Freeze-Drying Microencapsulation of *Ruellia tuberosa* L. Extracts: A Comparative Study Using Different Polymers as Encapsulants

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Received: April 1, 2024
Accepted: September 30, 2024

DOI: 10.22146/ijc.95246

Abstract: Ruellia tuberosa *L. leaf and root extracts have been investigated for their biological activity and potential health advantages, including their antidiabetic, antioxidant, and antidiuretic qualities. This research evaluates the freeze-drying microencapsulation of* R. tuberosa *L. extracts using gum Arabic, maltodextrin, and their combination as coating materials. The resulting microcapsules were tested for encapsulation efficiency, biological activity, and controlled release. Characterization techniques included scanning electron microscopy (SEM), Fourier-transform infrared (FTIR) spectroscopy, and particle size analysis (PSA). The choice of encapsulant significantly influenced encapsulation efficiency, morphology, and biological activity. Microcapsules using a combination of gum Arabic and maltodextrin exhibited more spherical shapes and smaller particle sizes than those using either material alone. Alpha-amylase inhibition tests showed that microcapsules effectively inhibit the enzyme, with the coating combination performing best, followed by gum Arabic and then maltodextrin. All microcapsules exhibit moderate antioxidant activity, again in the same order. The active compound release was greater at pH 7.4 compared to pH 2.2 from 0 to 120 min. Therefore, freeze-drying microencapsulation with biodegradable polymers is a viable method for delivering the health benefits of* R. tuberosa *L. extracts, yielding a convenient powder form suitable for drug delivery systems.*

Keywords: *gum Arabic; freeze-drying; maltodextrin; microencapsulation;* R. tuberosa *L.*

■ INTRODUCTION

Indonesia is a country with diverse and abundant natural resources. The country offers a variety of herbal plants with various medicinal properties, making them valuable for traditional treatments of various illnesses [1]. Throughout history, humans have relied on botanical resources to address various health issues. World Health Organization advocates the use of herbal plants in medicine, considering that their utilization has been ongoing since early civilizations to treat a multitude of diseases [2-3].

The *R. tuberosa* L. plant is one of the plants in the *Acanthaceae* family. Due to its secondary metabolite compounds, this plant has been widely used as an antidiuretic, antidiabetic, antioxidant, analgesic, and antihypertensive [4]. Flavonoids, commonly found in plants, often exhibit low bioavailability and can be influenced by environmental factors such as pH and digestive enzymes [5-7]. Microencapsulation is acknowledged as a straightforward yet effective strategy to improve compound bioavailability and shield it from external influences [8-9].

Microencapsulation is a process that involves coating small particles or droplets containing active compounds with a protective wall to form micro-sized capsules. Microencapsulation protects the core or active compound from environmental influences such as moisture, oxygen, light, pH, and several other

environmental factors [10-11]. One commonly used method in the microencapsulation process is freeze drying. Freeze drying is often used, especially for active compounds sensitive to high temperatures. Various factors can influence microencapsulation, one of which is the coating material selection. Some common examples of polymer coating materials include gum Arabic and maltodextrin [12-13].

Gum Arabic is a dried exudate obtained from the stems of the acacia tree. Gum Arabic is commonly used as a coating material in microencapsulation due to its tasteless, non-toxic, water-soluble, and stabilizing agent properties [14]. On the other hand, maltodextrin is a polysaccharide produced through the acid or enzymatic hydrolysis of starch derived from corn, potatoes, or wheat. Maltodextrin is often utilized as a coating material because it is easily soluble in water, has low viscosity, is tasteless, and does not alter the color of the solution. Microencapsulation can be carried out using gum Arabic, maltodextrin, or a combination of both as coating materials [15]. Hence, this research is essential to provide information regarding optimal coating formulation strategies for the water extract of *R. tuberosa* L. leaves. Differences in coating types can influence the physicochemical characteristics of microcapsules, including size, morphology, and solubility under various environmental pH conditions.

Additionally, it is plausible that coating type variations may have an impact on the biological activities that the microcapsules generate. The extract of *R. tuberosa* L. is known to have therapeutic potential, such as anti-diabetic and antioxidant activities [16]. The chemical structure of flavonoids present in the extract allows them to interact with the active site of the amylase enzyme [17-19]. Therefore, by understanding the impact of different coating materials on the resulting microcapsules, this research can help identify the most effective formulations for delivering the active ingredients of *R. tuberosa* L. leaves, which have not been previously studied. Given the background information mentioned above, we conducted further research on the microencapsulation of *R. tuberosa* L. water extract using coating materials such as gum Arabic, maltodextrin, and their combination. This study aimed to assess its potential as a new candidate for traditional medicine and determine the most suitable encapsulant for *R. tuberosa* L. extract. Tests for encapsulation efficiency, controlled release, and biological activity assessment will be used to evaluate the effectiveness of the produced microcapsules.

