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Encapsulation of *Lansium domesticum* leaves extract: advancing polyphenol stability and antioxidant activity

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Lansium domesticum, commonly known as *duku* in Indonesia, is a plant rich in bioactive compounds, particularly phenol and flavonoid, which shows potent antioxidant properties. However, these compounds are highly susceptible to degradation under high-temperature conditions, limiting stability and effectiveness. To address the limitations, encapsulation technology offers a promising method to protect bioactive compounds from degradation, enhancing stability and potential applications in food, pharmaceutical, and cosmetic industries. Therefore, this study aimed to determine the most effective encapsulation method for producing microcapsules from *L. domesticum* leaves extract. The extraction process was carried out using the sonication method with ethyl acetate as the solvent and maltodextrin as the coating material. A total of four different encapsulation methods were evaluated, namely freeze-drying, microwave oven-drying, convection oven-drying, as well as a combination of freeze-drying and microwave oven-drying. The results showed that encapsulation method significantly influenced the yield, moisture content, particle size, phenol, and flavonoid content, including antioxidant activity of microcapsules. Among the tested methods, freeze-drying produced the highest quality microcapsules, with a total phenol content of 9.04 ± 0.3 mg AGE/g, total flavonoid content of 33.36 ± 1.8 mg QE/g, and DPPH free radical scavenging activity of 46.86 ± 2.6%. The results were in with the United Nations Sustainable Development Goals (SDGs), particularly Goal 3 (Good Health and Well-being) and Goal 12 (Responsible Consumption and Production). By enhancing the stability and bioavailability of natural antioxidants, this study contributed to the development of sustainable functional foods, nutraceuticals, and natural-based pharmaceuticals.

Keywords: antioxidant activity; encapsulation; *Lansium domesticum*; phenolic

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INTRODUCTION

Lansium domesticum, commonly known as duku in Indonesia, is a popular tropical fruit in the local community and mostly consumed fresh. This fruit is widely distributed across Southeast Asian nations, particularly Thailand, Malaysia, Indonesia, and the Philippines (Abdallah et al., 2022). *L. domesticum* contains nutritional values such as carbohydrates (glucose and fiber), vitamin B, and vitamin C (Tilaar et al., 2008). Moreover, it has been traditionally used to treat various diseases (Venkatachalam, 2019), including malaria, worms, insect bites, scorpion stings, eye inflammation, ulcers, diarrhea, dysentery, fever, spasms, and flatulence (Abdallah, et al., 2022). Based on previous reports, *L. domesticum* has pharmacological activities as a colonic anticancer and mouth epidermal anticancer (Manosroi et al., 2012, 2013). The seeds also have antioxidant activity by capturing O_2 and OH- free radicals. Ethanol extract of *L. domesticum* seeds acts as an antioxidant by increasing GSH (antioxidant) levels and decreasing rat blood plasma MDA (oxidant) levels (Wibowo et al., 2024).

Based on previous research, L. domesticum bears fruit once a year, while its leaves remain underutilized despite the potential benefits. According to Lubis et al. (2022), *L. domesticum* leaves have antioxidant and anti-inflamatory properties. The bioactive compounds found in these leaves, primarily phenolics such as flavonoid (Manosroi et al., 2013) and terpenoid (Ragasa et al., 2014), belong to a group of naturally occurring compounds with significant potential for pharmaceutical and nutraceutical applications. However, these compounds are highly susceptible to oxidation and degradation because of environmental factors such as oxygen, temperature, and pH variations. To ensure stability and bioavailability, encapsulation technology provides an effective method for preserving their potency and extending usability.

The use of *L. domesticum* leaves is in line with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 12 (Responsible Consumption and Production). The extraction and stabilization of bioactive compounds from unused plant parts support sustainable resource use by reducing agricultural waste and promoting the development of nature-based pharmaceuticals. Additionally, encapsulation technology enhances stability and efficacy, ensuring long-term effectiveness in healthcare applications. By transforming underutilized plant resources into valuable health-promoting products, this study contributes to

sustainable innovation in the fields of medicine, nutrition, food, and environmental conservation.

