratios of these three components for maximizing encapsulation efficiency and production yield for avocado oil are not well understood. This study, therefore, aimed to (1) evaluate the effect of different ratios of MD, GA, and GG as wall materials on the physicochemical properties of spray-dried virgin avocado oil powder, and (2) identify an optimized formulation. The target success metrics for a stable and commercially viable powder were defined as achieving an encapsulation efficiency (EE) $\geq 50\%$, a water activity (a.w.) ≤ 0.20 , and a final moisture content $\leq 4\%$.

2. Materials and methods

2.1 Materials

Virgin avocado oil (VAO) was extracted from the mesocarp of commercially mature, unripe Hass variety Persea Americana Mill. avocados, procured from a fresh produce market in Sakon Nakhon, Thailand. Maltodextrin (MD, DE 10-12), gum Arabic (GA) from Acacia senegal, and guar gum (GG) were obtained from Krungthepchemi Ltd. (Bangkok, Thailand).

2.2 Preparation of Virgin Avocado Oil (VAO)

The avocados were washed, and the pulp (mesocarp) was separated and sliced into 0.25 cm thick pieces. The slices were arranged on drying trays and oven-dried at 60°C for 12 h to reduce moisture content. The dried avocado slices were then finely ground, and the oil was extracted using a screw press (cold pressing). The resulting VAO was filtered through Whatman No. 4 filter paper and stored in airtight, foil-wrapped containers at -20°C until use.

2.3 Emulsion Formulation and Preparation

An experimental mixture design was used to prepare five different oil-in-water (O/W) emulsion formulations (AOE1–AOE5) with varying wall material compositions, as detailed in Table 1. The wall material solution was prepared by dissolving blends of MD, GA, and GG in deionized water to a final concentration of 25% (w/w). The core material (VAO) was then added to the wall material solution at a fixed ratio of 1:4 (oil: wall material solids, w/w). The final emulsions had a total solids content of approximately 30% (w/w) and a pH in the range of 4.0–4.5. To create the emulsions, the mixture was homogenized using a high-shear rotor-stator device (IKA T18 Ultra-Turrax, Germany) at 15,000 rpm for 5 min. The temperature of the emulsion was maintained below 40°C during homogenization.

Table 1 Wall material composition of the five avocado oil-in-water emulsion formulations

Sample Code	Maltodextrin (MD) (% w/w)	Gum Arabic (GA) (% w/w)	Guar Gum (GG) (% w/w)
AOE1	70	29	1
AOE2	70	25	5
AOE3	55	40	5
AOE4	59	40	1
AOE5	62.5	35	2.5

2.4 Microencapsulation by Spray Drying

All five emulsion formulations were converted into powder using a laboratory-scale spray dryer (Mobile Minor 2000, GEA Niro, Denmark). The operating conditions were as follows: inlet air temperature of 150°C, outlet air temperature of 80 $\pm$ 2°C, and emulsion feed rate of 1.0 L/h. The emulsions were atomized using a two-fluid nozzle with an atomization pressure of 1.5 bar. The resulting microencapsulated powder was collected from the cyclone separator and stored in sealed, airtight containers at -20°C for further analysis.

2.5 Physicochemical Characterization of Microcapsules

2.5.1 Production Yield

Production yield was calculated as the ratio of the mass of the powder collected after spray drying to the initial mass of solids in the feed emulsion, expressed as a percentage:

$$\text{Yield (\%)} = \frac{\text{Mass of powder collected (g)}}{\text{Total solids in feed emulsion (g)}} \times 100$$

2.5.2 Encapsulation Efficiency (EE)

Encapsulation efficiency was determined by measuring the total oil and surface oil content of the powder. Total oil was extracted from 5 g of powder by Soxhlet extraction using petroleum ether for 6 h. To measure surface oil, 5 g of powder were dispersed in 50 mL of petroleum ether and shaken for 2 min. The mixture was then filtered and the solvent was evaporated from the filtrate in an oven at 105°C for 30 min, and the mass of the extracted surface oil was determined. EE was calculated using the following formula:

$$EE (\%) = \frac{\text{Total oil (g)} - \text{Surface oil (g)}}{\text{Total oil (g)}} \times 100$$

2.5.3 Moisture Content and Water Activity

Moisture content was determined gravimetrically by drying 1 g of powder in an oven at 105°C until a constant weight was achieved (AOAC, 2000). Water activity (a_w) was measured at $25 \pm 1^\circ\text{C}$ using a water activity meter (AquaLab 4TE, Decagon Devices, USA).

