



A New Approach in Preparing Curcumin Microcapsules from Temulawak (*Curcuma Xanthorrhiza* Roxb.) Extract as A Source of Natural Antioxidants for The Pharmaceutical and Food Industries

ALI ROSIDI¹, EDY SOESANTO², ENIK SULISTYOWATI³
and DIODE YONATA^{4*}

¹Department of Nutrition, Universitas Muhammadiyah Semarang, Semarang, Indonesia.

²Department of Nursing, Universitas Muhammadiyah Semarang, Semarang, Indonesia.

³Department of Nutrition, Health Polytechnic of Semarang, Indonesia.

⁴Department of Food Technology, Universitas Muhammadiyah Semarang, Semarang, Indonesia.

Abstract

Temulawak (*Curcuma xanthorrhiza* Roxb.) is a native Indonesian plant rich in curcumin. The utilization of curcumin in the food and pharmaceutical industries is restrained mainly by its poor solubility in aqueous systems and its instability. Therefore, this study proposes applying microencapsulation technology to overcome these problems. This study focuses on a new approach for microencapsulating curcumin from temulawak extract using single and composite coating materials with spray drying. The results showed that the yield of microcapsules reached 65.34-72.71%, with a curcumin content of 284.93-404.67 mg/100g. Using composite coating materials significantly increased the microencapsulation efficiency, total phenolic content, total flavonoid content, and antioxidant activity of microcapsules. All coating materials produced microcapsules with bright yellow color profiles, high solubility (89.52-97.23%), moisture content of around 2.13-3.71%, low aw (0.31-0.33), and tended to be non-hygroscopic with microparticles with an average size of around 1.13-2.43 μm . The morphological structure of microcapsules prepared with composite coating materials was mainly round and oval, with a smooth surface, no cracks, and some wrinkles. In conclusion, using composite coating materials in the microencapsulation process of curcumin from temulawak extract generally refines the physicochemical properties of the resulting microcapsules. In particular, WPI- β CD coating material is recommended for producing curcumin microcapsules from temulawak extract.



Article History

Received: 03 March 2025

Accepted: 12 May 2025

Keywords

Curcumin;
Microencapsulation;
Physicochemical
Properties;
Spray Dryer;
Temulawak.

CONTACT Diode Yonata ✉ yonata@unimus.ac.id 📍 Department of Food Technology, Universitas Muhammadiyah Semarang, Semarang, Indonesia.



© 2025 The Author(s). Published by Enviro Research Publishers.

This is an Open Access article licensed under a Creative Commons license: Attribution 4.0 International (CC-BY).

Doi: <https://dx.doi.org/10.12944/CRNFSJ.13.Special-Issue-July.08>

Introduction

Temulawak (*Curcuma xanthorrhiza* Roxb.), also known as Java turmeric, is a native plant in Indonesia. In addition, temulawak is cultivated in other Southeast Asian countries such as the Philippines, Malaysia, and Vietnam.¹ It is reported that temulawak cultivation in Indonesia has been carried out massively, with a production area reaching 13.05 million m² and a harvest of around 24.33 million kg.² In Indonesia, temulawak is commonly used as a food supplement and herbal medicine to treat and control various diseases. This is inseparable from the health effects of temulawak, which have been confirmed to have pharmacological properties such as anti-oxidative, anti-inflammatory, antitumor, antibacterial, nephroprotective, and neuroprotective to hepatoprotective activities.³

Curcuminoids are the most abundant phytochemicals reported in temulawak. Therefore, the health effects of temulawak mostly come from this compound.⁴ Curcuminoids in temulawak consist of curcumin, demethoxycurcumin, and bisdemethoxycurcumin,⁵ of which are abundant in the temulawak rhizome.³ Specifically, curcumin from temulawak rhizome has been reported to be obtained through liquid-liquid extraction using ethanol and n-hexane solvents. The resulting extract showed intense antioxidant activity, with an IC₅₀ value of 87.01 ppm.⁶ Despite its various health effects, curcumin has drawbacks such as low solubility in water, short shelf life due to poor chemical stability, low bioavailability due to suboptimal absorption, rapid metabolism that is easily eliminated, and most molecules produce a bitter taste.^{3,7}

Microencapsulation of curcumin compounds by spray drying is a new approach that has been recommended.⁸ This method is known to be more competitive on an industrial scale and allows the production of commercially profitable powders.^{9,10} The method produces curcumin microcapsules applied to dairy products and their derivatives.¹¹⁻¹³ Spray drying has been shown to increase curcumin's stability significantly.¹⁴ The resulting microcapsules contain bioactive components in the core surrounded by a layer of coating material. Coatings provide a physical barrier that prevents molecular diffusion and chemical reactions, thereby increasing the stability of the encapsulated compound. Therefore, selecting coating materials is an essential step

in the microencapsulation process of curcumin.¹⁵ Amount studies have summarized various types of coating materials that can be used in curcumin microencapsulation, such as the use of Maltodextrin (MDE) in microencapsulation of curcumin from *Curcuma longa*,¹⁶ whey protein isolate (WPI) in microencapsulation of commercial curcumin powder¹⁷⁻¹⁸ and gum arabic (GAR) in microencapsulation of curcumin from *Zingiber officinale*.¹⁹

Microcapsules with a single coating material generally have lower performance, while combining two structurally different polymers may provide better results, especially regarding stability and solubility in water.²⁰ using composite coating materials has been proposed to prepare curcumin microcapsules. This is associated with the ability of the composite coating material, which has a role as an emulsifier, film former, matrix former, and filler.²¹ Based on previous studies, it was concluded that the addition of β -cyclodextrin (β CD) as a composite coating material significantly increased the efficiency of curcumin microencapsulation, followed by increased stability to high temperatures and acidic conditions.¹⁵ In addition, the addition of β CD as a coating material has been confirmed to cover the bitter taste of catechin,²² prevent hygroscopicity, and maintain bioactive compounds from the core material.²³ These results are also expected in the microencapsulation of curcumin from temulawak.

Based on the description above, various studies have reported the superior efficacy of curcumin microencapsulation from various coating materials. However, no study has used MDE, WPI, and GAR composite coating materials combined with β CD to microencapsulate curcumin from temulawak extract. Therefore, this study was conducted to prepare curcumin microcapsules from temulawak using composite coating materials MDE, WPI, and GAR combined with β CD produced by spray drying. This study provides a precious reference for selecting the best coating material in preparing curcumin microcapsules from temulawak using spray drying.

Materials and Methods

Materials and Chemicals

Temulawak rhizome powder was obtained from local farmers in Semarang, Indonesia. MDE with DE 10-12 from Lihua Starch (China), WPI with 90% protein

content from Beyon Nutrisi (Indonesia), GAR from Ingredion (Thailand), and β CD from Landor Trading Company (Thailand). Chemicals such as ethanol, n-hexane, methanol, curcumin, quercetin, gallic acid, folin-ciocalteu and 2,2-Diphenyl-1-picrylhydrazyl (DPPH) from Sigma Chemical Company (Sigma-Aldrich, St. Louis, Missouri, USA).

Preparation of Curcumin Extract

Temulawak rhizome powder was macerated using 70% ethanol at room temperature for 24 hours, filtered (200 mesh), and concentrated using an evaporator at 50 °C. The extract obtained was then purified using the liquid-liquid extraction method, n-hexane 1:3, for 30 minutes, using a separating funnel. The temulawak extract was in the ethanol phase (bottom layer). The ethanol solvent was then separated using an evaporator until a thick temulawak extract was obtained.^{6,24}

Preparation of Curcumin Microcapsules

Curcumin microcapsules of Javanese ginger were formed using various composite coating materials consisting of structure-forming materials (MDE, WPI, and GAR) and auxiliary materials (β CD). First, at room temperature, each structure-forming material (19 g) was dissolved in 100 ml of distilled water using a homogenizer for 10 minutes (10,000 rpm). Then, β CD (1 g) was added and homogenized using a homogenizer for 10 minutes at 10,000 rpm at 50 °C, until completely dissolved. Curcumin extract (1 g) was then added to the composite coating material solution and homogenized for 30 minutes at 10,000 rpm. Microencapsulation of Javanese ginger curcumin with a single coating material (MDE/WPI/GAR) was also prepared as a comparison using the same steps. All prepared solutions were then dried using spray drying under the following conditions: inlet temperature, outlet temperature, air flow rate, and air pressure were set at $150 \pm 1^\circ\text{C}$, $80 \pm 2^\circ\text{C}$, 4 ml/min at $25 \pm 2^\circ\text{C}$, and 5 bar, respectively.^{8,15,18}