■ EXPERIMENTAL SECTION

Materials

The *R. tuberosa* L. leaves powder was obtained from UPT Materia Medica Batu, gum Arabic (Merck, analytical standard), maltodextrin (Sigma-Aldrich, analytical standard), alpha-amylase enzyme obtained from *Aspergillus oryzae* (Sigma-Aldrich, ≥ 150 U/mg), phenol (Smart-Lab, analytical standard), aluminum chloride (Sigma-Aldrich, analytical standard), sodium acetate (Merck, analytical standard), acetic acid (Smart-Lab, analytical reagent), glucose (Sigma-Aldrich, ≥ 99.5%), acarbose (OGB Dexa, ≥ 95% 50 mg), sodium hydroxide (Smart-Lab, analytical standard), sodium potassium tartrate (Supelco, analytical standard), 2,2-diphenyl-1-picrylhydrazyl (DPPH) (Sigma-Aldrich, analytical standard), soluble starch (from potato, ACS grade), and 3,5-dinitrosalicylic acid (DNS) reagent (Himedia, ≥ 98% analytical reagent).

Instrumentation

The instrumentations utilized in this study were a Fourier transform infrared spectrometer (FTIR) from Shimadzu Prestige 21, Shimadzu UV-vis spectrophotometer, scanning electron microscopy (SEM TM 3000 Hitachi), and particle size analyzer (PSA CILAS 1090 PSA).

Procedure

Extraction of R. tuberosa *L.*

An amount of 100 g *R. tuberosa* L. leaves powder was macerated with 400 mL of distilled water in a preheated manner for 24 h. Subsequently, the obtained extract was pressed using a hydraulic press. The liquid extract was then filtered using filter paper to separate from the particulates. The liquid extract was evaporated using a water bath until a concentrated extract was obtained.

Microencapsulation

R. tuberosa L. extract was prepared in 0.1 g and dissolved in 5.0 mL of distilled water. Various coating materials, including gum Arabic, maltodextrin, and a combination of both, were then added. The mixture was stirred with a magnetic stirrer at 800 rpm for 90 min. The resulting mixture was freeze-dried to form microcapsules. The encapsulation efficiency indicates the effectiveness of the coating material in encapsulating and protecting the extract. Encapsulation efficiency (EE) is calculated using the Eq. (1).

$$\text{Encapsulation efficiency (\%)} = \frac{\text{total flavonoid content in microcapsules}}{\text{total flavonoid content in the extract}} \times 100\% \quad (1)$$

Alpha amylase enzyme inhibitory activity test

The *R. tuberosa* L. extract, microcapsules, and acarbose were prepared at various concentrations: 10, 20, 40, 60, 80, and 100 µg/mL. Subsequently, 250 µL was taken from each concentration and placed into reaction tubes. Then, 250 µL of a 50 µg/mL alpha-amylase enzyme solution was homogenized to each tube. This mixture was incubated for 30 min at 37 °C. Afterward, 250 µL of 1% (w/v) starch was added and incubated for 10 min at room temperature. Next, 500 µL of DNS reagent was added to each tube and incubated in boiling water for 5 min until the solution turned reddish-brown. The solution was then cooled using running water, 5 mL of distilled water was added and homogenized, and the absorbance was measured at the maximum wavelength. The recorded absorbance values were used to calculate the percentage inhibition of alpha-amylase enzyme activity using the Eq. (2).

$$\%\text{Inhibition} = \frac{A_{control} - A_{sample}}{A_{control}} \times 100\% \quad (2)$$

The $A_{control}$ absorbance represents the absorbance without the inhibitor. In contrast, the sample absorbance represents the absorbance with the inhibitor from the water extract of *R. tuberosa* L., microcapsules, or acarbose. Subsequently, a curve was created relating the concentration of the sample solution to the percentage inhibition, with the concentration of the sample solution on the x-axis and the percentage inhibition on the y-axis. After obtaining the regression equation y = ax + b, the IC_{50} value was calculated.

Antioxidant activity test

After preparing the sample solution with various concentrations, 3 mL was taken from each solution and placed into dark vials to avoid exposure to light. Subsequently, 2 mL of DPPH solution was added to each vial. After homogenization, the mixtures were incubated for 20 min at room temperature in the dark. Following incubation, the solution's absorbance was measured using a UV-vis spectrophotometer at the maximum wavelength with an ethanol solution as the blank (Eq. (3)).

$$\%\text{Antioxidant} = \frac{A_{control} - A_{sample}}{A_{control}} \times 100\% \quad (3)$$

$A_{control}$ represents the sample's absorbance without adding the extract, microcapsules, or ascorbic acid. Next, a curve was created relating the concentration of the sample solution to the percentage inhibition, with the concentration of the sample solution on the x-axis and the percentage inhibition on the y-axis. After obtaining the regression equation, the IC_{50} value was calculated.

