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Microencapsulation of Safflower Oil Using Complex Coacervates Between Hydrolyzed Karaya Gum and Protein Isolate from *Phaseolus Lunatus*

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ABSTRACT

This research focused on optimizing microencapsulation techniques for safflower oil using the complex coacervate between hydrolyzed karaya gum and Lima bean protein isolate and analyzing the influence of various drying methods on encapsulation efficiency and stability. Optimal complex formation for microencapsulation was achieved using a 1:3 ratio of karaya gum to protein isolate, with a recovery efficiency of 86.4% at pH 3.6. High-speed homogenization (9000 rpm) and an increased emulsifier concentration (2% Tween 80) significantly improved microcapsule droplet size distribution, with a marked reduction in microcapsule droplet size and increase in uniformity. By comparing freeze-drying, vacuum drying, and convective drying, freeze-drying emerged as the superior method, enhancing color, solubility and oxidative stability. Overall, our findings highlight the critical role of drying techniques in the microencapsulation process, presenting freeze-drying as an effective approach to improve the stability and functional properties of encapsulated ingredients in food products.

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1. Introduction

The demand for high-quality and safe food products among consumers is higher than ever before. However, some bioactive compounds in foods are unstable during processing, including unsaturated fatty acids in vegetable oils. For example, safflower oil is a vegetable oil rich in linoleic acid, but it is susceptible to oxidation, especially when exposed to oxygen, light, moisture, and heat, leading to a reduced shelf life and deterioration of sensory properties [1]. The oxidative degradation, formation of off-flavors, and generation of free radicals in oils can diminish food quality when incorporated, so microencapsulation technology offers a viable solution to maintain the biological and functional characteristics of vegetable oils [2]. The flexibility of this technology depends on the techniques and materials used in the encapsulation process. Microencapsulation using complex coacervates is a sophisticated technique in food science that encapsulates sensitive bioactive compounds to improve their stability and control their release. This method involves the interaction between oppositely charged polymers, forming a coacervate phase that encapsulates the active ingredient.

For encapsulating nutrients, a wide range of wall materials can be employed, including carbohydrates, proteins, hydrocolloids, cellulose, and lipids [3]. The combination of proteins and gums as wall materials can provide an effective barrier against oxygen and unwanted odors. In this study, we used karaya gum as the anionic polysaccharide and Lima bean proteins isolate as cationic protein wall materials.

Karaya gum, also known as Indian tragacanth, is a natural polysaccharide extracted from the *Sterculia urens* tree. It is a complex heteropolysaccharide composed of galactose, arabinose, rhamnose, and glucuronic acid residues [4]. Karaya gum possesses several functional properties, including thickening, emulsifying, and stabilizing, making it a valuable ingredient in various food and pharmaceutical applications [5]. Hydrolysis of karaya gum with alkali can improve its solubility and reduce its viscosity, making it more suitable for microencapsulation applications [6]. This modification

enhances the gum's ability to interact with proteins and form stable complexes, which are essential for effective encapsulation.

Lima beans, or *Phaseolus lunatus*, are a nutritious legume known for their creamy texture and mild flavor, making them a staple in various cuisines. Lima bean proteins are extracted from the legume, offering a high-quality plant-based protein alternative. These proteins are distinguished by their excellent emulsification properties, enhancing the texture and stability of food products. Their functional characteristics, including gel formation and water-binding capacity, make them suitable for a wide range of applications in the food industry. Research into lima bean proteins focuses on their potential health benefits, including hypoallergenic properties and contributions to a balanced diet. The exploration of these proteins continues to expand, driven by the growing demand for sustainable and nutritious food ingredients [7].

This research aims to explore the optimal conditions for forming a stable and effective encapsulating matrix, assessing factors such as the charge interactions between the *Phaseolus lunatus* proteins and hydrolyzed karaya gum at different pH levels and the encapsulation efficiency at varying core-to-coating ratios. The significance of this research lies in its potential application in the food industry, where extending the stability of bioactive compounds can significantly impact food quality and safety. By understanding the interactions between different encapsulating materials and optimizing the microencapsulation process, this study contributes to the broader field of food science research, providing a foundation for future studies and technological advancements in food preservation.