Bioactive compounds are commonly used as potential natural-based drugs and functional food but are easily oxidized or degraded due to environmental factors such as oxygen, temperature, and pH. The high susceptibility to degradation shows the need to maintain stability through encapsulation technology (Zabot et al., 2022). In this context, microencapsulation is a method for coating active ingredients in the form of solids, liquids, or gases, which aims to protect the core material in the form of bioactive compounds such as phenolic, tannin, flavonoid, and others from various environmental influence including light, oxygen, water, and temperature (Delviani et al., 2024; Tarigan et al., 2023). Compounds that are not resistant to environmental influence, such as bioactive compounds, vitamins, enzymes, and other compounds, can be maintained by microencapsulation.

Various encapsulation methods are used in the industry, including freeze-drying, which is widely applied to protect heat-sensitive food and bioactive compounds, but the process is time-consuming (Ananda et al., 2022; Tarigan et al., 2023) and costly. In comparison, microwave technology, traditionally used for heating food, is currently gaining significant attention for encapsulation. This method significantly reduces processing time, serving as a more economical method that enhances product quality. Microwave encapsulation has been successfully applied to blueberry extract (Ahmad et al., 2020) and purple sweet potato (Padzil, et al., 2018). Generally, encapsulation is a widely used method to protect bioactive compounds from degradation, enhance stability, and improve controlled release in various applications, particularly in food and pharmaceutical industries. As a common method, freeze-drying has a long processing time and high cost, leading to the development of alternative or combined techniques, such as microwave-assisted drying, to enhance efficiency (Prosapio & Norton, 2017). Microwave has been shown to reduce drying time, lower energy consumption, and improve product quality compared to conventional freeze-drying.

Despite the potential, the application of microwave-assisted freeze-drying for encapsulation of *L. domesticum* leaves extract remains unexplored. *L. domesticum* leaves are known to contain high levels of phenolic and flavonoid, contributing to their significant antioxidant activity. However, the effects of different encapsulation methods on the retention of these bioactive compounds and their antioxidant properties have not been studied. Therefore, this study aimed to evaluate the impact of various encapsulation methods on phenolic, flavonoid, and antioxidant activity of *L. domesticum* leaves extract, providing information into optimizing encapsulation strategies for preserving bioactive compounds.

MATERIALS AND METHODS

Materials

The leaves used in this study were selected from small-holder plantations in Kumpeh District, Muaro Jambi Regency, Jambi Province, Indonesia. Ethyl acetate, ethanol, Folin–Ciocalteu, Na_2CO_3, CH_3COOK, and $AlCl_3$ were purchased from Merck Co. (Darmstadt, Germany). 2,2-Diphenyl-1-picrylhydrazyl (DPPH), galic acid, and quercetin were purchased from Sigma-Aldrich (St Louis, USA), and maltodextrin (Sigma-Aldrich).

Methods

Extraction procedure

Initially, mature leaves were harvested, thoroughly washed with water, and air-dried at room temperature for 7 days. Once dried, leaves were ground into a fine powder using a Philips blender. The powdered form was subjected to extraction using ethyl acetate as the solvent in an ultrasonic bath (Sonorex Digitec, Bandelin), with a material-to-solvent ratio of 1:20 (w/v). Subsequently, the extraction process was conducted at 50ºC for 80 min, followed by filtration using Whatman No. 41 filter paper (GE Healthcare) to separate the solid residues. The resulting filtration was concentrated using a rotary vacuum evaporator (Stuart) at 50ºC to remove the solvent. The final extract was stored at -10°C until further processing into microcapsules (Tarigan et al., 2023).