Release test

There were 2 variations or pH environments in the release test of microcapsule active ingredients: pH 2.2 or simulated gastric fluid (SGF) and pH 7.4 or simulated intestinal fluid (SIF). The SGF is created with a mixture of phosphate-buffered saline and HCl, while SIF is created with a mix of phosphate-buffered saline and NaOH. Microcapsule samples were prepared in the amount of 0.1 g. Then, 10 mL of SGF or SIF solution was added. Following that, it was stirred with a magnetic stirrer at a temperature of 37 °C with a speed of 100 rpm for 30, 60, 90, and 120 min, with a collection of 2.5 mL at each time variation. After that, the absorbance was measured at a wavelength of 420 nm. The percentage release of microcapsule active ingredients can be calculated using Eq. (4).

$$\%\text{Release} = \frac{\text{total flavonoid content (t)}}{\text{total flavonoid content (opt)}} \times 100\% \quad (4)$$

FTIR, SEM, and PSA analysis

The microcapsules were analyzed using a FTIR spectrophotometer with wavenumbers within the 4,000–400 cm^{-1} range. The particle size and distribution of the microcapsules were assessed using a PSA. The shape and morphology of the microcapsules were examined through SEM with magnifications ranging from 1,000 to 15,000 times.

Data analysis

Statistical analysis was performed using SPSS software version 27.0 on the Windows operating system. The obtained data were analyzed for normality and variance homogeneity using the Kolmogorov-Smirnov test. Subsequently, a one-way ANOVA test was conducted with a confidence level of 95% ($\alpha = 0.05$). Further, post-hoc Tukey HSD tests were performed to determine significant differences between treatments.

■ RESULTS AND DISCUSSION

Encapsulation Efficiency

The EE of each sample is calculated by measuring the total flavonoid content (TFC) in the sample [20]. The EE value is a crucial factor in ensuring the success of an encapsulation process, regardless of the microencapsulation method or materials used. TFC is calculated using a colorimetric method with an $AlCl_3$ reagent, which forms a colored complex. $AlCl_3$ binds with flavonoids containing 5-hydroxy-4-keto, 3-hydroxy-4-keto, or *o*-dihydroxyl groups, resulting in an orange-colored complex whose intensity can be measured using a UV-vis spectrophotometer.

Table 1 shows the results of the EE percentage based on determining TFC. The EE results indicate that the combination of coating materials has the highest rate, followed by microcapsules with gum Arabic and maltodextrin alone as coating agents. This is because a single coating material is considered insufficient to possess all the characteristics necessary for efficient encapsulation. Therefore, a combination of coating materials emerges as an effective strategy to protect the core material. The highest efficiency in combining gum Arabic and maltodextrin may be attributed to its structural composition. Gum Arabic is a branched heteropolymer of sugars containing a small amount of protein, while maltodextrin is a long-chain carbohydrate [21-22]. Hence, according to Mahdavi et al. [23], the protein within gum Arabic covalently binds to the maltodextrin carbohydrate chain to form a good film or layer, thus enhancing encapsulation efficiency.

Inhibition Activity Test

The test for alpha-amylase enzyme inhibition activity is one way to determine the potential of plant extracts as antidiabetic drugs. This is because the alpha-amylase enzyme catalyzes the hydrolysis of α-(1,4)-D-glycosidic bonds in starch, breaking it down into smaller fragments and other glucose polymers. Therefore, inhibiting alpha-amylase activity can impede further sugar digestion, helping to reduce blood sugar levels. Table 2 shows the results of the alpha-amylase enzyme inhibition activity test by microcapsules with various encapsulants, the extract of the *R. tuberosa* L plant, and acarbose [24].

Table 2. Result of the alpha-amylase enzyme inhibition assay

Sample	IC_{50} (μg/mL)
Microcapsules with maltodextrin coating	84.01 ± 1.15^{e}
Microcapsules with Arabic gum coating	76.13 ± 1.16^{d}
Microcapsules with combination coating	68.01 ± 1.32^{c}
R. tuberosa L. extract	51.14 ± 1.84^{b}
Acarbose	27.54 ± 0.53^{a}

*Different letter notations indicate significant differences between samples at the level of α = 5%

Table 1. Encapsulation efficiency of various microcapsule

Sample	Encapsulation efficiency (%)
Microcapsules with maltodextrin coating	45.60 ± 1.50^{a}
Microcapsules with Arabic gum coating	57.47 ± 0.80^{b}
Microcapsules with combination coating	68.46 ± 0.90^{c}

*Different letter notations indicate significant differences between samples at the level of α = 5%

The alpha-amylase enzyme inhibition activity test was conducted using the spectrophotometric method with a DNS reagent. The results are expressed in IC_{50} representing the sample concentration necessary to inhibit 50% of the alpha-amylase enzyme activity. It can be observed that the three microcapsules produced different IC_{50} values. The highest was observed with maltodextrin as the encapsulant, followed by microcapsules with gum Arabic as the encapsulant and the lowest IC_{50} value was for microcapsules with a combination of encapsulants. This variability is likely due to the different active ingredients trapped in each microcapsule, as evident from the encapsulation efficiency results. Microcapsules with a combination of encapsulants produced a higher EE value than microcapsules with a single encapsulant. The greater the efficiency value of microcapsules, the more extract compounds they contain. Microcapsules can inhibit alpha-amylase enzyme activity because they contain active flavonoid compounds. The hydroxyl groups on the flavonoid ring can interact with amino acid residues at the active site, thus inhibiting alpha-amylase enzyme activity [17-19].