Spray-Drying Yield, Curcumin Content and Curcumin Recovery

The yield (%) of the spray drying process was studied and expressed as the ratio of the recovered powder compared to the amount of solid raw material used. Curcumin content was determined based on the previous method.²⁴ Standard solutions of curcumin in ethanol were prepared at concentrations of 0, 2, 4, 6, 8, 10, and 12 ppm. The absorbance

was measured at a wavelength of 425 nm using a UV-Vis spectrophotometer (UV-1800, Shimadzu Scientific Instrument, Japan) and used to obtain a standard curve equation. Each sample weighed 1 g, dissolved in 10 ml of ethanol, and centrifuged at 5000 rpm for 5 minutes. Then, the absorbance was measured at a wavelength of 425 nm using a UV-Vis spectrophotometer (UV-1800, Shimadzu Scientific Instrument, Japan). A calibration curve of the standard solution was developed to evaluate the concentration of curcumin and expressed in mg/100g. Curcumin recovery from temulawak extract with various coating materials was calculated as follows: (Total curcumin content in the obtained microcapsules – Curcumin content on the surface of the obtained microcapsules)/ Total curcumin content in the obtained microcapsules.¹⁷

Total Phenolic Content

Total phenolic content (TPC) in the microcapsules was quantified using the Folin-Ciocalteu method.²⁷ A 0.5 g microcapsule sample was homogenized with 5 ml of 10% (v/v) Folin-Ciocalteu reagent for 5 minutes in the dark. Subsequently, 4 ml of 7.5% (w/v) Na_2CO_3 solution was added, followed by a 60-minute incubation at room temperature. A gallic acid standard curve (100-500 ppm in ethanol) was used to determine TPC, measured at 765 nm via UV-Vis spectrophotometry and expressed as mg gallic acid equivalents per gram of temulawak extract microcapsules (mg GAE/g).

Total Flavonoid Content

Determination of total flavonoid content (TFC) was carried out using a modified previous research method.²⁵ A 0.5 g microcapsule sample was prepared with ethanol (1.5 ml), 10% AlCl_3 (0.1 ml), 1 M CH_3COOK (0.1 ml), and distilled water (2.8 ml) in a dark test tube. After homogenization and 30-minute incubation at $25 \pm 1^\circ\text{C}$, absorbance was measured at 415 nm using a UV-Vis spectrophotometer against a distilled water blank. A quercetin standard curve (20-100 ppm) was employed, and TFC was expressed as mg quercetin equivalents per gram of temulawak extract microcapsules (mg QE/g).

Antioxidant Activity

The antioxidant activity (AA) of the microcapsules (0.2 g) was assessed using the DPPH method.²⁰ After adding 1.5 ml of 0.2 mM DPPH ethanol solution and 3.5 ml of ethanol to the microcapsules

in a sealed test tube, the mixture was homogenized and incubated in the dark at room temperature for 60 minutes. UV-Vis spectrophotometry at 517 nm determined absorbance, with the percentage radical scavenging activity (RSA) calculated from the difference between sample and blank absorbances.

Color Profile

The color profile of curcumin microcapsules of temulawak was determined using the Minolta CR-310 Chroma Meter instrument (Konica Minolta, Japan), with CIELab scale parameters (L*, a* and b*), where L* indicates brightness, a* red and green, and b* yellow and blue.²¹

Moisture Content and Water Activity (a_w)

A moisture analyzer instrument (Shimadzu MOC63u, Japan) was used to determine the moisture content of microcapsules. In contrast, a water activity analyzer instrument (Rotronic Hygropalm-HP23-Aw-A, Switzerland) was used to determine the law of microcapsules operated at 25 °C.

Hygroscopicity

The hygroscopicity of microcapsules was obtained by placing 1 g of sample in an airtight jar containing saturated NaCl solution (relative humidity ± 75%) and storing for 7 days at a controlled temperature (± 25 °C). The hygroscopicity value was expressed in g of water vapor adsorbed per 100 g dry sample (g/100g).²⁶

Hygroscopicity (g/100g) = adsorbed moisture (g) / sample weigh (g) x 100

Solubility

The solubility of microcapsules was obtained by preparing 1 g of sample added to 100 ml of distilled water with magnetic stirring for 10 minutes. The suspension was filtered, and the filtrate was dried at 105 °C until a constant residual weight was obtained.²⁷ The solubility of microcapsules is expressed in percent.

Solubility (g/100g) = weight of the powder in the supernatant (g) / weight of the powder in the solution (g) x 100

Foaming Capacity and Foaming Stability

The samples' foaming capacity (FC) and foaming stability (FS) were evaluated using a previously

reported method.²⁸ Microcapsules were prepared in as much as 1 g, dissolved in distilled water, and the pH was adjusted to 7.0. The samples were then homogenized using a homogenizer for 5 minutes at a speed of 4000 rpm, and the results were then transferred into a 250 ml measuring cylinder. The volume of foam formed after whipping was recorded at 0 and 30 minutes. The increase in volume percentage represents the FC value, and the FS Value is calculated based on the stability of foam volume after whipping.

FC (%) = Volume after whipping (ml) - Volume before whipping (ml) / Volume before whipping (ml) x 100

FS (%) = Foam volume after time (t)(ml) / Initial foal volume (ml) x 100

Wettability

The wettability of microcapsules was assessed using earlier research methods, in which 1 g of sample was added to 100 ml of distilled water in a 250 ml beaker at room temperature. The time required for the powder particles to sink and disappear from the water surface was recorded as wettability.²⁸

Dispersibility

The dispersibility of microcapsules was obtained by preparing 1 g of microcapsules in a 50 ml beaker and adding 10 ml of distilled water. Constant stirring was carried out for 30 minutes until the microcapsules were dispersed entirely and did not form lumps at the bottom of the beaker. The sample was filtered using a 200-mesh sieve, and the filtrate obtained was dried to constant weight.²⁸

Dispersibility (%) = $\frac{(10 + a) \times TS}{a \times \frac{10-b}{100}} \times 100$

where, 'a' is the amount of powder sample being used, 'b' is the moisture content of the powder, and TS are the total solids of the filtrate.

Particle Size Distribution and Morphology Structure

The laser instrument particle size analyzer LLPA-C10 (Labron Equipment Ltd., United Kingdom) was used to measure microcapsules' particle size using the laser light scattering principle. Meanwhile, the morphology structure of the samples was evaluated using scanning electron microscopy (SEM) type

JSM-6510LA (Jeol Ltd., Japan). The prepared microcapsules were then coated with gold with an ion layer and observed at an acceleration voltage of 12 kV.

Statistical Analysis

All experiments were performed in triplicate and presented as mean ± standard deviation. ANOVA test was used to see significant differences between treatment. When a significant difference ($p < 0.05$) was identified, further testing was conducted using Duncan’s test at a 95 % confidence level with SPSS software version 22.0.

Results

Spray-Drying Yield, Curcumin Content and Curcumin Recovery

The product yield was calculated as the ratio of the mass of solids obtained from the drying process to the mass of solids in the feed solution. The yield

of all microcapsules ranged from 62.34 to 72.72% (Figure 1A). In general, the yield of WPI-based microcapsules (70.54-72.21%) was better than that of MDE-based microcapsules (65.34-68.10%), while the lowest yield was GAR-based coating material (63.24-63.41%). Using composite coating materials significantly increased the yield of microcapsules for all treatments. The curcumin content of the microcapsules from temulawak extract ranged from 284.94 to 404.67 mg/100 g (Figure 1B). Based on the type of coating material, MDE (361.97-404.67 mg/100 g) significantly produced the highest curcumin content of microcapsules, followed by WPI (349.94-359.38 mg/100 g) and GAR (284.93-302.21 mg/100 g). Meanwhile, the microencapsulation efficiency of curcumin varies from 64.76 to 91.97% (Figure 1C). MDE-based coating material resulted in the highest microencapsulation efficiency, while the presence of βCD as a composite coating material had a statistically positive impact.