Encapsulation process

Microcapsules are made with coating material, namely maltodextrin, which was dissolved in distilled water (solution 20 %) and kept in a shaker at 35ºC for 2 hr. Leaves extract 0.5% and 2% tween 80 were added. This mixture was homogenized with a homogenizer (ultra-turrax) at 10000 rpm for 10 min. Subsequently, the mixture was dried using four different methods: (1) freeze-drying with a Salford Scientific freeze dryer for 48 hours; (2) drying in a Sharp microwave oven for 12 minutes; (3) drying in a Memmert convection oven for 4 hours; and (4) a

combination method involving freeze-drying for 12 hours followed by microwave drying using a sharp oven for 8 min. The resulting encapsulated powder was stored at 15ºC. The yield was calculated based on the ratio between the weight of encapsulated powder produced and the weight of the initial raw material used (Heriyanti et al., 2024), as shown in Equation 1.

$$\text{Yield } (\%) = \frac{\text{microcapsules weight (g)}}{\text{initial weight (g)}} \times 100\% \quad (1)$$

Determination of moisture content and solubility

Moisture content of microcapsules was determined using the gravimetric method by calculating the weight loss between the initial and final sample weight. The calculation was based on the weight difference between the initial sample and the blank (Heriyanti et al., 2024). Meanwhile, solubility of microcapsules was determined based on a previously established procedure (Nuralang et al., 2025). Microcapsules weighed 1 g, dissolved in 20 mL of distilled water, and then filtered with Whatman-41 paper dried in an oven at 105ºC for 30 min. The filter paper and the residue were dried at 105ºC for 1 hr, followed by cooling in a desiccator for 15 min and weighing. The solubility was calculated using Equation 2.

$$\text{Solubility } (\%) = \left(1 - \frac{c-b}{\frac{a*(100-mc)}{100}}\right) * 100\ \%$$

Notes:

a = sample weight (g); b = filter paper (g); c = filter paper + residue (g); mc = moisture content (%)

Particle size, zeta potential, and morphological structure

Particle size, polydispersity index (PDI), and zeta potential of microcapsules were measured using a particle size analyzer and a Nano Zeta Sizer (Malvern Instruments, Worcestershire, UK). The samples were prepared in emulsion form and placed in the sample holder for analysis. Measurements of particle size, PDI, and zeta potential were then conducted following the method described by the previous study (Ballesteros et al., 2017) Additionally, the morphological structure of microcapsules was examined using Scanning Electron Microscopy (SEM) at 250× magnification, as described by previous study (Tarigan et al., 2023).

Determination phenol content

Total phenol content was determined using the Folin-Ciocalteu colorimetric method. Initially, 200 µL of the sample was transferred into a test tube, followed by the addition of 1 mL of 10% Folin-Ciocalteu reagent. After incubating for 1 min, 3 mL of a 20% Na_2CO_3 solution was added. The mixture was then incubated in a dark room at room temperature for 2 hours. Finally, the absorbance was measured using UV-Vis spectrophotometer at a wavelength of 760 nm. Total phenol content was quantified using a gallic acid standard curve and expressed as milligrams of gallic acid equivalent per gram (mg GAE/g) (Erskine et al., 2022).

Determination flavonoid content

Total flavonoid content was determined using the coulometric method. Initially, 500 µL of the sample was transferred into a test tube, followed by the addition of 100 µL of 10% $AlCl_3$, 100 µL of 1 M CH_3COOK, and 4.3 mL of distilled water. The mixture was then vortexed and incubated at room temperature for 30 minutes. Finally, the absorbance was measured using UV-Vis spectrophotometer at a wavelength of 415 nm. Total flavonoid content was quantified using a quercetin standard curve and expressed as milligrams of quercetin equivalent per gram (mg QE/g) (Heriyanti et al., 2024).

Radical scavenging (antioxidant activity)

The sample was first dissolved in ethanol, where 0.2 mL was mixed with 3.8 mL of a 125 mM DPPH solution and vortexed thoroughly. The mixture was then incubated in a dark room for 30 minutes to allow the reaction to take place. After incubation, the absorbance was measured using a spectrophotometer at a wavelength of 517 nm. The percentage of DPPH inhibition by the extract was calculated using Equation 3.

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

Data Analysis

The data were analyzed using one-way Analysis of Variance (ANOVA) by SPSS 21 software. Significant was observed at 5 %, and Duncan's Multiple Range Test (DMRT) multiple comparison tests were performed to determine the significant differences.