The water extract of *R. tuberosa* L. without microencapsulation produced a lower IC_{50} value than other microcapsules. This discrepancy arises because the active compound content in the microcapsules may not be fully released and remains retained within them. Additionally, the active compounds in the extract cannot be wholly entrapped, as indicated by the EE value not reaching 100%. The primary objective of microencapsulation is not to enhance biological activity but to protect the active compounds or core material. Therefore, the microcapsules of the water extract of *R. tuberosa* L. can still function as an inhibitor of alpha-amylase enzyme. Acarbose, used as a reference, is an antihyperglycemic drug, exhibiting the lowest IC_{50} value as it has been proven to competitively inhibit the enzyme activity [25-26].

Antioxidant Activity Test

Antioxidants are compounds capable of neutralizing free radicals or oxidants. An imbalance where oxidants outnumber antioxidants in the body is termed oxidative stress. Prolonged oxidative stress in the body can lead to various diseases, such as cancer, heart problems, and degenerative diseases [27-28]. Therefore, antioxidant activity tests are conducted to measure the effectiveness of microcapsules in preventing oxidative stress.

The antioxidant activity test was conducted spectrophotometrically using DPPH compound. The test results are expressed in IC_{50}. The smaller the IC_{50} concentration, the more influential the antioxidant activity of a sample. As seen in Table 3, ascorbic acid exhibits the most potent antioxidant activity. This is reasonable because ascorbic acid, is one of the strongest and non-toxic natural antioxidant compounds [29-30]. Microcapsules with various coating materials produce different IC_{50} values. The IC_{50} values in sequence from highest to lowest are microcapsules with maltodextrin coating, followed by gum Arabic, and the weakest with a combination of maltodextrin and gum Arabic. These results are similar to the IC_{50} values in the alpha-amylase enzyme inhibition activity, possibly because the combination of coatings serves as a better wall material, thereby enhancing encapsulation efficiency compared to single-coating materials. These results also align with the study by Laureanti et al. [31], which stated that combining gum Arabic and maltodextrin produces better antioxidant activity by 31% compared to microcapsules with maltodextrin or gum Arabic alone.

The water extract of *R. tuberosa* L. and microcapsules can exhibit antioxidant activity due to the presence of active flavonoid compounds. The hydroxyl groups on flavonoids' B and C rings can donate electrons to reactive oxidants, making them more stable [32-33].

Table 3. Result of antioxidant activity assay

Sample	IC_{50} (µg/mL)
Microcapsules with maltodextrin coating	147.32 ± 0.90^{e}
Microcapsules with Arabic gum coating	136.27 ± 1.19^{d}
Microcapsules with combination coating	122.49 ± 3.48^{c}
R. tuberosa L. extract	74.76 ± 1.42^{b}
Ascorbic acid	4.07 ± 0.23^{a}

*Different letter notations indicate significant differences between samples at the level of α = 5%

Antioxidant activity can be classified based on its strength. Ascorbic acid is a potent antioxidant with an IC_{50} value of < 50 µg/mL. Followed by the water extract of *R. tuberosa* L. is considered a powerful antioxidant with IC_{50} values in the range of 50–100 µg/mL. Finally, all three microcapsules fall into the moderate antioxidant category with IC_{50} values ranging from 101 to 150 µg/mL. Based on Table 3, microcapsules exhibit a lower antioxidant activity level than directly encapsulated extract compounds. This reduction in activity may be attributed to the limitations of microcapsules in fully releasing all active compounds contained within them. This limitation can reduce the effectiveness of microcapsule antioxidants, as not all active compounds can interact with their surroundings. However, microcapsules of the water extract of *R. tuberosa* L. still retain antioxidant properties, making them a potential candidate for traditional medicine [34].

Release Test Results

The ability to regulate or control the release of active substances from within microcapsules into the surrounding environment is called controlled release or controlled release microcapsules. Microcapsules with controlled release are expected to release active compounds at the desired target and time. The pH environment in the digestive system can be used as a reference to control the release of active substances in microcapsules. The microcapsule environment is made acidic, with a pH of 2.2, and neutral, with a pH of 7.4 to represent when microcapsules are present in the digestive tract, specifically the stomach and intestines. This study used phosphate buffer with pH 2.2 and 7.4 to simulate the microcapsule environment in the stomach and intestines [35].

The release test used phosphate buffer at pH 2.2 and 7.4 over 30–120 min at 37 °C. Fig. 1 shows the release profile of gum Arabic microcapsules with consecutive percentage values of 24.05, 26.09, 26.63, and 27.71% at pH 2.2 over 30–120 min. Subsequently, at pH 7.4, there was an increase in the percentage within the same time range, consecutively reaching 37.76, 40.34, 44.16, and 47.40%. The smaller percentage values at pH 2.2 may be attributed to the carboxyl groups in protonated gum Arabic. As a result, the increased hydrogen bonding within the system causes the microcapsule matrix to tighten, making it more difficult for the active substance or core material to be released [36]. SEM results of the release at pH 2.2 after 120 min indicate that Fig. 2(a) presents aggregated morphology. In contrast, at pH 7.4 (Fig. 2(b)), it shows aggregated and porous characteristics [37].