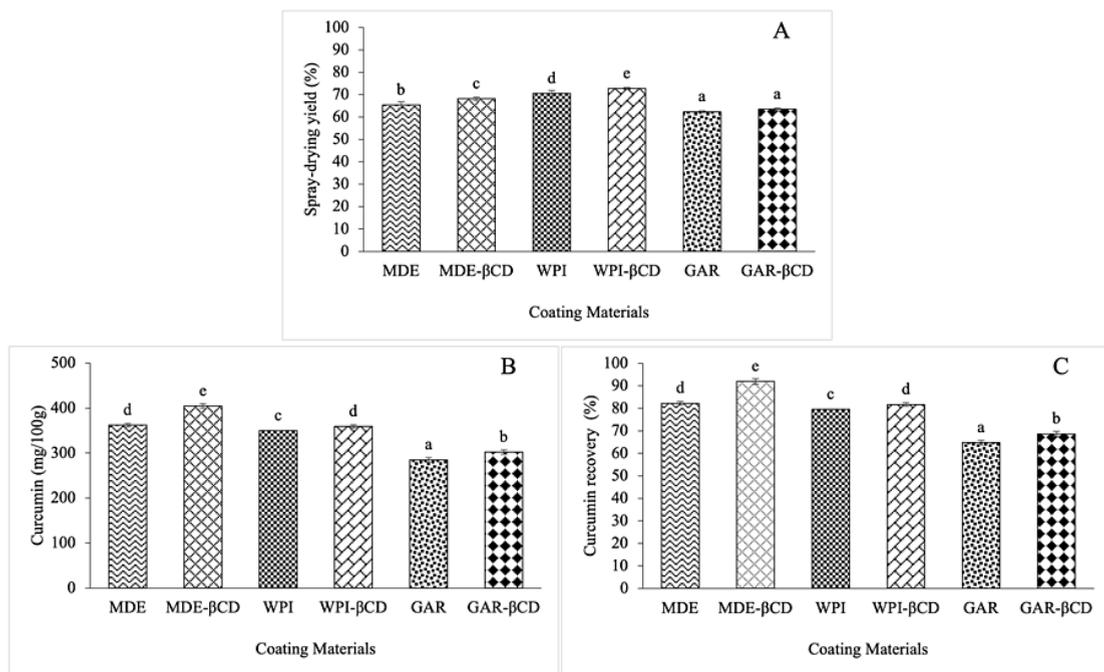


Fig. 1. Spray-drying yield (A), curcumin content (B), and curcumin recovery (C) of microcapsule curcumin from temulawak extract. Different superscripts in (a-e) each figure indicate statistically significant differences ($P < 0.05$), as determined by Duncan’s test

Total Phenolic Content, Total Flavonoids Content, and Antioxidant Activity

Temulawak extract microcapsules produced with WPI (40.35 mg GAE/g) coating material had higher TPC than those made with MDE (38.32 mg GAE/g)

and GAR (37.48 mg/ GAE/g) coating materials. In contrast, composite coating material significantly increased the TPC for all microcapsules, ranging from 43.76 to 45.23 mg GAE/g (Table 1). The average TFC of microcapsules from temulawak

extract ranged from 29.68 to 97.49 mg QE/g (Table 1). Each coating material produced significantly different TFC, while the presence of β CD as a composite coating material significantly increased the TFC trapped in the microcapsules. Based on the data in Table 1, the microcapsules of temulawak extract have AA values of 67.70 to 77.56 %RSA.

Each coating material produces microcapsules with significantly different AA values. The WPI- β CD composite coating material significantly produced microcapsules with the highest AA value, while the lowest was observed in microcapsules prepared with GAR coating material.

Table 1. Chemical properties and AA of microcapsule curcumin from temulawak extract

Coating materials	TPC (mg GAE/g)	TFC (mg QE/g)	AA (% RSA)
MDE	38.42 ± 1.51 ^a	84.15 ± 1.52 ^e	71.60 ± 0.60 ^c
MDE- β CD	44.08 ± 1.33 ^c	97.49 ± 2.88 ^f	73.80 ± 0.27 ^d
WPI	40.36 ± 1.11 ^b	65.89 ± 2.03 ^c	75.54 ± 1.13 ^e
WPI- β CD	45.23 ± 0.08 ^d	80.40 ± 2.20 ^d	77.56 ± 0.13 ^f
GAR	37.48 ± 1.15 ^a	29.68 ± 3.71 ^a	67.70 ± 0.53 ^a
GAR- β CD	43.76 ± 0.42 ^c	40.11 ± 3.56 ^b	68.69 ± 0.20 ^b

Note: The data are representation of the mean values ±standard deviation. Different superscript letters in each column indicate significant differences at P <0.05.

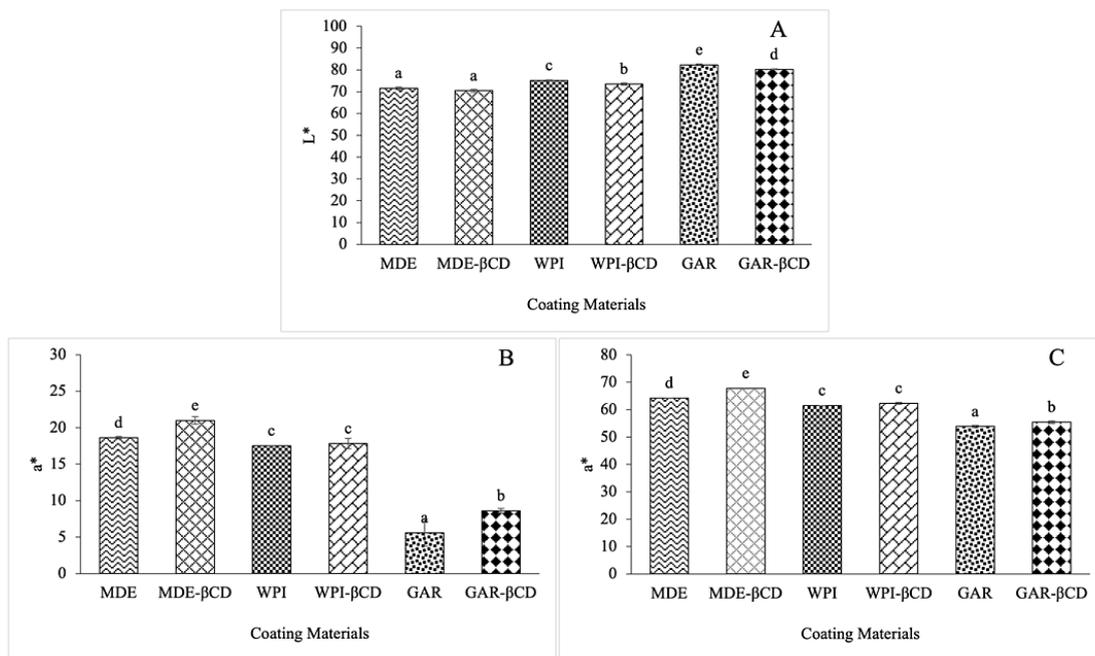


Fig. 2. Color properties of microcapsule curcumin from temulawak extract. Different superscripts in (a-e) each figure indicate statistically significant differences (P < 0.05), as determined by Duncan's test

Color Profile

The color profile reflects curcumin microcapsule particles' brightness and saturation levels from the

temulawak extract. All microcapsules showed a very high brightness level with L* values ranging from 70.44 to 82.34 (Figure 2A). The a* value was in the

range of 5.56-20.98 (Figure 2B), which indicated a slight reddish tendency. While the b* value is relatively high, around 53.82-67.77 (Figure 2C), indicating that the microcapsules have a significant yellow color.

Table 2. Physical properties of microcapsule curcumin from temulawak extract

Coating materials	Moisture (%)	a _w	Hygroscopicity (%)	Solubility (%)
MDE	3.28 ± 0.01 ^e	0.33 ± 0.01	8.30 ± 0.04 ^b	97.23 ± 0.06 ^e
MDE-βCD	3.71 ± 0.06 ^f	0.32 ± 0.01	8.11 ± 0.12 ^a	95.64 ± 0.10 ^d
WPI	2.13 ± 0.05 ^a	0.32 ± 0.00	9.90 ± 0.11 ^f	90.60 ± 0.80 ^b
WPI-βCD	2.31 ± 0.06 ^b	0.32 ± 0.01	9.47 ± 0.14 ^e	89.52 ± 0.47 ^a
GAR	2.99 ± 0.04 ^c	0.32 ± 0.00	8.98 ± 0.18 ^d	93.73 ± 0.53 ^c
GAR-βCD	3.08 ± 0.09 ^d	0.31 ± 0.00	8.59 ± 0.17 ^c	91.99 ± 0.08 ^b

Note: The data are representation of the mean values ± standard deviation. Different superscript letters in each column indicate significant differences at P <0.05.

Moisture Content and a_w

The moisture content of the microcapsules from temulawak extract was 2.13 to 3.71% (Table 2), and all coating materials produced particles with moisture content below 5%. Significant differences were observed for all microcapsule water contents; the composite coating materials produced statistically higher microcapsule water contents than the single coating materials. In contrast to moisture content, the a_w value of microcapsules from temulawak extract did not differ between treatments, ranging from 0.31-0.33 (Table 2).

Hygroscopicity and Solubility

The hygroscopicity of temulawak extract microcapsules varies, ranging from 8.11 to 9.90%, which is highly dependent on the type and composition of the coating material. It can be

observed that microcapsules prepared with MDE have a lower hygroscopicity value compared to GAR. At the same time, WPI coating material produces the most hygroscopic product. The solubility of microcapsules from temulawak extract ranged from 89.52-97.23% (Table 2). Based on the type of coating material, microcapsules prepared with MDE had the highest solubility, followed by GAR and the lowest WPI. Meanwhile, the presence of βCD in the composite coating material significantly reduces the solubility of microcapsules.