RESULTS AND DISCUSSION

The yield of microcapsules is presented in Figure 1a, ranging from 81 ± 0.6% to 92 ± 1.3%. ANOVA analysis showed that microencapsulation method significantly influenced the yield ($P < 0.05$). A higher yield showed a more efficient and effective microencapsulation process. The highest yield (92 ± 1.3%) was obtained using microwave oven method, while the lowest (81 ± 0.6%) was observed in freeze-drying method.

Moreover, the higher yield in microwave oven method is attributed to short drying time (11 min), minimizing material loss. In comparison, the lower yield in freeze-drying method is due to prolonged drying process (48 hr), causing loss of volatile compounds. Freeze-drying process removes water through sublimation at low temperatures, leading to greater material loss (Liew et al., 2020). The yield of microcapsules above 80% shows that microencapsulation process has been running well (Hassana & Muhamad, 2017). In order, the yield from highest to lowest are microwave oven > convection oven > freeze-drying combined with microwave oven > freeze-drying. The yield obtained using freeze-drying method in this study was approximately twice higher as blueberry extract microcapsules coated with maltodextrin through freeze-drying, which was 43.7% (Wilkowska et al., 2016). The yield of microcapsules produced using the combined freeze-drying and microwave oven method was comparable to *Elateriospermum tapos* seed microcapsules. Moreover, these microcapsules were coated with a mixture of maltodextrin and sodium caseinate, achieving a yield of 80.4-84.7% when dried with the same combination method (Hassana & Muhamad, 2017). Moisture content of microcapsules obtained from different microencapsulation methods is presented in Figure 1b, with values ranging from 2.49 ± 0.1% to 5.19 ± 0.2%. ANOVA analysis showed that microencapsulation method significantly influenced moisture content of microcapsules ($P < 0.05$).

Low moisture content is desirable in microcapsules to prevent cracking and agglomeration (Padzil *et al.,* 2018). In this study, the highest moisture content was observed in convection oven drying (5.19 ± 0.2%), while the lowest was in freeze-drying (2.49 ± 0.1%). Moisture content of oven-dried microcapsules was higher than freeze-drying (Najjaa et al., 2022). Similarly, previous studies reported a higher value for *Clitoria ternatea* flower extract microcapsules when dried using an oven compared to freeze-drying and ultrasonic spray drying (Padzil *et al.*, 2018). Moisture content for all microcapsules is below 5%, suggesting that a higher value indicates susceptibility to damage (Sukri et al., 2023). Moisture content in oven-dried is two times higher than freeze-drying. The use of microwave oven produces moisture content that is not different from freeze-drying. However the time needed to dry by microwave oven is shorter, causing a reduction in energy consumption (Wang et al., 2009). The combination of freeze-drying and microwave drying produces moisture content that is no different from using only microwave or freeze-drying. Solubility is a crucial parameter for microcapsules intended for application in food products. In this study, solubility of microcapsules obtained from different microencapsulation methods is presented in Figure 1c, ranging from 86.10 ± 1.4% to 87.77 ± 1.1%. ANOVA analysis showed that microencapsulation method did not significantly affect the solubility of microcapsules ($P > 0.05$). This result was in line with the previous study (Fernandes et al., 2013), where drying conditions did not influence the solubility of microcapsules. Meanwhile, the solubility of microcapsules was primarily determined by the type of material and coating used in encapsulation process.