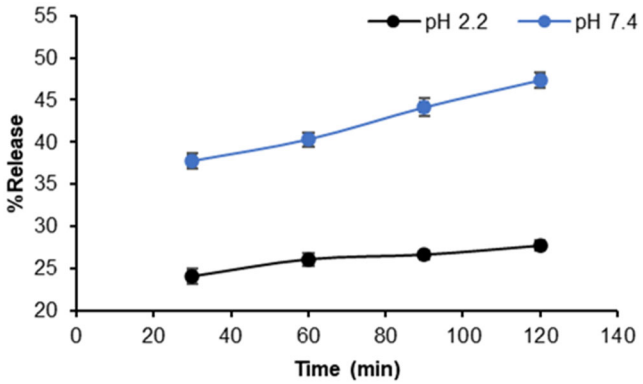


Fig 1. Release profile of Arabic gum-coated microcapsules at pH 2.2 and 7.4

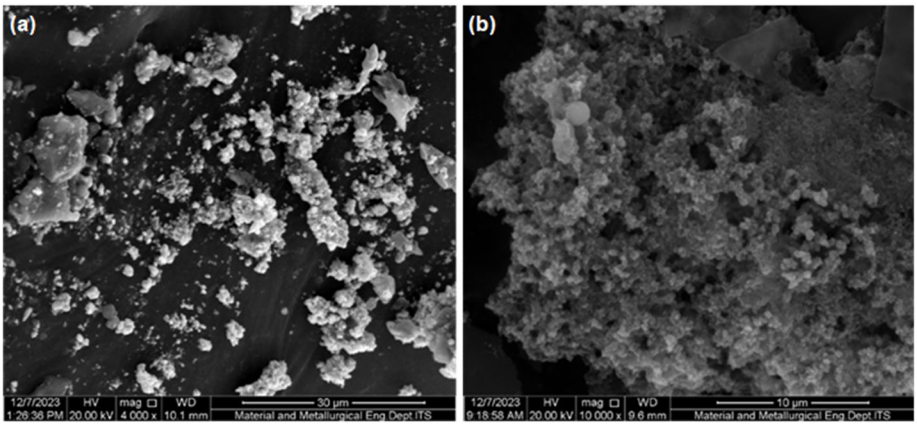


Fig 2. SEM images of gum Arabic-coated microcapsules after release test for 120 min at (a) pH 2.2 and (b) pH 7.4

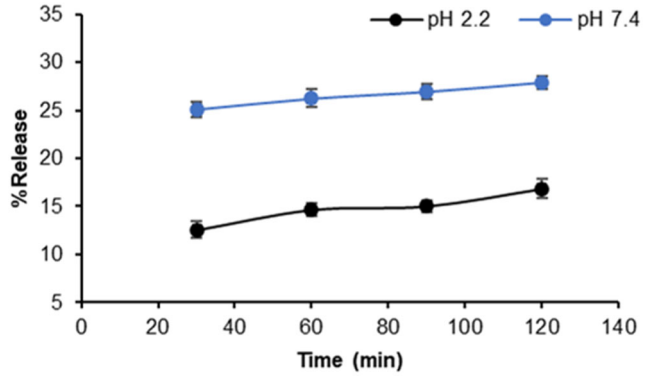


Fig 3. Release profile of maltodextrin-coated microcapsules at pH 2.2 and 7.4

Subsequently, microcapsules with maltodextrin coating (Fig. 3) at pH 2.2 exhibited consecutive percentage release values of 12.59, 14.66, 15.04, and 16.49% over 30–120 min. Meanwhile, at pH 7.4, there was only a slight increase, consecutively 22.60, 25.09, 26.21, 26.92, and 27.87% over the same time range. The release profile results indicate that at pH 2.2 and pH 7.4, maltodextrin only experienced a slight increase in the percentage release in each 30-min interval. According to the study by Ribeiro et al. [38], this may be due to the inherent properties of maltodextrin, making it more challenging to release the active substance than gum Arabic or combining gum Arabic with maltodextrin. This theory is supported by Fig. 4, which shows SEM results of the release at pH 2.2 and 7.4, respectively. Both SEM results indicate that after 120 min, the microcapsules still maintain irregular lumps and appear intact, showing no signs of breaking or releasing the active substance within them [39].

Based on Fig. 5, it can be observed that the release percentage of combination-coated microcapsules at pH 2.2 was 27.79% at 30 min, 29.87% at 60 min, 30.49% at 90 min, and 31.57% at 120 min. Meanwhile, there was an increase in release percentage with the rise in pH to 7.4, which was 40.96% at 30 min, 44.74% at 60 min, 46.69% at 90 min, and 52.97% at 120 min. There was a difference in release of 21.4% between pH 2.2 and 7.4 after 120 min. This difference is suspected to be associated with the protonation of carboxyl groups in gum Arabic at pH 2.2. This protonation process can cause an increase in hydrogen bonding within the microcapsule structure, thereby reducing the percentage of active ingredient release. Conversely, at pH 7.4, which is more fundamental, the protonation of carboxyl groups decreases, reducing hydrogen bonding and allowing for more efficient active ingredient release. The SEM release results after 120 min show that Fig. 6(b) provides a more