Foaming Capacity and Foaming Stability

The average FC and FS values of temulawak extract microcapsules were 12.36-58.66% and 33.29-81.02%, respectively (Table 3). This study obtained significantly higher FC and FS values in microcapsules with WPI-based coating materials.

Table 3: Functional properties of microcapsule curcumin from temulawak extract

Coating materials	Foam capacity (%)	Foam stability (%)	Wettability (s)	Dispersibility (%)
MDE	12.36 ± 0.88 ^a	33.29 ± 0.66 ^a	65.36 ± 4.01 ^a	80.78 ± 0.71 ^a
MDE-βCD	12.48 ± 0.57 ^a	35.50 ± 1.24 ^b	100.65 ± 3.59 ^a	79.18 ± 0.28 ^a
WPI	58.66 ± 0.80 ^c	80.36 ± 1.70 ^e	222.25 ± 2.78 ^a	74.88 ± 0.44 ^a
WPI-βCD	58.52 ± 0.79 ^c	84.02 ± 0.04 ^f	278.86 ± 3.94 ^a	71.84 ± 0.77 ^a
GAR	46.64 ± 0.53 ^b	77.50 ± 0.21 ^c	119.28 ± 4.75 ^a	79.04 ± 0.45 ^a
GAR-βCD	46.43 ± 0.62 ^b	77.31 ± 0.64 ^d	148.39 ± 4.39 ^a	77.31 ± 0.40 ^a

Note: The data are representation of the mean values ± standard deviation. Different superscript letters in each column indicate significant differences at P <0.05.

Wettability and Dispersibility

The effect of coating type and composition on the wettability and dispersibility of microcapsules is shown in Table 3. Significant differences were observed in these properties and were greatly influenced by the coating material used, including the presence of β CD as a composite coating material. The lowest wettability of microcapsules (65.36 seconds) was provided by MDE coating material, while the highest wettability (278.86 seconds) was observed in microcapsules with WPI- β CD coating material. On the contrary, the lowest dispersibility

value of microcapsules was produced by WPI- β CD coating material (71.84%), while the highest was produced by MDE coating material (80.78%). It can be concluded that microcapsules with short wettability tend to have higher dispersibility.

Particle Size

Figure 3 presents the particle size distribution pattern of temulawak extract microcapsules. The average particle size of the resulting microcapsules ranged from 1.13 to 2.43 μ m, with a unimodal distribution pattern.

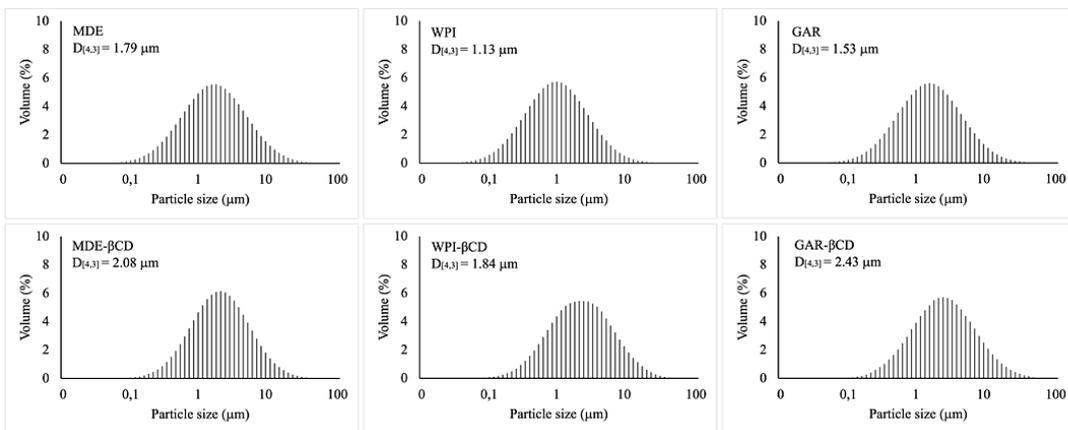


Fig. 3. Particle size distribution of microcapsule curcumin from temulawak extract by different coating materials (MDE; MDE- β CD; WPI; WPI- β CD; GAR and GAR- β CD)

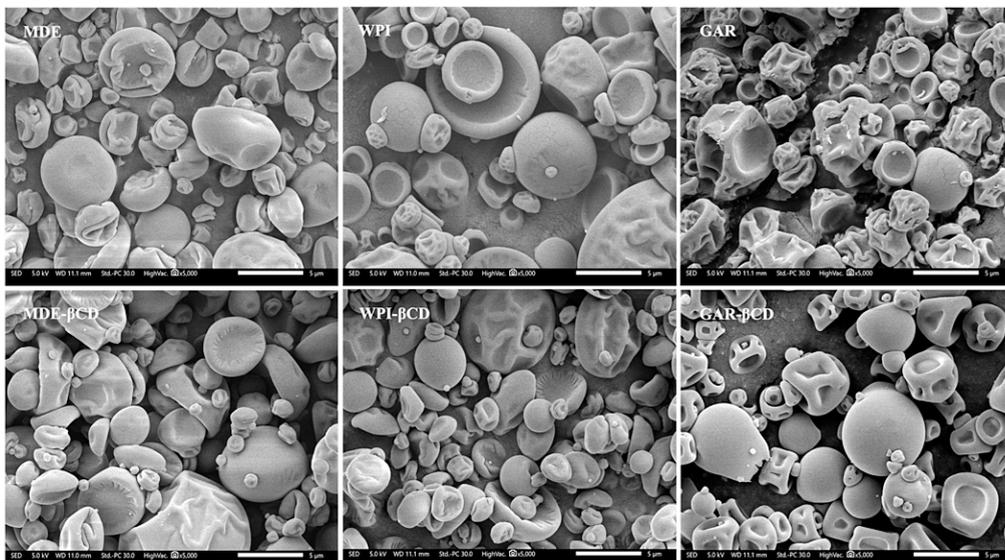


Fig. 4. SEM micrograph of microcapsule curcumin from temulawak extract by different coating materials (MDE; MDE- β CD; WPI; WPI- β CD; GAR and GAR- β CD)

Morphology Structure

The morphological structure of temulawak extract microcapsules examined by SEM is presented in Figure 4. In addition to differences in particle size, microcapsules prepared with various types of coating materials produce very different characteristics. In general, temulawak extract microcapsules have very diverse shapes. Specifically, microcapsules prepared with GAR coating materials have irregular surfaces, are very rough, and have cracks and many wrinkles.

Discussion

The yield of WPI-based microcapsules is the highest. WPI is a promising coating material for curcumin encapsulation. At the same time, GAR is less than optimal due to the hydrophilic nature of the short-chain branch structure of GAR, which causes many components not to be atomized perfectly and stick to the spray dryer wall.²⁹ Using composite coating materials significantly resulted in higher microcapsule yields than single coating materials, except for GAR-based microcapsules. The inclusion process and loading of more curcumin with the presence of β CD have been reported.³⁰ The presence of β CD in composite coatings significantly increased the glass transition temperature of the particles.³¹ When the glass transition temperature is above the drying temperature, there is a decrease in the rate of physicochemical changes in the product, such as stickiness, breakdown, and agglomeration, which is inhibited so that the availability of coating materials is greater to form microcapsules and the product yield increases.³²⁻³³ This result is higher than the previous report, reaching only 46.1% to 57.3%.⁸ High yield in production is essential and related to the efficiency and effectiveness of the process.

The curcumin content of the microcapsules from temulawak extract is similar to microcapsules from turmeric extract, which are 324-425 mg/100 g,³⁴ and 432-569 mg/100 g.³⁵ These results are higher than the curcumin content of microencapsulated fermented turmeric extract, which is only 86.6 mg/100 g.³⁶ These results are quite interesting. Generally, curcumin binding activity becomes more effective with the presence of protein fractions.³⁷ Also, the presence of proteins that can form a protective layer around the core material can maintain curcumin's stability.²¹ This provides information that curcumin from temulawak extract is coated more optimally

using MDE. MDE is known to have high solubility in water and can form a very stable film layer and a hollow structure that is effective in trapping curcumin during the microencapsulation process.³⁸ While using GAR produces microcapsules with the lowest curcumin content, it is less effective in the microencapsulation process of curcumin from temulawak extract. On the other hand, composite coating materials significantly increase the curcumin content of microcapsules, both those prepared from MDE- β CD, WPI- β CD, and GAR- β CD. This confirms that curcumin can be encapsulated into the β CD cavity through the inclusion complexation process between curcumin and β CD. This process occurs through Van der Waal interactions, hydrogen bonds, and hydrophilic interactions.³¹

Microencapsulation efficiency describes the coating material's effectiveness in protecting the encapsulated core compound from loss or oxidation. Thus, the microencapsulation efficiency value aligns with the curcumin content produced. The microencapsulation efficiency obtained in this study is slightly better than that of previous studies, namely 31-70%,²⁷ and 41.36-82.50%.¹⁵ However, this value is still lower than reported, namely 95.0-97.5%.¹³ The use of composite coating materials significantly increases microencapsulation efficiency. The curcumin inclusion complex and the increase in the glass transition temperature of the particles have been able to explain the mechanism of increasing the microencapsulation efficiency of curcumin from temulawak extract with the presence of β CD in the composite coating.