2. Materials and Methods

2.1. Hydrolysis of Karaya Gum

Initially, 2g of gum was hydrated in 100 mL distilled water for 24 h and then underwent alkaline hydrolysis with 33.3 mL of 1M NaOH for 30 min to remove acetyl groups and precipitate divalent cations [6]. After hydrolysis, excess NaOH was neutralized with 1N HCl to a pH of 4. The hydrolyzed karaya gum (HKG) was precipitated using a 3:1 volume ratio of 99.5% ethanol, stirred thoroughly for recovery, and washed twice with 75% ethanol. Finally, the gum was dried at 50 °C for 6 h, milled, and sieved to uniform particle size for storage and further use.

2.2. Production of Phaseolus lunatus protein isolate (PPI)

Lima beans were soaked in water at a ratio of 1:2 w/v for 3 h and then washed to remove the hulls and impurities. After that, the beans were convectively dried at 50 °C until reaching a moisture content of less than 10% over approximately 12 h. The dried beans were then ground into a fine, uniform powder using a Seka Z10 grinding mill, with the process divided into small batches to prevent excessive heat that could denature the proteins. The powder was sifted through a 100-mesh sieve to increase the surface area for protein extraction.

For protein extraction, the bean powder was mixed with water at a 1:6 w/v ratio, stirred and pH adjusted to 11 using 1N NaOH solution. The mixture was stirred for 2 h and centrifuged at 3000 rpm for 20 min to collect the protein extract. The proteins were then precipitated by adjusting the pH to the isoelectric point of the globulins (pH 4.5), allowing it to settle for 5 h at 4°C, followed by centrifugation at 3000 rpm for 20 min to collect the protein precipitate. The protein precipitate was washed by adding 0.1N acetic acid to adjust the pH to 4.5, followed by centrifugation at 3000 rpm for 20 min to further remove salt content. The protein suspension was then spread into thin layers and convectively dried at 45 °C for 1 h, ground, and sieved to produce a uniform powder of PPI.

2.3. Zeta potential measurements

HKG and PPI dispersions were prepared at a 0.05% w/v concentration. pH of the dispersions were adjusted using 1N HCl and 1N NaOH. Zeta potentials of the dispersions were measured at 25 °C using a Zetasizer Pro.

2.4. Determination of optimal conditions for HKG-PPI complex formation

PPI dispersion was prepared at 0.05% w/v and pH of 10 for complete dissolution of the proteins. The PPI dispersion was mixed with the 0.05% w/v HKG dispersion to various ratios (1:1, 2:1, 1:2, 1:3, 1:4)

and then stirred for 3 h. The pH was adjusted from 7 to 2 using 1N and 0.1N HCl solutions. After pH equilibration, the absorption of the mixture was measured at 600 nm [8]. The pH yielding the highest absorbance for each PPI:HKG ratio was considered the optimal pH for HKG-PPI complex formation.

2.5. Recovery efficiency of the HKG-PPI complex

Mixtures with different HKG-PPI ratios were adjusted to their optimal pH, allowed to settle at 4 °C for 3 h, and centrifuged at 6000 rpm for 10 min to recover the solid phase, which was then dried at 105 °C until a constant weight was achieved. The coacervate yield (CY%) was calculated using the formula [9]:

$$\text{CY (\%)} = \frac{m_C}{m_{HKG}+m_{PPI}} \times 100 \quad (1)$$

Where m_C is the dried mass of the HKG-PPI complex (g), m_{HKG} is the initial mass of HKG (g), and m_{PPI} is the initial mass of PPI used to produce the complex (g).

2.6. Microencapsulation of safflower oil using HKG-PPI complex

Firstly, 1% PPI dispersion was prepared in water, adjusted to pH 10 for optimal solubility, followed by homogenization with the safflower oil and Tween 80 for emulsification. Additional homogenization was performed after adding a HKG solution to complete the microencapsulation. The mixture was then stirred for 30 min and cooled overnight in a refrigerator to promote phase separation. The microcapsules were recovered by centrifugation, drying and milling to achieve the desired moisture content and particle size [10]. In this study, we compared the physico-chemical properties of the microcapsules obtained by 3 drying techniques: oven drying, vacuum drying and freeze drying.

2.7. Microcapsule droplet Size Distribution

The microstructure of the newly formed microcapsules was analyzed using an Amscope M158C-E optical microscope. The effects of homogenization speed (5000 and 9000 rpm) and emulsifier (Tween 80) concentration (0%, 1%, and 2%) on microcapsule droplet size distribution were observed. Measurements were recorded using Image J software and analyzed with Origin 2021 software.