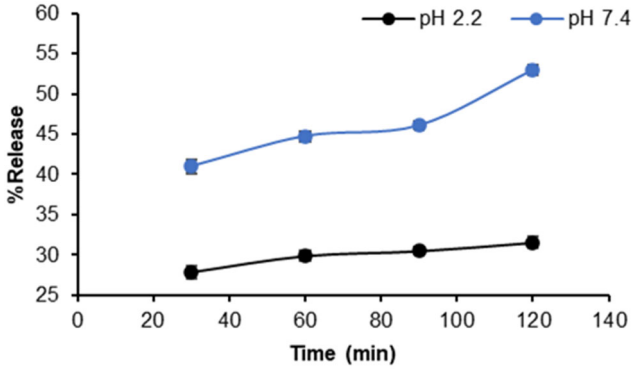


Fig 5. Release profile of combination coated microcapsules at pH 2.2 and 7.4

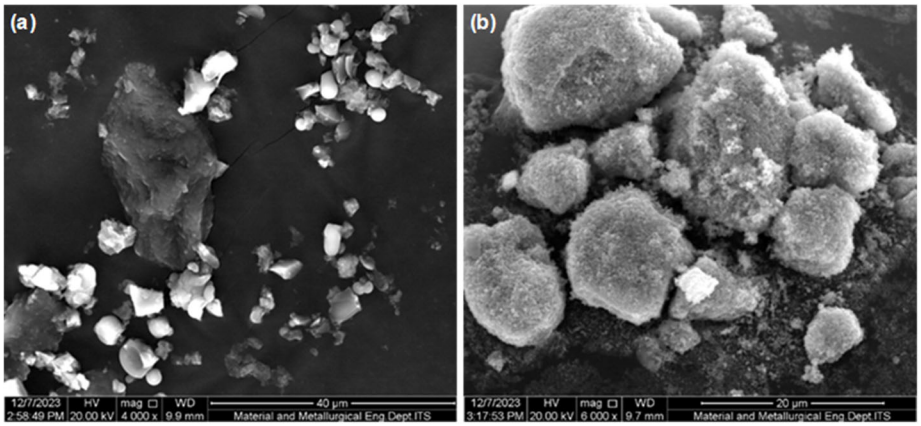


Fig 4. SEM images of maltodextrin-coated microcapsules after release test for 120 min at (a) pH 2.2 and (b) pH 7.4

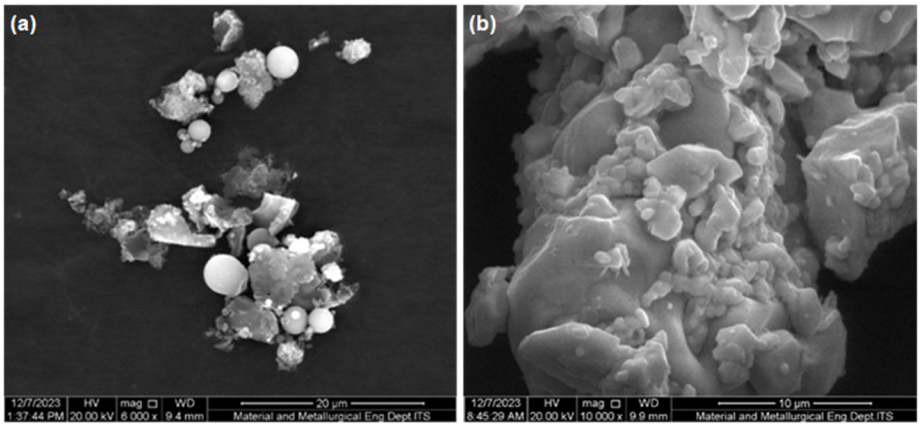


Fig 6. SEM images of combination-coated microcapsule after release test for 120 min at (a) pH 2.2 and (b) 7.4

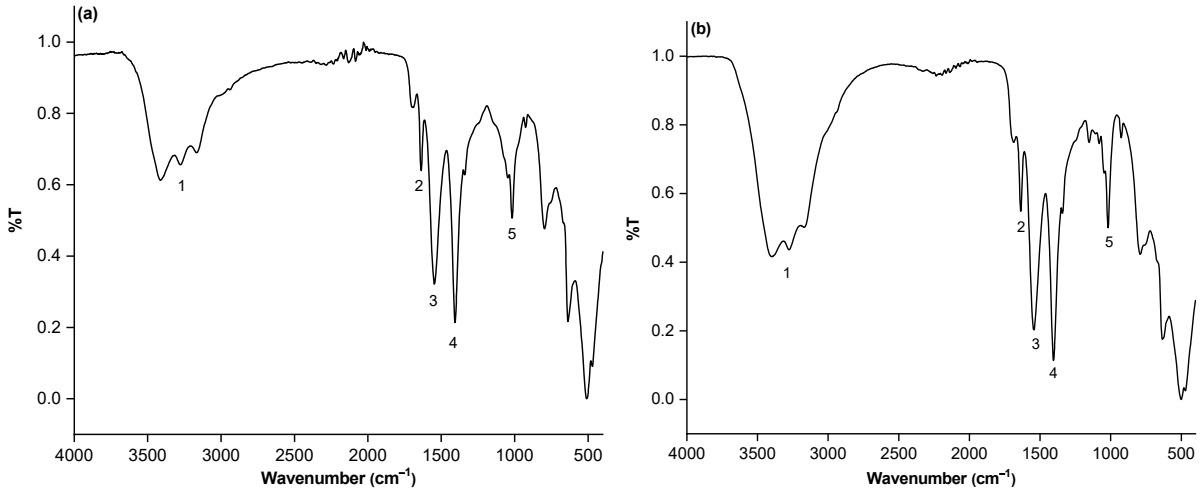
uniform and aggregated morphology, while at pH 2.2 (Fig. 6(a)), it is not aggregated, and some still appear round [37].