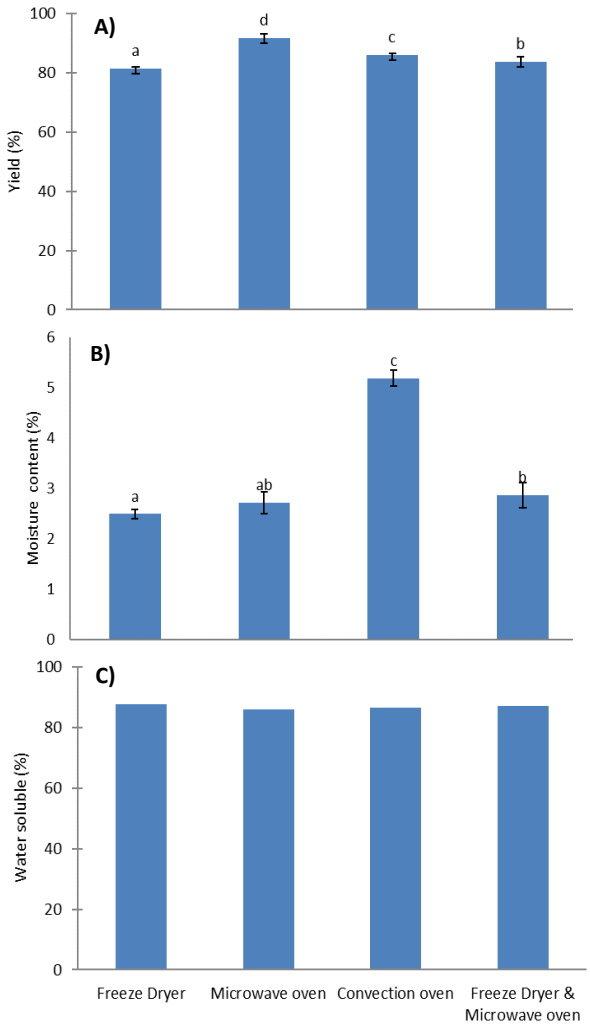

Figure 1. The yield (A), moisture content (B), and solubility (C) of *L. domesticum* leaves extract microcapsules obtained using various methods are presented. The values are expressed as mean ± standard deviation (SD) (n = 3). According to Duncan's test (p <

0.05), different letters indicate statistically significant differences among the groups.

Particle size and polydispersity index

Microcapsule and PDI particle sizes are presented in Table 1. Particle sizes ranged from 0.158 ± 0.00 to 0.354 ± 0.01 µm, and PDI varied from 0.379 ± 0.16 to 0.863 ± 0.04. ANOVA results showed that microencapsulation method affected particle size and PDI of microcapsules produced (P <0.05). The smallest size of microcapsules was produced by oven and freeze-drying method, while the largest was by the combination freeze-drying and microwave. DMRT test showed that particle size of microcapsules dried by freeze-drying, microwave, and convection oven did not differ. All microencapsulation methods produced microcapsules that were micro-sized. An object is considered to have a micro size when the size ranges from 0.1 to 1.0 µm (Kusmayadi et al., 2019). Microcapsule size is good because it produces a very small size, serving as a suitable option for application to various products. In this study, microcapsule size was smaller than phenolic component of polyherbal extract in the previous report, which had a size of 18.95 - 151.13 µm (Hussain et al., 2018). PDI describes the distribution of particles in an emulsion, with values ranging from 0 to 1. Based on categorization, PDI values close to 0 indicate good emulsion stability and a narrower particle size distribution. Meanwhile, a value below 0.3 generally signifies uniform particle distribution and high stability. In this study, all encapsulation methods produced PDI values greater than 0.3, indicating a wide particle size distribution and relatively low stability. PDI values of microcapsules, ranked from lowest to highest, were observed in the following order, convection oven < freeze-drying < microwave oven < combination of freeze-drying and microwave oven. Additionally, PDI values obtained in this study were higher than microcapsules derived from apple peels (Mujica-Alvares & Barra, 2020). PDI is a crucial parameter for evaluating emulsion stability in microcapsules. Particle size significantly influences biodistribution and pharmacokinetics, directly impacting the efficiency and effectiveness of microcapsules in target cells.