This study's TPC of temulawak extract microcapsules was higher than that of temulawak extract microcapsules from Malaysia, which was only 9.99 mg GAE/g.³⁹ However, this value was still lower than that of turmeric extract microcapsules, which reached 81.69-86.89 mg GAE/g.⁴⁰ Interesting results were observed in microcapsules with GAR coating material; the resulting TPC value was not different from MDE. The branched structure of GAR can bind to the phenolic groups of temulawak extract.⁴¹ On the other hand, phenolic compounds have been confirmed to interact positively with milk proteins, so the recovery of phenolic compounds increases.¹⁸ The use of β CD as a composite coating material significantly increased the TPC of microcapsules. This was associated with the ability of β CD to form

inclusion complexes with phenolic compounds from temulawak extract. The interaction between polyphenols and cyclodextrins has been confirmed to increase the stability of phenolic compounds so that the TPC of microcapsules increases.⁴² The phenolic compounds, which are antioxidants, play a role in preventing and treating various degenerative diseases, including cancer, diabetes mellitus, premature aging, and immune system disorders. Therefore, microcapsules with high levels of phenolic compounds offer significant potential health benefits.

Previous researchers have reported that microcapsules from temulawak extract prepared with sodium tripolyphosphate and chitosan have TFC values of 6.30-33.58 mg QE/g.⁴³ This means that MDE, WPI, and GAR coating materials more effectively protect flavonoid compounds from temulawak extract. The TFC value of microcapsules tends to have the same pattern as the curcumin content. High TFC values do not always indicate high flavonoid content in a product. However, high TFC values can be caused by other compounds that are also measured because they react with aluminium chloride.⁴⁴ Curcuminoid compounds have ortho hydroxyl groups, which will be read as flavonoids when reacted with aluminium chloride. Therefore, the TFC value will have the same pattern as the curcumin content.^{45,46} This phenomenon was also observed in the microencapsulation process of curcumin extract from turmeric.

This AA comes from the curcumin compound.¹⁸ Although the curcumin in microcapsules with WPI coating material is lower than that of the MDE coating material, the curcumin-WPI microcapsules show higher AA. Similar results have also been reported previously.¹⁷ The free radical scavenging activity of the curcumin compound is not affected after being encapsulated with sodium caseinate, a protein from milk. Even the antioxidant capacity of curcumin produced increased significantly.⁴⁷ This phenomenon is acceptable because WPI has been confirmed to show AA from protein components.⁴⁸ The increase in AA in microcapsules with WPI coating materials shows curcumin's effectiveness in donating its hydrogen atoms to radicals.⁴⁹ In addition, the AA value of microcapsules was significantly higher when encapsulated with composite coating materials. In addition to increasing the glass transition temperature of particles, the presence of

β CD effectively forms inclusion complexation with curcumin.^{31,50} This complexation has good stability against light exposure, pH changes, and storage.⁵¹ A study has concluded that increased AA of curcumin microcapsules can be obtained with WPI coating materials complex with β CD.⁵² This has confirmed why curcumin microcapsules from temulawak extract have the highest AA after being encapsulated with WPI- β CD. Consuming a diet rich in antioxidants through natural foods is key to maintaining health and preventing future disease.⁵³

Curcumin microcapsules with a high b^* value indicate a higher availability of curcumin in the microcapsules, which can be confirmed in Figure 1B that the microcapsules prepared with the MDE- β CD composite coating material contain higher levels of curcumin. In contrast, the lowest is prepared with the GAR coating material. The microcapsules prepared with the composite coating material showed a lower brightness level (L^*) than the single coating material. This finding is consistent with previous studies showing that the brightness value of microcapsules decreases with the presence of β CD.⁵⁴ This decrease can be attributed to the TPC value of microcapsules. Microcapsules with higher TPC values will be more susceptible to oxidation and impact decreasing particle brightness.⁵⁵ Interestingly, the presence of β CD significantly increases the b^* value of microcapsules. This means that there is a good inclusion complex between curcumin and β CD. Previous findings support these results; the color of microcapsules resulting from curcumin- β CD complexation has excellent yellow color stability, even stable against sunlight, pH, storage, and isothermal heating compared to natural dyes without complexation with β CD.⁵¹

Curcumin microcapsules with water content below 5% are made from the right coating material.⁵⁶ Microcapsules prepared with WPI coating materials produced the lowest moisture content significantly. Higher moisture content was observed in microcapsules prepared with composite coating materials. Similar findings include microcapsules from seaweed extract,²³ *Elshottltzia ciliata* Herb extracts,⁵⁷ and grape cane extract.⁴² β CD can form hydrophobic cavities that can trap core materials, and some trapped water molecules are difficult to evaporate when the feed liquid is dried.⁵⁸ Powder products with moisture content below 5% have

been confirmed to have good long-term storage stability.⁵⁹ In addition, aw values below 0.4 can be considered ideal conditions to prevent the growth of microorganisms and overcome coagulation problems during storage.⁶⁰

Hygroscopicity is closely related to the capacity of microcapsules to absorb moisture in the environment and can also affect physical-chemical stability, product shelf life, and product fluidity.⁶¹ An observation is related to the fact that GAR has a higher glass transition temperature than MDE, thus increasing the hygroscopicity of the product.⁶² Also, using protein-based coating materials produces microcapsules with high hygroscopicity values. The resulting microcapsules tend to have a more porous morphological structure, making them more likely to absorb water from the environment.⁶³ This study observed that the increase in hygroscopicity was inversely proportional to the moisture content, so microcapsules with lower moisture content tended to be hygroscopic. This can be attributed to the more significant water concentration gradient between the particles and the surrounding air, leading to a greater capacity to absorb water at room temperature.²⁹ The presence of β CD tends to increase the hygroscopicity value of the microcapsules. This result is not surprising; β CD is known to have a solid capacity to attract water molecules from the surrounding air.³¹ The hygroscopicity of a product is a challenge in the food and pharmaceutical industries. Understanding the hygroscopicity of a product allows for proper handling, especially for products with low hygroscopicity that are easier for consumers to store.

The solubility of curcumin microcapsules in this study was slightly better than that of microcapsules from turmeric extract, which was 86.71-89.52%.²¹ However, the solubility trend of curcumin extract microcapsules is similar to that of microcapsules from grape skin extract and black rice prepared with MDE coating materials, high-protein skim milk powder, and GAR.⁶³⁻⁶⁴ The high hydroxyl groups (-OH) in MDE can be the reason for the high solubility of microcapsules.⁶⁵ Meanwhile, GAR-based microcapsules have better solubility than WPI. A study observed the effect of the GAR to soy lecithin ratio on curcumin's solubility, concluding that a more dominant GAR ratio produced microcapsules with higher solubility.²⁷ The solubility of GAR is reported to be around 90%,⁶⁶ like the solubility of GAR-based

microcapsules in this study (Table 2). The decrease in solubility in microcapsules prepared with WPI is due to the formation of cross-links between protein fragments by disulfide bridges, which then reduce the solubility of the particles.⁶⁷ Meanwhile, microcapsules prepared with composite coating materials tend to have lower solubility. β CD has a hydrophobic structure, where hydrogen bonds between hydroxyl groups can cause the structure to become rigid, making it difficult to dissolve.⁶⁸⁻⁶⁹ This is also confirmed by a study reporting that spray-dried microcapsules prepared with β CD have a solubility of around 40-60%.⁵⁷

The increase in FC values in WPI-based microcapsules can be associated with partial protein folding, resulting in increased flexibility of the protein chain if aggregates are not formed.⁷⁰ In addition, WPI protein molecules decompose when heated and reveal their reactive side so that the FS value of the particles increases.⁷¹ The presence of β CD in the composite coating material does not affect the FC value of the microcapsules. This is because FC is related to the amount of air trapped in the foaming system. In contrast, the addition of β CD significantly increased the FS of microcapsules for all coating materials, meaning that the interfacial layer formed was stronger.⁷² MDE is hydrophilic. Thus, the hydrophilicity of the particle wall system increases and helps in the accessibility and penetration of microcapsules into water.⁷³ In addition, particles with fast wettability are generally produced from coating materials with high solubility,²⁶ making them easier to disperse maximally.²¹ The faster the wettability of a particle and the higher its dispersibility, the better its physical properties in food processing.⁷³⁻⁷⁴