2.5.4 Wettability and Solubility

Wettability was determined by gently sprinkling 1 g of powder onto the surface of 100 mL of distilled water at 25°C without agitation. The time taken for the last of the powder particles to become completely submerged was recorded in seconds [16]. Solubility was measured by dispersing 1 g of powder in 10 mL of distilled water, stirring for 5 min, and then centrifuging at 3,000 rpm for 10 min. A known volume of the supernatant was transferred to a pre-weighed dish and dried at 105°C to a constant weight. Solubility was expressed as the percentage of the dried solids relative to the initial powder weight [17].

2.5.5 Color Analysis

Instrumental color analysis of the powder samples was performed using a colorimeter (ColorFlex XE, HunterLab, USA). The color was expressed in CIE Lab* coordinates, where L* indicates lightness (0 = black, 100 = white), a* indicates redness (+) or greenness (-), and b* indicates yellowness (+) or blueness (-). Chroma (C^* , color intensity) and hue angle (h° , the tone of the color) were calculated as follows:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

$$C^* = \arctan\left(\frac{b^*}{a^*}\right)$$

2.5.6 Morphological Analysis

The external morphology of the microcapsules was examined using a scanning electron microscope (SEM) (Eclipse H550S, Nikon, Japan). Powder samples were mounted onto aluminum stubs using double-sided adhesive tape and then sputter-coated with gold in a vacuum evaporator. The samples were observed at an accelerating voltage of 15 kV.

2.5.7 Total Soluble Solids (°Brix)

Total soluble solids of the feed emulsions were measured using a digital refractometer (ATAGO, PAL-1, Japan) at room temperature ($25 \pm 1^\circ\text{C}$).

2.6 Statistical Analysis

All experiments were conducted in triplicate, and the results are presented as the mean $\pm$ standard deviation (SD). The data were subjected to analysis of variance (ANOVA) using SPSS Statistics 22.0 (IBM, USA). Prior to ANOVA, the data were checked for normality and homogeneity of variances using the Shapiro-Wilk and Levene's tests, respectively. Significant differences between means were determined using Tukey's honestly significant difference (HSD) post-hoc test at a significance level of $p < 0.05$.

3. Results and discussion

3.1 Color and Morphology of Microcapsules

The color of the encapsulated powder is a critical quality attribute for consumer acceptance. As shown in Table 2, the original dark, greenish virgin avocado oil (VAO) ($L^* = 3.3$) was transformed into a light-colored powder ($L^* > 83$) after microencapsulation. This significant increase in lightness (L^*) is due to the encapsulation of the oil droplets within the white carbohydrate-based wall material matrix, which masks the oil's natural color [18]. All microcapsule formulations exhibited statistically significant differences in their color parameters ($p < 0.05$). The powders showed a shift towards a more yellow-red hue compared to the neat oil. The chroma (C^*) and hue angle (h°) values, which were recalculated to correct inconsistencies in the original manuscript, quantify this change. The variations in color among the formulations are subtle and are primarily influenced by the slight differences in oil dispersion and particle structure created by the different wall material ratios.

Table 2 Color parameters of virgin avocado oil (VAO) and avocado oil microcapsules.

Sample	L^* ¹	a^* ²	b^* ³	C^* ⁴	h° ⁵
VAO	3.3 ± 0.04	0.25 ± 0.09	0.51 ± 0.12	0.57 ± 0.11	63.9 ± 0.11
AOE1	$84.59^b \pm 0.11$	$0.69^c \pm 0.01$	$6.41^c \pm 0.03$	$6.45^b \pm 0.05$	$83.88^c \pm 0.02$
AOE2	$85.46^a \pm 0.06$	$0.89^a \pm 0.01$	$6.70^b \pm 0.02$	$6.76^c \pm 0.03$	$82.43^d \pm 0.02$
AOE3	$84.21^c \pm 0.05$	$0.84^b \pm 0.02$	$7.78^a \pm 0.03$	$7.83^a \pm 0.15$	$83.84^b \pm 0.02$
AOE4	$83.85^d \pm 0.15$	$0.70^c \pm 0.00$	$5.53^d \pm 0.03$	$5.57^d \pm 0.02$	$82.78^c \pm 0.03$
AOE5	$85.36^a \pm 0.03$	$0.62^d \pm 0.01$	$6.78^b \pm 0.01$	$6.81^c \pm 0.03$	$84.76^a \pm 0.02$