Zeta potential

Zeta potential is an indicator used to evaluate the stability of microparticles in a suspension, determined by calculating electrostatic interactions between particles. According to Kusmayadi et al. (2019), zeta potential load on microcapsules affects biodistribution and pharmacokinetics (Kusmayadi et al., 2019). Based on the results shown in Table 1, zeta potential ranges from -31.50 ± 1.3 to -29.93 ± 1.0 mV. ANOVA showed that encapsulation method affected values produced (P <0.05) (Han et al., 2025; Kusmayadi et al., 2019). The lowest value was generated by the convection oven method. Zeta potential value between freeze-drying, microwave oven, and the combination freeze-drying and microwave oven are not different. Generally, higher zeta potential correlates with more stable suspension, preventing agglomeration. Based on categorization, values above ±60 mV, ±30 mV, ±20 mV, and ±5 mV represent very good stability, good stability, short-term stability, and rapid aggregation, respectively (Honary & Zahir, 2013). Microcapsules dried in a convection oven were stable for a short time (zeta potential -23.17 ± 0.3 mV), while freeze-drying, microwave oven, and freeze-drying combined with microwave oven had good stability (zeta potential -29.93 ± 1.0 to -31.50 ± 1.3 mV). The value produced in this study was almost the same as the phenolic component microcapsules from frozen apple peels (El-Messery et al., 2019).

Total phenol and total flavonoid

The bioactive compounds mostly found in ethyl acetate extract of *L. domesticum* leaves are phenol and flavonoid, which function as an antioxidant. Phenol and flavonoid content in microcapsules in various encapsulation methods is presented in Figure 2. Phenol content ranges from 6.46 ± 0.6 to 9.04 ± 0.3 mg AGE / g. Flavonoid content ranged from 18.31 ± 0.8 to 33.36 ± 1.8 mg QE/g. ANOVA showed that encapsulation method affected phenol and flavonoid content of microcapsules (P <0.05).

Table 1. Particle size, polydispersity index, and zeta potential of *L.domesticum* leaves extract microcapsules by various methods.

Microencapsulation Methods	Particle Size ± SD (µm)	PDI ± SD	Zeta Potential ± SD (mV)
Freeze-drying	0.158 ± 0.00^{a}	0.514 ± 0.03^{a}	-29.93 ± 1.0^{a}
Microwave oven	0.177 ± 0.05^{a}	0.652 ± 0.02^{b}	-31.50 ± 1.3^{a}
Convection oven	0.158 ± 0.07^{a}	0.379 ± 0.16^{a}	-23.17 ± 0.3^{b}
Freeze-drying and microwave oven	0.354 ± 0.01^{b}	0.863 ± 0.04^{c}	-31.13 ± 3.7^{a}

Values are presented as mean ± SD (n = 3). Different superscript letters within a column indicate significant differences based on Duncan's test ($p < 0.05$).

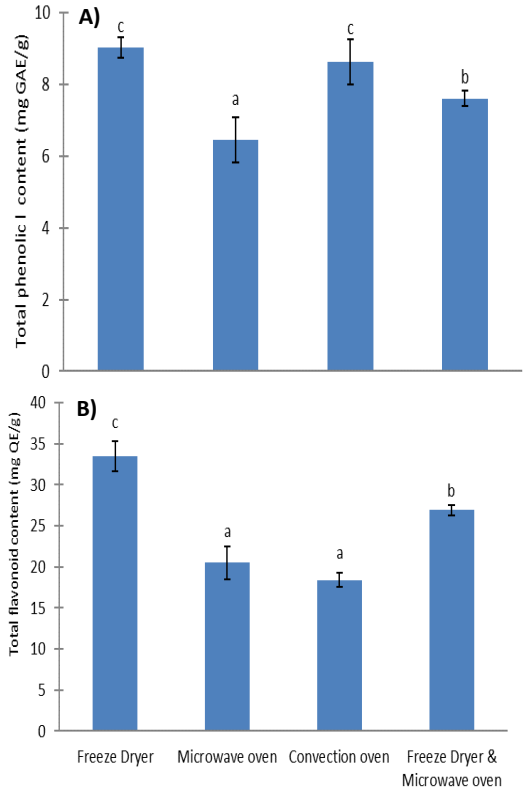

Figure 2. The total phenol (A) and flavonoid (B) content of *L. domesticum* leaves extract was microencapsulated using various methods. The values are presented as the mean ± standard deviation (n = 3). Based on Duncan's test ($p < 0.05$), different letters indicate significant differences.