Previous researchers reported that the average particle size of curcumin prepared by spray drying was 3.31 μ m.²⁰ Generally, curcumin microcapsules prepared by spray drying have a size of 10 μ m.¹⁵ The smaller particle size of the microcapsules in this study was due to the extraction of curcumin using ethanol-aquadest. It has been confirmed that curcumin's particle size from turmeric extract tends to be smaller when extracted using ethanol-aquadest compared to ethanol alone.²⁵ WPI as a coating material produces microcapsules with smaller particle sizes than GAR and MDE. In comparison, composite coating materials produce microcapsules with larger sizes. Similar results were

also observed in the microencapsulation of seaweed extract using MDE and GAR combined with β CD.²³ Microcapsules with larger sizes are preferred for releasing bioactive compounds because they tend to have a porous structure, while microcapsules with smaller sizes generally provide better techno-functional properties.⁷⁵

GAR has been confirmed to produce microcapsules with slightly cracked surfaces, shrinkage, and many wrinkles as a curcumin coating material.²⁹ Microcapsules prepared with MDE tend to be more regular and have smooth surfaces; some particles are round and oval, and some have depressions without cracks. These results strengthen previous findings that MDE produces much smoother curcumin microcapsules with few wrinkles.¹⁸ WPI coating materials also produce particle morphology with the same characteristics as MDE, but there are many cracks on the surface. The presence of β CD in the composition of the composite coating material generally does not change the shape of the particles. However, what is interesting is that the resulting particles have a smooth surface without cracks. This can be attributed to the increase in the glass transition temperature of the particles by β CD.³¹ It is recognized that the encapsulation agent is the leading cause of the morphological characteristics of the formed microcapsules.¹⁶ The regular or irregular nature of the particle surface provides a first insight into the stability of the formed microcapsules. Generally, particles with smooth surfaces encourage less interaction with other particles, which may be useful in certain applications.⁷⁶ On the other hand, some researchers reported that microcapsules with rough surfaces had a slower release process.⁷⁷⁻⁷⁸

Conclusion

In conclusion, the results of this study indicate that each coating material significantly affects the yield, curcumin content, microencapsulation efficiency, and physicochemical properties of curcumin microcapsules from temulawak extract, except for the aw value. Composite coating materials produce microcapsules with better physicochemical characteristics than single-coating materials. Based on the curcumin content, microencapsulation efficiency, hygroscopicity, color profile, and morphological structure of the microcapsules, MDE- β CD coating material is highly recommended. Meanwhile, microcapsules prepared

with WPI- β CD coating material produced better yield, chemical properties, and foaming profile. These results provide valuable information on the effectiveness of adding β CD in the composite coating material formula in preparing curcumin microcapsules from temulawak extract that can be applied in the food and pharmaceutical industries. It is interesting to study the application of the obtained microcapsules in functional products such as health drinks, instant milk, and yogurt. However, before that, further research is needed on the stability of the products produced on a pilot plant scale before being commercialized.

Acknowledgement

The authors gratefully acknowledge the Ministry of Education, Culture, Research and Technology, the Republic of Indonesia, for financial support through the Fundamental Research Grant program on behalf of Dr. Ali Rosidi.

Funding Sources

Fundamental Research Grant [grant numbers 022/LL6/PB/AL.04/2024 and 001/061026/PB/SP2H/AK.04/2024] from Ministry of Education, Culture, Research and Technology, the Republic of Indonesia.

Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, so informed consent was not required.

Clinical Trial Registration

This research does not involve any clinical trials.

Permission to Reproduce Material from other Sources

This statement does not apply to this article.

Author Contributions

- **Ali Rosidi:** Funding, Conceptualization, Methodology, Writing Original Draft.
- **Edy Soesanto:** Visualization, Project Administration, Writing Review
- **Enik Sulistyowati:** Supervision, Technical and Material Support
- **Diode Yonata:** Data Collection, Analysis, Writing Review and Editing.

References

1. Salleh NM, Ismail S, Ab Halim MR. Effects of *Curcuma xanthorrhiza* extracts and their constituents on phase ii drug-metabolizing enzymes activity. *Pharmacognosy Res.* 2016;8(4):309–315. doi:10.4103%2F0974-8490.188873
2. Anonymous. Produksi tanaman biofarmaka (Obat), 2021-2023 [Internet]. Jakarta; 2023 [cited 2024 Sep 25]. Available from: <https://www.bps.go.id/id>
3. Rahmat E, Lee J, Kang Y. Javanese turmeric (*Curcuma xanthorrhiza* Roxb.): Ethnobotany, phytochemistry, biotechnology, and pharmacological activities. *Evidence-Based Complementary and Alternative Medicine.* 2021;1:9960813. doi:10.1155/2021/9960813
4. Zhang C, Fan P, Li M, Lou H. Two new sesquiterpenoids from the Rhizomes of *Curcuma xanthorrhiza*. *Helv Chim Acta.* 2014;97(9):1295–1300. doi:10.1002/hlca.201300440
5. Cahyono B, Ariani J, Failasufa H, Suzery M, Susanti S, Hadiyanto H. Extraction of homologous compounds of curcuminoid isolated from temulawak (*Curcuma xanthorrhiza* Roxb.) plant. *Rasayan Journal of Chemistry.* 2019;12(1):7–13. doi:10.31788/RJC.2019.1213092
6. Rosidi A, Khomsan A, Setiawan B, Riyadi H, Briawan D. Antioxidant potential of temulawak (*Curcuma xanthorrhiza* Roxb). *Pakistan Journal of Nutrition.* 2016;15(6):556–560. doi:10.3923/pjn.2016.556.560
7. Rafiee Z, Nejatian M, Daeihamed M, Jafari SM. Application of different nanocarriers for encapsulation of curcumin. *Crit Rev Food Sci Nutr.* 2019;59(21):3468–3497. doi:10.1080/10408398.2018.1495174
8. Lucas J, Ralaivao M, Estevinho BN, Rocha F. A new approach for the microencapsulation of curcumin by a spray drying method, in order to value food products. *Powder Technol.* 2020;362:428–435. doi:10.1016/j.powtec.2019.11.095
9. Bucurescu A, Blaga AC, Estevinho BN, Rocha F. Microencapsulation of curcumin by a spray-drying technique using gum arabic as encapsulating agent and release studies. *Food Bioproc Tech.* 2018;11(10):1795–1806. doi:10.1007/s11947-018-2140-3
10. Nurhidajah, Rosidi A, Yonata D, Nurrahman, Pranata B. Physicochemical characteristics of anthocyanin extract powder from black rice based on maltodextrin and skimmed milk powder ratio as encapsulant. *Journal of Agricultural Engineering.* 2023;12(1):152–161. doi:10.23960/jtep-l.v12i1.152-161
11. Verma K, Tafafdar A, Jumar D, Kumar Y, Rana JS, Badgujar PC. Formulation and characterization of nano-curcumin fortified milk cream powder through microfluidization and spray drying. *Food Res Inter.* 2022;160:111705. doi:10.1016/j.foodres.2022.111705
12. Ipar VS, Singhal RS, Devarajan PV. An innovative approach using microencapsulated turmeric oleoresin to develop ready-to-use turmeric milk powder with enhanced oral bioavailability. *Food Chem.* 2022;373:131400. doi:10.1016/j.foodchem.2021.131400
13. Meena S, Gote S, Prasad W, Khamrui K. Storage stability of spray dried curcumin encapsulate prepared using a blend of whey protein, maltodextrin, and gum Arabic. *J Food Process Preserv.* 2021;45:15472. doi:10.1111/jfpp.15472
14. Yonata D, Ulvie YNS, Soesanto E, Sulistyowati E, Pranata B, Rosidi A. Stabilization and controlled release of curcumin from temulawak by spray-drying microencapsulation with composite wall materials. *Trends in Scie.* 2025;22:9125. doi:10.48048/tis.2025.9125
15. Guo J, Li P, Kong L, Xu B. Microencapsulation of curcumin by spray drying and freeze