Values in the same column with different superscript letters are significantly different ($p < 0.05$)

¹ L^* : Lightness (0=black, 100=white). ² a^* : Red-green axis. ³ b^* : Yellow-blue axis. ⁴ C^* : Chroma or color saturation. ⁵ h° : Hue angle.*

SEM analysis (Figure 1) revealed that the powders consisted of semi-spherical particles of varying sizes. Most microcapsules exhibited the wrinkled and indented surfaces characteristic of powders produced by spray drying. This morphology results from the rapid evaporation of water from the atomized droplet surface, causing the outer wall to solidify and then partially collapse as the internal pressure drops. This formation of a dense, amorphous, glassy shell is crucial for entrapping the oil core and protecting it from oxidation [19].

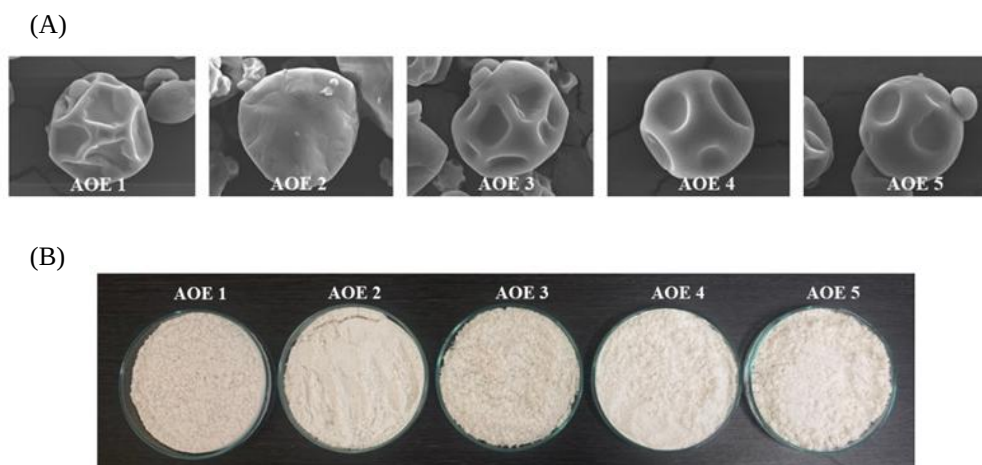


Figure 1 SEM micrograph of avocado oil microcapsules prepared with formulations AOE1–AOE4 (A). Physicochemical characteristics of the spray-dried emulsion powder (B).

3.2 Physicochemical Properties and Encapsulation Performance

The physicochemical properties of the five spray-dried avocado oil powders are presented in Table 3. The production yield varied significantly ($p < 0.05$) among the formulations, ranging from a low of 29.50% (AOE2)

to a high of 78.88% (AOE5). A clear trend emerged: formulations with a high concentration of guar gum (5%, i.e., AOE2 and AOE3) had significantly lower yields. This is because GG is a powerful thickening agent that drastically increases the viscosity of the feed emulsion. High viscosity impedes efficient atomization and increases the adhesion of the product to the walls of the drying chamber, thereby reducing the collected yield [12]. In contrast, formulations with only 1% GG (AOE1 and AOE4) achieved high yields (>74%). The oil encapsulation efficiency (EE) ranged from 32.47% to 51.25%. The highest EE was achieved by formulation AOE4 (51.25%), which combined a high concentration of GA (40%) with a low concentration of GG (1%). This result highlights the superior emulsifying and film-forming properties of GA, whose arabinogalactan-protein complex forms a robust interfacial layer around oil droplets, preventing coalescence and improving oil retention during atomization [11, 20]. The combination of high MD content (providing bulk solids) and high GA content (providing emulsification), coupled with low GG content (maintaining low viscosity), proved to be the most effective strategy for maximizing both production yield and encapsulation efficiency.