The highest phenol content was produced by freeze-drying method, while the lowest was by microwave oven. Since freeze-drying was carried out at low temperatures, several phenol contents were damaged. In comparison, microwave drying causes friction between molecules, particularly water, thereby increasing temperature (Feng et al., 2012). Phenol is a secondary metabolite compound that breaks down easily at high temperatures, functioning as antioxidant (Tanase et al., 2019). In this study, phenol content in microcapsules was lower than the value obtained from the spent coffee ground microcapsules (Ballesteros et al., 2017). Differences in encapsulated material are expected to alter the extraction of bioactive compounds. Freeze-drying microcapsules showed the highest flavonoid content (33.36 ± 1.8 mg QE/g), while microwave-dried samples had the lowest. Similarly, a previous study showed that *Clitoria ternatea* flower microcapsules produced through freeze-drying retained higher flavonoid content than a convection oven. The superior retention in freeze-drying samples is likely due to the low-temperature process, which minimizes the thermal degradation of flavonoid (Liew et al., 2020). This is because the freeze-drying process is carried out below freezing to avoid damaging microcapsule flavonoid that breaks down easily at high temperatures. DMRT analysis showed that the flavonoid content of microcapsules dried by microwave and convection oven was not different.

Antioxidant activity

Antioxidant activity of microcapsules in various encapsulation methods is presented in Figure 3. Antioxidant activity is expressed by its ability to inhibit DPPH free radicals, with values ranging from 34.52 ± 1.2 to 46.86 ± 2.6%. ANOVA results showed that microencapsulation method affected antioxidant activity ($P < 0.05$). Similarly, Liew et al., (2020) showed that antioxidant activity of *C. ternatea* flower microcapsules dried by freeze-drying was higher than convection oven. This is because phenol and flavonoid compounds function as antioxidants in *L. domesticum* leaves extract. The results showed that phenol and flavonoid components were higher in microcapsules dried by freeze-drying.

Morphology structure

Microcapsule structure morphology produced with a magnification of 250 x is shown in Figure 4. Based on the results, the shape was irregular, and the size for each method was different. This is in line with the previous study that drying method affects the morphology of microcapsules produced (Liew et al., 2020). SEM images show that encapsulates have irregular (a) plate-like structures with varying degrees of roughness (b), cracks (c), and aggregation (d), suggesting differences in encapsulation efficiency and

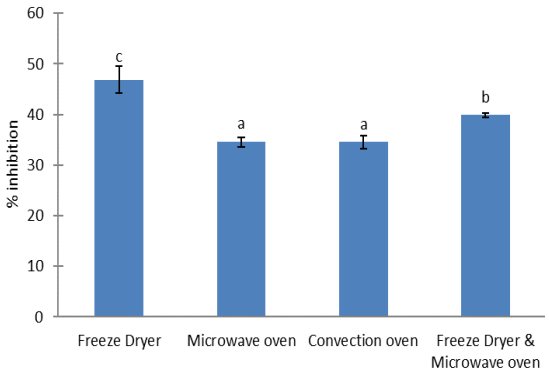

Figure 3. Antioxidant activity of *L. domesticum* leaves extract microcapsules prepared using various methods. Values are

presented as the mean ± SD (n = 3). Different superscript letters within a column indicate significant differences based on Duncan's test ($p < 0.05$)