- drying. *LWT*. 2020;132:109892. doi:10.1016/j.lwt.2020.109892
16. Goëlo V, Chaumun M, Gonçalves A, Estevinho BN, Rocha F. Polysaccharide-based delivery systems for curcumin and turmeric powder encapsulation using a spray-drying process. *Powder Technol.* 2020;370:137–146. doi:10.1016/j.powtec.2020.05.016
 17. Liu W, Chen XD, Cheng Z, Selomulya C. On enhancing the solubility of curcumin by microencapsulation in whey protein isolate via spray drying. *J Food Eng.* 2016;169:189–195. doi:10.1016/j.jfoodeng.2015.08.034
 18. Chen FP, Liu LL, Tang CH. Spray-drying microencapsulation of curcumin nanocomplexes with soy protein isolate: Encapsulation, water dispersion, bioaccessibility and bioactivities of curcumin. *Food Hydrocoll.* 2020;105:105821. doi:10.1016/j.foodhyd.2020.105821
 19. Umaira Jaidi E, Firdhaus Mad Nordin M, Sari Mohd Kassim A. Wall material formulations for Zingiberaceae family rhizome extracts (*Curcuma longa*, *Curcuma xanthorrhiza* and *Zingerol officinale*) on microencapsulation efficiency of spray drying processing. *Progress in Engineering Application and Technology.* 2023;4(1):1–12.
 20. Patel SS, Pushpadass HA, Franklin MEE, Battula SN, Vellingiri P. Microencapsulation of curcumin by spray drying: Characterization and fortification of milk. *J Food Sci Technol.* 2022;59(4):1326–1340. doi:10.1007/s13197-021-05142-0
 21. Meena S, Prasad W, Khamrui K, Mandal S, Bhat S. Preparation of spray-dried curcumin microcapsules using a blend of whey protein with maltodextrin and gum arabica and its in-vitro digestibility evaluation. *Food Biosci.* 2021;41:100990. doi:10.1016/j.fbio.2021.100990
 22. Ho S, Thoo YY, Young DJ, Siow LF. Stability and recovery of cyclodextrin encapsulated catechin in various food matrices. *Food Chem.* 2019;275:594–599. doi:10.1016/j.foodchem.2018.09.117
 23. Aminah S, Nurrahman, Pranata B, Amalia R, Siregar ANAP, Yonata D. Microencapsulation of seafood flavor enhancers from Indonesian brown seaweed with maltodextrin, Arabic gum, and β -cyclodextrin. *Egypt J Aquat Biol Fish.* 2023;27(2):811–821. doi:10.21608/ejabf.2023.297775
 24. Rosidi A, Farha R, Jauharany FF, Sulistyaningrum H, Firtiyanti AR, Nurhidajah, *et al.* The thermostability of temulawak extract encapsulation with several coating variations of sodium tripolyphosphate and chitosan. *Food Res.* 2023;7(6):214–219. doi:10.26656/fr.2017.7(6).909
 25. Park J, Do S, Lee M, Ha S, Lee KG. Preparation of turmeric powder with various extraction and drying methods. *Chemical and Biological Technologies in Agriculture.* 2022;9(1):39. doi:10.1186/s40538-022-00307-1
 26. Nurhidajah, Pranata B, Yusuf M, Sya'di YK, Yonata D. Microencapsulation of umami flavor enhancer from Indonesian waters brown seaweed. *Current Research in Nutrition and Food Science Journal.* 2022;10(1):349–359. doi:10.12944/CRNFSJ.10.1.29
 27. Nguyen VT, Huynh TM, Nguyen TNQ, Le TH. Enhancing the stability of synthesized curcumin by spray-drying microencapsulation with soy lecithin and gum Arabic. *Brazilian Journal of Chemical Engineering.* 2021;38(3):563–572. doi:10.1007/s43153-021-00124-3
 28. Adsare SR, Annature US. Microencapsulation of curcumin using coconut milk whey and Gum Arabic. *J Food Eng.* 2021;298:110502. doi:10.1016/j.jfoodeng.2021.110502
 29. Tonon R V., Brabet C, Hubinger MD. Influence of process conditions on the physicochemical properties of açai (*Euterpe oleraceae* Mart.) powder produced by spray drying. *J Food Eng.* 2008;88(3):411–418. doi:10.1016/j.jfoodeng.2008.02.029
 30. Arya P, Raghav N. In-vitro studies of Curcumin- β -cyclodextrin inclusion complex as sustained release system. *J Mol Struct.* 2021 Mar;1228:129774. doi:10.1016/j.molstruc.2020.129774
 31. Laokuldilok N, Thakeow P, Kopermsub P, Utama-ang N. Optimisation of microencapsulation of turmeric extract for masking flavour. *Food Chem.* 2016;194:695–704. doi:10.1016/j.foodchem.2015.07.150
 32. Truong V, Bhandari BR, Howes T. Optimization of co-current spray drying process of sugar-rich foods. Part I—Moisture and glass

- transition temperature profile during drying. *J Food Eng.* 2005;71(1):55–65. doi:10.1016/j.jfoodeng.2004.10.017
33. Quispe-Condori S, Saldaña MDA, Temelli F. Microencapsulation of flax oil with zein using spray and freeze drying. *LWT - Food Science and Technology.* 2011;44(9):1880–1887. doi:10.1016/j.lwt.2011.01.005
 34. Martins RM, Pereira SV, Siqueira S, Salomão WF, Freitas LAP. Curcuminoid content and antioxidant activity in spray dried microparticles containing turmeric extract. *Food Research International.* 2013;50(2):657–663. doi:10.1016/j.foodres.2011.06.030
 35. Ali HA. Encapsulation of turmeric extract and rice bran oil in alginate hydrogel microcapsules. *Food Technology Research Journal.* 2024;3(1):47–58. doi:10.21608/ftj.2024.267889.1056
 36. Sharma P, Kashyap P, Dhakane A. Exploring the antioxidant potential of fermented turmeric pulp: effect of extraction methods and microencapsulation. *Prep Biochem Biotechnol.* 2023;53(8):968–977. doi:10.1080/10826068.2022.2163256
 37. Mohammadian M, Salami M, Momen S, Alavi F, Emam-Djomeh Z. Fabrication of curcumin-loaded whey protein microgels: Structural properties, antioxidant activity, and in vitro release behavior. *LWT.* 2019;103:94–100. doi:10.1016/j.lwt.2018.12.076
 38. Wang S, Ye F, Wei F, Zhao G. Spray-drying of curcumin-loaded octenylsuccinated corn dextrin micelles stabilized with maltodextrin. *Powder Technol.* 2017;307:56–62. doi:10.1016/j.powtec.2016.11.018
 39. Ramlie NNH, Kassim ASM, Nordin MF binti M. Gum Arabic Microencapsulation of Zingiberaceae family Rhizome extracts (*C. longa*, *C. xanthorrhiza* and *Z. officinale*) using spray drying processing and its characterization. *Progress in Engineering Application and Technology.* 2023;4(2):996–1008.
 40. Febrianta H, Yuniarto VD, Nurwantoro N, Bintoro VP. Freeze-drying microencapsulation of turmeric (*Curcuma Longa* L.) using an amorphous matrix of maltodextrin, modified cassava flour and skim milk. *The Annals of the University Dunarea de Jos of Galati Fascicle VI – Food Technology.* 2020;44(2):26–42. doi:10.35219/foodtechnology.2020.2.02
 41. Busch VM, Pereyra-Gonzalez A, Šegatin N, Santagapita PR, Poklar Ulrih N, Buera MP. Propolis encapsulation by spray drying: Characterization and stability. *LWT.* 2017;75:227–235. doi:10.1016/j.lwt.2016.08.055
 42. Escobar-Avello D, Mardones C, Saéz V, Riquelme S, von Baer D, Lamuela-Raventós RM, *et al.* Pilot-plant scale extraction of phenolic compounds from grape canes: Comprehensive characterization by LC-ESI-LTQ-Orbitrap-MS. *Food Research International.* 2021;143:110265. doi:10.1016/j.foodres.2021.110265
 43. Rosidi A, Syaroh U, Rizky Fitriyanti A, Noor Setiawati Ulvie Y, Fikri Jauharany F, Aminah S, *et al.* Total flavonoids content and antioxidant activity encapsulation of Curcuma extract based on variation of coating concentrations. *Journal of Hunan Univ Nat Scie.* 2021; 48(11):157-164.
 44. Widyastuti I, Luthfah HZ, Hartono YI, Islamadina R, Can AT, Rohman A. Antioxidant activity of Temulawak (*Curcuma xanthorrhiza* Roxb.) and its classification with Chemometrics. *Indonesian Journal of Chemometrics and Pharmaceutical Analysis.* 2020;1(1):29–41. doi:10.22146/ijcpa.507
 45. Priyadarsini K. The chemistry of Curcumin: from extraction to therapeutic agent. *Molecules.* 2014;19(12):20091–20112. doi:10.3390/molecules191220091
 46. Sepahpour S, Selamat J, Abdul Manap M, Khatib A, Abdull Razis A. Comparative analysis of chemical composition, antioxidant activity and quantitative characterization of some phenolic compounds in selected herbs and spices in different solvent extraction systems. *Molecules.* 2018;23(2):402. doi:10.3390/molecules23020402
 47. Pan K, Zhong Q, Baek SJ. Enhanced dispersibility and bioactivity of Curcumin by encapsulation in casein nanocapsules. *J Agric Food Chem.* 2013;61(25):6036–6043. doi:10.1021/jf400752a
 48. Kerasiotti E, Stagos D, Priftis A, Aivazidis S, Tsatsakis AM, Hayes AW, *et al.* Antioxidant effects of whey protein on muscle C2C12 cells. *Food Chem.* 2014;155:271–278. doi:10.1016/j.foodchem.2014.01.066