FTIR, SEM, and PSA Analysis

The microcapsules were analyzed and identified using FTIR. The FTIR results are presented in Fig. 7, and the assignment of the relevant peaks is provided in Table 4. The spectra generated by all three microcapsules exhibit remarkable similarity or equivalence. Specifically, peak number 1 indicates the presence of alcohol O–H. Following this, peak number 2 shows the presence of the C=C, while peak number 3 indicates the presence of the C–H alkane [40].

Moreover, peak number 4 illustrates the vibrational pattern of the carboxylate COO^- bond and peak number 5 shows the vibrational behavior of the ether C–O–C bond. Based on Fig. 8, microcapsules with gum Arabic and combination coating have similar morphologies, characterized by small and spherical shapes with certain irregularities and roughness. Meanwhile, those with maltodextrin coating exhibit a flatter and more aggregated shape.

PSA analysis was also carried out to measure the size and distribution of the particles shown in Fig. 9. All microcapsules produce polymodal shapes with average diameters for microcapsules with gum Arabic coating at 142.88 μm, microcapsules with maltodextrin coating at 185.43 μm, and microcapsules with a combination of coatings at 135.81 μm. These microcapsules fall within the size range of microcapsules produced by the freeze-drying method, ranging in size from 70 to 800 μm [41-42].



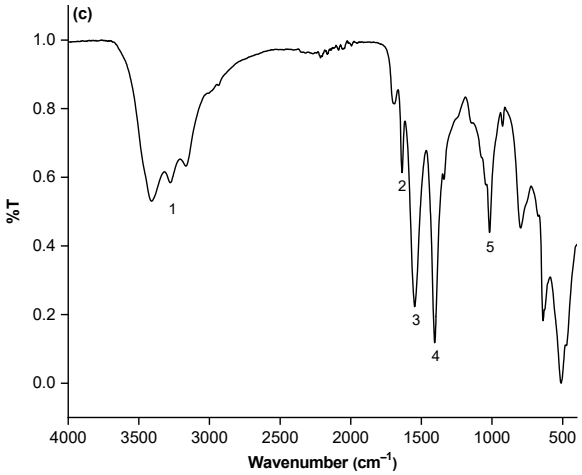


Fig 7. FTIR spectra of (a) gum Arabic-coated microcapsules, (b) maltodextrin-coated microcapsules, and (c) combination-coated microcapsules

Table 4. Assignment for FTIR spectra

Peak Number	Wavenumber (cm^{-1})			Functional group
	Microcapsule with maltodextrin coating	Microcapsule with gum Arabic coating	Microcapsule with combination coating	
1	3570–3200	3570–3200	3570–3200	O–H alcohol
2	1680–1620	1680–1620	1680–1620	C=C alkene
3	1485–1445	1485–1445	1485–1445	C–H alkane
4	1420–1300	1420–1300	1420–1300	COO carboxylate
5	1150–1050	1150–1050	1150–1050	C–O–C ether

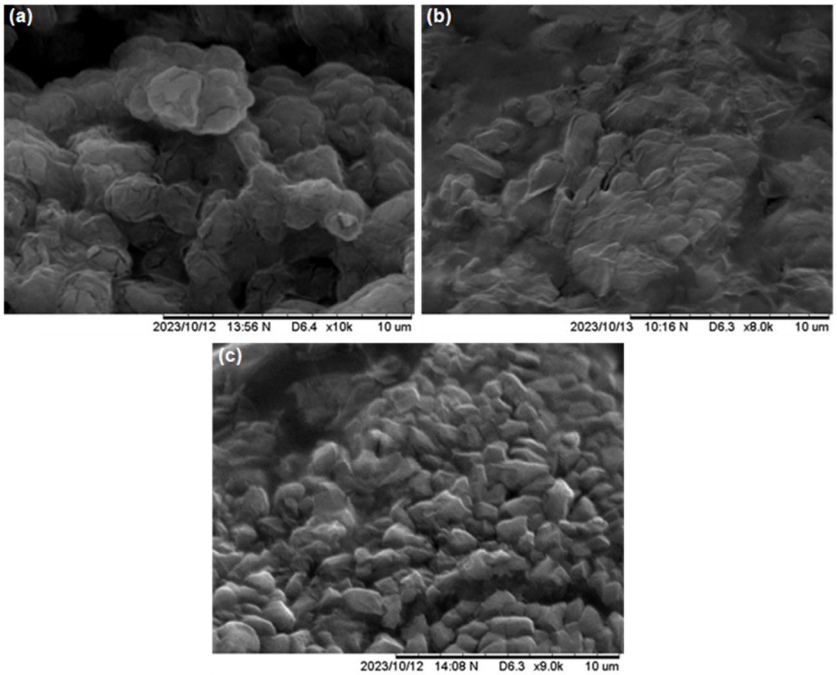


Fig 8. SEM images of (a) gum Arabic-coated microcapsules, (b) maltodextrin-coated microcapsules, and (c) combination-coated microcapsules