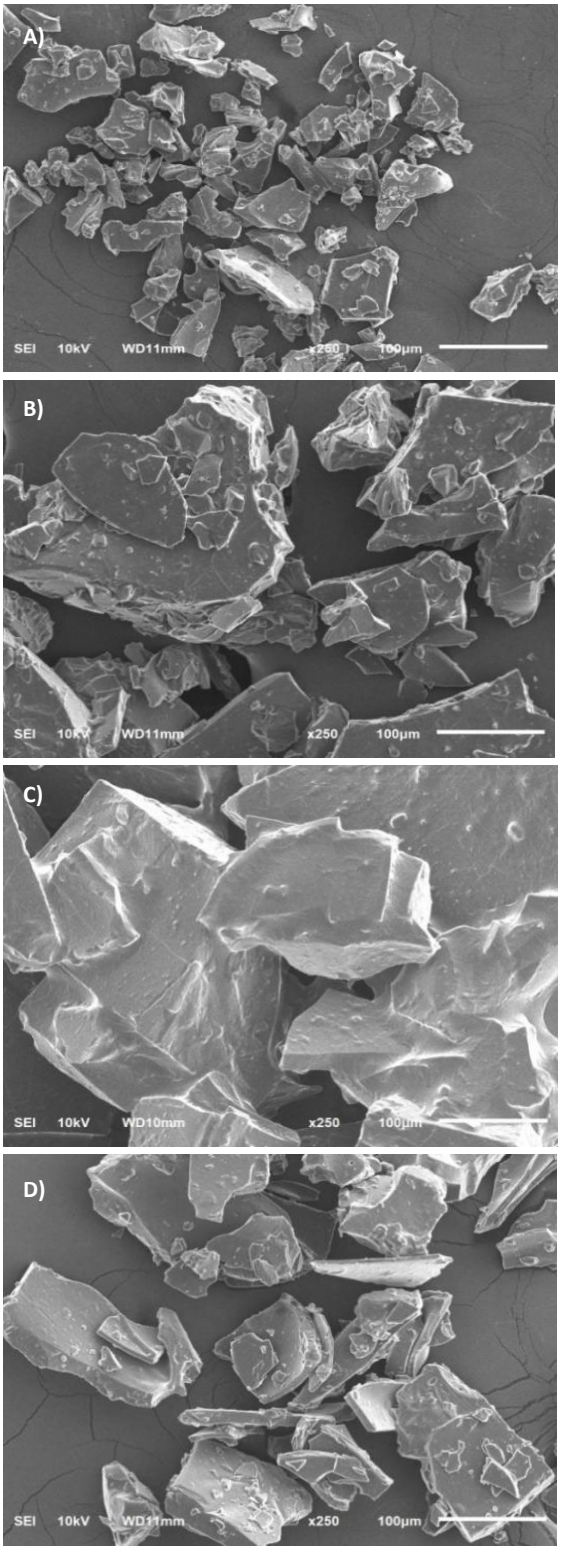

Figure 4. Scanning electron microscope (SEM) image of microcapsule *L. domesticum* leaves extract with 250 x magnification. (A) freeze dryer, (B) microwave oven, (C) convection oven, and (D) freeze dryer and microwave oven.

drying methods. Compared to previous studies, the morphology closely resembles freeze-dried encapsulates, which tend to form brittle, fragmented structures, unlike the smoother, spherical particles typically observed in spray-dried encapsulates (Munin & Edwards-Lévy, 2011; Santana et al., 2018). The presence of cracks and rough surfaces can indicate incomplete encapsulation or exposure of core material, potentially affecting stability and bioactive retention. Additionally, particle aggregation suggests strong intermolecular interactions in encapsulant matrix, which has been previously reported in high-polymer-concentration formulations. Optimizing encapsulation conditions, such as drying parameters and encapsulant composition, may enhance particle integrity and improve protection of encapsulated material (Lee et al., 2021; Stabrauskiene et al., 2024).

CONCLUSION

In conclusion, the encapsulation method significantly influenced the physicochemical characteristics of microcapsules. Among the tested methods, freeze-drying produced microcapsules with the highest quality, as shown by total phenol content of 9.04 ± 0.3 mg AGE/g, total flavonoid content of 33.36 ± 1.8 mg QE/g, and DPPH radical scavenging activity of 48.86 ± 2.6%. These results showed that freeze-drying microcapsules retained higher levels of bioactive compounds and had superior antioxidant activity compared to microwave and convection oven. Furthermore, a combination of freeze-drying followed by microwave oven served as an efficient alternative to enhance encapsulation process while maintaining bioactive compound stability.

This study was in line with the United Nations SDGs, particularly SDG 3 (Good Health and Well-being) and SDG 12 (Responsible Consumption and Production). By improving the stability and bioavailability of natural antioxidants, encapsulation technology contributed to the development of sustainable functional food, nutraceuticals, and pharmaceuticals, reducing reliance on synthetic additives. The use of *L. domesticum* leaves also supported sustainable agriculture and waste minimization, further promoting environmentally responsible production practices.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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