49. Tapal A, Tiku PK. Complexation of curcumin with soy protein isolate and its implications on solubility and stability of curcumin. *Food Chem.* 2012;130(4):960–965. doi:10.1016/j.foodchem.2011.08.025
50. Benucci I, Mazzocchi C, Lombardelli C, Del Franco F, Cerreti M, Esti M. Inclusion of curcumin in β -cyclodextrin: a promising prospective as food ingredient. *Food Additives & Contaminants: Part A.* 2022;39(12):1942–1952. doi:10.1080/19440049.2022.2135764
51. Mangolim CS, Moriwaki C, Nogueira AC, Sato F, Baesso ML, Neto AM, *et al.* Curcumin– β -cyclodextrin inclusion complex: Stability, solubility, characterisation by FT-IR, FT-Raman, X-ray diffraction and photoacoustic spectroscopy, and food application. *Food Chem.* 2014;153:361–370. doi:10.1016/j.foodchem.2013.12.067
52. Abbastabr B, Azizi MH, Nabavi SR. Curcumin microparticles produced by electro spraying technique with whey protein isolate and β -cyclodextrin complex. *Journal of Agricultural Science and Technology.* 2020;22(3):709–722.
53. Rahaman MM, Hossain R, Herrera-Bravo J, Islam MT, Atolani O, Adeyemi OS, *et al.* Natural antioxidants from some fruits, seeds, foods, natural products, and associated health benefits: An update. *Food Sci Nutr.* 2023;13(4):1657-1670. doi:10.1002/fsn3.3217
54. Zhang ZH, Li X, Ma A, Gao X, Zhu S, Li B. Characteristics of pomegranate (*Punica granatum* L.) peel polyphenols encapsulated with whey protein isolate and β -cyclodextrin by spray-drying. *Int J Biol Macromol.* 2024;278:135279. doi:10.1016/j.ijbiomac.2024.135279
55. Estiasih T, Eko Witoyo J, Kania Mapandin Runtung G, Deannova Pasha Moelyono D, Rahmayani Murini A, Setyaningsih W, *et al.* The characteristics of foam-mat dried red and purple roselle calyces powder prepared with commercial emulsifiers as the foaming agents. *CyTA - Journal of Food.* 2024;22(1). doi:10.1080/19476337.2024.2356847
56. Cano-Higuita DM, Malacrida CR, Telis VRN. Stability of Curcumin microencapsulated by spray and freeze drying in binary and ternary matrices of maltodextrin, gum arabic and modified starch. *J Food Process Preserv.* 2015;39(6):2049–2060. doi:10.1111/jfpp.12448
57. Pudziuvelyte L, Marksa M, Jakstas V, Ivanauskas L, Kopustinskiene DM, Bernatoniene J. Microencapsulation of *Elsholtzia ciliata* herb ethanolic extract by spray-drying: impact of resistant-maltodextrin complemented with sodium caseinate, skim milk, and beta-cyclodextrin on the quality of spray-dried powders. *Molecules.* 2019;24(8):1461. doi:10.3390/molecules24081461
58. Zhu G, Zhu G, Xiao Z. A review of the production of slow-release flavor by formation inclusion complex with cyclodextrins and their derivatives. *J Incl Phenom Macrocycl Chem.* 2019;95(1–2):17–33. doi:10.1007/s10847-019-00929-3
59. Manickavasagan A, Thangavel K, Dev SRS, Delfiya DSA, Nambi E, Orsat V, *et al.* Physicochemical characteristics of date powder produced in a pilot-scale spray dryer. *Drying Technology.* 2015;33(9):1114–1123. doi:10.1080/07373937.2015.1014045
60. Chew SC, Tan CP, Nyam KL. Microencapsulation of refined kenaf (*Hibiscus cannabinus* L.) seed oil by spray drying using β -cyclodextrin/gum arabic/sodium caseinate. *J Food Eng.* 2018;237:78–85. doi:10.1016/j.jfoodeng.2018.05.016
61. Mohd Nawi N, Muhamad II, Mohd Marsin A. The physicochemical properties of microwave-assisted encapsulated anthocyanins from *Ipomoea batatas* as affected by different wall materials. *Food Sci Nutr.* 2015;3(2):91–99. doi:10.1002/fsn3.132
62. Laureanti EJG, Paiva TS, de Matos Jorge LM, Jorge RMM. Microencapsulation of bioactive compound extracts using maltodextrin and gum arabic by spray and freeze-drying techniques. *Int J Biol Macromol.* 2023;253:126969. doi:10.1016/j.ijbiomac.2023.126969
63. Nurhidajah, Yonata D, Pranata B. Microencapsulation of anthocyanin-rich extract from Indonesian black rice using maltodextrin, arabic gum and skimmed milk powder as wall material by spray drying. *Trends in Sciences.* 2024;21(8):7971. doi:10.48048/tis.2024.7971

64. Kalušević A, Lević S, Čalija B, Pantić M, Belović M, Pavlović V, *et al.* Microencapsulation of anthocyanin-rich black soybean coat extract by spray drying using maltodextrin, gum Arabic and skimmed milk powder. *J Microencapsul.* 2017;34(5):475–87. doi:10.1080/02652048.2017.1354939
65. Ávila EL, Rodríguez MC, Velásquez HJC. Influence of maltodextrin and spray drying process conditions on sugarcane juice powder quality. *Rev Fac Nac Agron Medellin.* 2015;68(1):7509–20. doi:10.15446/rfnam.v68n1.47839
66. Bhushette PR, Annapure US. Comparative study of *Acacia nilotica* exudate gum and acacia gum. *Int J Biol Macromol.* 2017;102:266–271. doi:10.1016/j.ijbiomac.2017.03.178
67. Mulcahy EM, Park CW, Drake M, Mulvihill DM, O'Mahony JA. Enhancement of the functional properties of whey protein by conjugation with maltodextrin under dry-heating conditions. *Int J Dairy Technol.* 2018;71(1):216–225. doi:10.1111/1471-0307.12411
68. Szente L, Szejtli J. Cyclodextrins as food ingredients. *Trends Food Sci Technol.* 2004;15(3–4):137–142. doi:10.1016/j.tifs.2003.09.019
69. Krishnaswamy K, Orsat V, Thangavel K. Synthesis and characterization of nano-encapsulated catechin by molecular inclusion with beta-cyclodextrin. *J Food Eng.* 2012;111(2):255–264. doi:10.1016/j.jfoodeng.2012.02.024
70. Osorio J, Monjes J, Pinto M, Ramírez C, Simpson R, Vega O. Effects of spray drying conditions and the addition of surfactants on the foaming properties of a whey protein concentrate. *LWT - Food Science and Technology.* 2014;58(1):109–115. doi:10.1016/j.lwt.2014.02.016
71. Bernard C, Regnault S, Gendreau S, Charbonneau S, Relkin P. Enhancement of emulsifying properties of whey proteins by controlling spray-drying parameters. *Food Hydrocoll.* 2011;25(4):758–763. doi:10.1016/j.foodhyd.2010.08.011
72. Cui L, Kimmel J, Zhou L, Rao J, Chen B. Combining solid dispersion-based spray drying with cyclodextrin to improve the functionality and mitigate the beany odor of pea protein isolate. *Carbohydr Polym.* 2020;245:116546. doi:10.1016/j.carbpol.2020.116546
73. Köprüalan Ö, İltir I, Akyıl S, Koç M, Kaymak Ertekin F. Improving the stability of oily turmeric extract by microencapsulation using spray drying technique. *J Dispers Sci Technol.* 2022;43(14):2240–2249. doi:10.1080/01932691.2021.1929290
74. Yusuf M, Yonata D, Pranata B. Utilization of swimming crab by-product as a seafood flavor microcapsule obtained by spray drying. *AACL-Bioflux.* 2021;15(2):716–724.
75. Čujić-Nikolić N, Stanisavljević N, Šavikin K, Kalušević A, Nedović V, Bigović D, *et al.* Application of gum Arabic in the production of spray-dried chokeberry polyphenols, microparticles characterisation and in vitro digestion method. *Lekovite Sirovine.* 2018;38:9–16.
76. Gonçalves B, Moeenfarid M, Rocha F, Alves A, Estevinho BN, Santos L. Microencapsulation of a natural antioxidant from coffee—chlorogenic acid (3-caffeoylquinic acid). *Food Bioproc Tech.* 2017;10(8):1521–1530. doi:10.1007/s11947-017-1919-y
77. Aguiar J, Costa R, Rocha F, Estevinho BN, Santos L. Design of microparticles containing natural antioxidants: Preparation, characterization and controlled release studies. *Powder Technol.* 2017;313:287–292. doi:10.1016/j.powtec.2017.03.013
78. Estevinho BN, Lopes AR, Sousa V, Rocha F, Nunes OC. Microencapsulation of *Gulosibacter molinivorax* ON4 T cells by a spray-drying process using different biopolymers. *J Hazard Mater.* 2017;338:85–92. doi:10.1016/j.jhazmat.2017.05.018