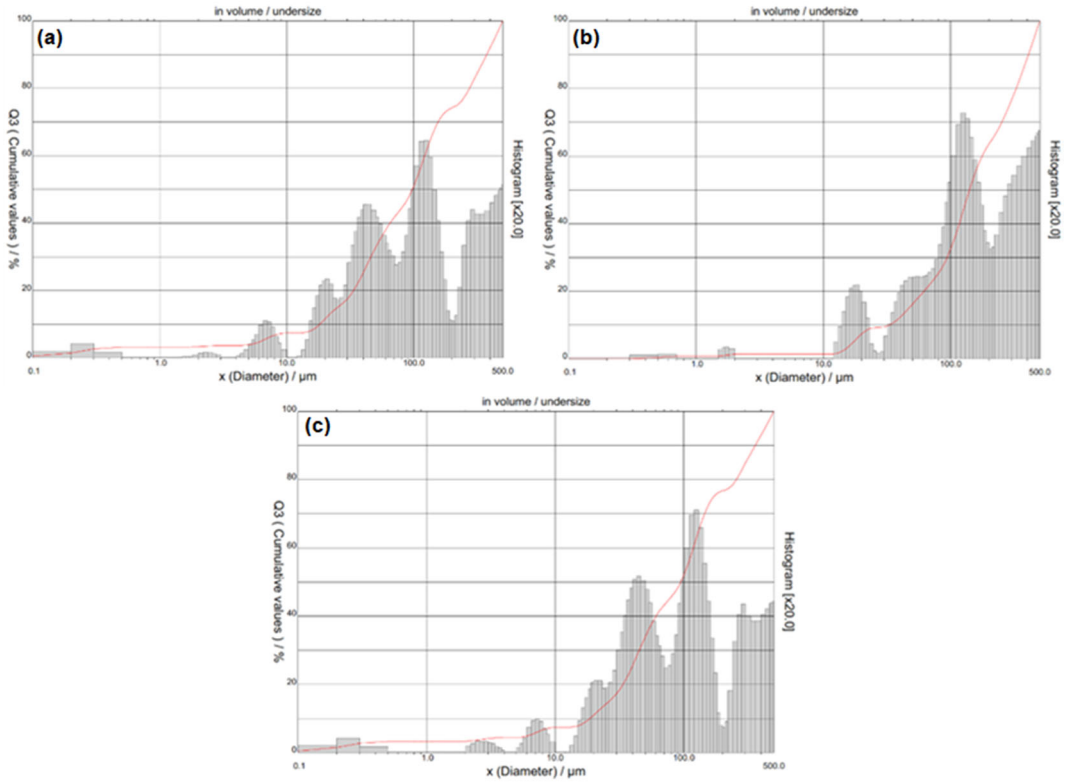


Fig 9. Particle size distribution of (a) gum Arabic-coated microcapsules, (b) maltodextrin-coated microcapsules, and (c) combination-coated microcapsules

■ CONCLUSION

The microencapsulation of *R. tuberosa* L. using the freeze-drying method with gum Arabic, maltodextrin, and their combination as coating materials was successfully achieved. Microcapsules combining gum Arabic and maltodextrin as coating materials showed the highest encapsulation efficiency at 68.46%. Analysis of alpha-amylase enzyme inhibition activity reveals that microcapsules with different coatings effectively inhibit the enzyme's activity, with IC_{50} values of 84.01 µg/mL for maltodextrin coating, 76.13 µg/mL for gum Arabic coating, and 68.01 µg/mL for combination coating. Furthermore, all three microcapsules exhibit moderate antioxidant activity, with IC_{50} values of 147.32 µg/mL for maltodextrin-coated microcapsules, 136.27 µg/mL for gum Arabic-coated microcapsules, and 122.49 µg/mL for combination-coated microcapsules. Additionally, over 120 min, the gum Arabic-coated microcapsules show a 19.7% increase in active component release at pH 7.4 relative to pH 2.2. In contrast, the combination and maltodextrin-coated microcapsules show more significant release percentages of 11.38 and 21.4%, respectively. Thus, a combination of gum Arabic and maltodextrin as coating materials was the optimum wall material in this study. Microencapsulation may serve as a method to protect core materials and improve the bioavailability of plant extracts.

■ ACKNOWLEDGMENTS

The funding for this research was provided by *Hibah Doktor* Grant 2024, Grant number: 02174.1/UN10.F0901/B/KS/2024.

■ CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

■ AUTHOR CONTRIBUTIONS

Firza Rajasa Gunawan conducted the experiment, Firza Rajasa Gunawan, Siti Mariyah Ulfa, Anna Safitri wrote and revised the manuscript. All authors agreed to

the final version of this manuscript.

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