The moisture content of all powders was below 4.6%, and the water activity (a_w) was below 0.26. The formulation AOE4 was again the top performer, with the lowest moisture content (2.83%) and water activity (0.153 a_w). These values are well below the critical thresholds for microbial growth ($a_w < 0.6$) and are low enough to significantly slow down lipid oxidation rates, indicating good potential for shelf stability [21]. The low a_w is a direct result of the effective water removal during spray drying and the ability of the amorphous wall material matrix to bind the residual water. The powders showed good rehydration properties. Solubility was high for all formulations (>66%), and wettability, measured as the time for the powder to become fully submerged in water, was rapid (<9 s). The differences in wettability were statistically significant ($p < 0.05$), with AOE4 again showing the best performance (fastest wetting time of 4.71 s). This was likely due to the balanced hydrophilic nature of the GA and MD in the wall material, facilitating rapid water penetration and dispersion of the powder.

Table 3 Physicochemical properties of the spray-dried avocado oil microcapsules

Physical parameter	Sample				
	AOE1 (70:29:1)	AOE 2 (70:25:5)	AOE 3 (55:40:5)	AOE 4 (59:40:1)	AOE5 (62.5:35:2.5)
Total Soluble Solids (°Brix)	20.5±0.08	21.2±0.07	20.9±0.11	20.4±0.13	20.7±0.09
Yield (%)	74.58 ^a ±1.24	29.50 ^c ±2.13	41.3 ^b ±2.32	78.72 ^a ±1.07	78.88 ^a ±1.53
Oil Encapsulation Efficiency (%)	36.15 ^b ±1.01	32.67 ^{cd} ±1.06	32.47 ^c ±1.21	51.25 ^a ±1.10	33.78 ^c ±1.03
Water Activity (a_w)	0.186 ^b ±0.00	0.255 ^a ±0.00	0.200 ^d ±0.00	0.153 ^a ±0.00	0.194 ^c ±0.00
Solubility (%)	66.40 ^d ±0.18	71.10 ^a ±0.20	66.25 ^d ±0.28	68.37 ^b ±0.20	67.32 ^c ±0.20
Moisture Content (%)	3.32 ^b ±0.10	4.56 ^c ±0.26	3.57 ^b ±0.03	2.83 ^a ±0.09	3.39 ^b ±0.17
Wettability (s)	5.72 ^b ±0.19	8.16 ^c ±0.18	6.72 ^d ±0.11	4.71 ^a ±0.16	6.21 ^c ±0.17

Values in the same row with different superscript letters are significantly different ($p < 0.05$).

4. Conclusion

This study successfully demonstrated the microencapsulation of virgin avocado oil using spray drying with a ternary wall material system of maltodextrin, gum Arabic, and guar gum. The composition of the wall materials was found to significantly influence the powder's physicochemical properties. An optimized formulation (59% MD, 40% GA, 1% GG) produced a powder with a high production yield (78.72%), an effective encapsulation efficiency (51.25%), low water activity (0.153), and low moisture content (2.83%). These properties, which met the target success metrics of this study, indicate that the microencapsulated powder has strong potential for enhanced stability against oxidative and microbial degradation. The findings underscore the critical importance of balancing the ratios of wall materials: gum Arabic was essential for emulsification and oil retention, maltodextrin provided the necessary bulk structure for high yield, and a minimal amount of guar gum was required to avoid detrimental increases in emulsion viscosity. These insights provide a fundamental basis for developing stable, powdered lipid ingredients for the food industry. Future work should focus on optimizing the spray-drying process parameters and conducting a formal shelf-life study by measuring oxidative stability markers, including peroxide value (PV) and thiobarbituric acid-reactive substances (TBARS), over storage time to validate the long-term effectiveness of the encapsulation system.

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6. Authors Contributions

Jarckrit Jeeunngoi: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft; Sukrichaya Hemathulin: Conceptualization, Resources, Supervision, Writing – review & editing; Budsarakum Saetang: Conceptualization, Resources, Writing – review & editing; Amonrut Morarach: Conceptualization, Writing – review & editing.

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