2.8. Microencapsulation Efficiency

The method of determining the surface oil and the total oil content in the microcapsules was adapted from a previously published study [11].

One gram of the microcapsules powder was dispersed in 10 mL of hexane and shaken for 5 min. The suspension was then filtered through a 3 µm filter paper. The solid residue retained on the filter paper was washed three times with 10 mL of hexane per wash. Both the filtrate and the wash solutions were collected, allowed to air dry predominantly at room temperature, and then completely dried at 70 °C for 1 h. Finally, the dried material was weighed to determine the amount of surface oil present per gram of powder (m_{SO}).

One gram of microencapsulated powder was dispersed into 10 mL of 4N hydrochloric acid and continuously stirred for 2 h at 50 °C to dissolve the outer coating. Subsequently, 20 mL of hexane was added, and the mixture was stirred for an additional 10 min to dissolve the oil. The mixture was then centrifuged at 3000 rpm for 15 min to separate the supernatant. The hexane extraction process was repeated to ensure complete recovery of the oil. The oil-containing phases were collected and dried to constant weight to obtain the total oil content per gram of microcapsule powder (m_{TO}).

Microencapsulation efficiency (ME%) was calculated based on the total and surface oil contents, using the formula:

$$\text{ME(\%)} = \frac{m_{TO}-m_{SO}}{m_{TO}} \times 100. \quad (2)$$

2.9. Physical Properties of Microencapsulated Powders

The external morphology of the microencapsulated powders was examined using scanning electron microscopy (SEM) on a TM4000 (Hitachi, Japan).

Color parameters were assessed using a Linshang LS171 colorimeter, calibrated with a white standard plate before each measurement. A uniform layer of powder, approximately 5 mm thick, was spread on white paper, and measurements were taken at three different locations per sample.

Solubility was evaluated with minor modifications to the method described by Yang et al. (2022). A 0.5 g sample was dissolved in 20 mL of distilled water and incubated at 37 °C for 1 h before centrifugation at 6000 rpm for 10 min. The solubility percentage was calculated from the dried supernatant weight after evaporation at 105°C. Effects of temperature (37°C, 50°C, and 70°C) and pH (2, 4, 6) on solubility were also investigated [12].

2.10. Oxidative Stability of Safflower Oil

The oxidative stability of safflower oil was assessed based on peroxide content using the Ferric thiocyanate method [13]. Microencapsulated powder samples and the control safflower oil samples were separately placed in glass beakers and maintained in an oven at 105°C. After 3 h, 0.1 mL of oil was mixed thoroughly with 0.1 mL of Tween 20 and 9.7 mL of distilled water. Subsequently, 20 µL of 30% potassium thiocyanate (KSCN) solution and 20 µL of 20 mM ammonium iron(II) sulfate hexahydrate ($(NH_4)_2Fe(SO_4)_2.6H_2O$) in 3.5% HCl were added. The mixture was shaken for 5 min. The peroxide content of the samples was determined by measuring absorbance at 500 nm wavelength. Before assessing the oxidative level of the encapsulated oil, the microencapsulated powder was stirred with 5 mL of 4N HCl for 2 h to break down the outer shell and release the oil. The oil was then extracted using hexane and evaporated. The measurement of the oil's oxidation level in both the powder and the control oil sample continued until maximum absorbance was reached.

3. Results and Discussion

3.1. Optimal Conditions for HKG-PPI Complex Formation

3.1.1. Zeta Potential of HKG and PPI

The zeta potential measurement, a significant indicator of surface electrical potential in liquids, reflects the magnitude of electrostatic repulsion or attraction between particles in a colloidal system. This potential is notably influenced by the pH level, reaching a null point at the isoelectric point, indicating the system's least stability. In this study, the zeta potentials HKG and PPI were measured across a pH range from 2 to 7 at a concentration of 0.05% w/v.

The results (Fig. 1) revealed a decreasing zeta potential for both HKG and PPI with increasing pH. HKG, being an anionic polysaccharide containing 37-40% galacturonic and glucuronic acids, demonstrates a negative charge across most pH levels due to the partial dissociation of its carboxyl groups into carboxylate ions (-COOH ⟶ -COO- + H+) in acidic environments. As pH increases, a greater degree of deprotonation occurs, shifting the zeta potential more negative [14].

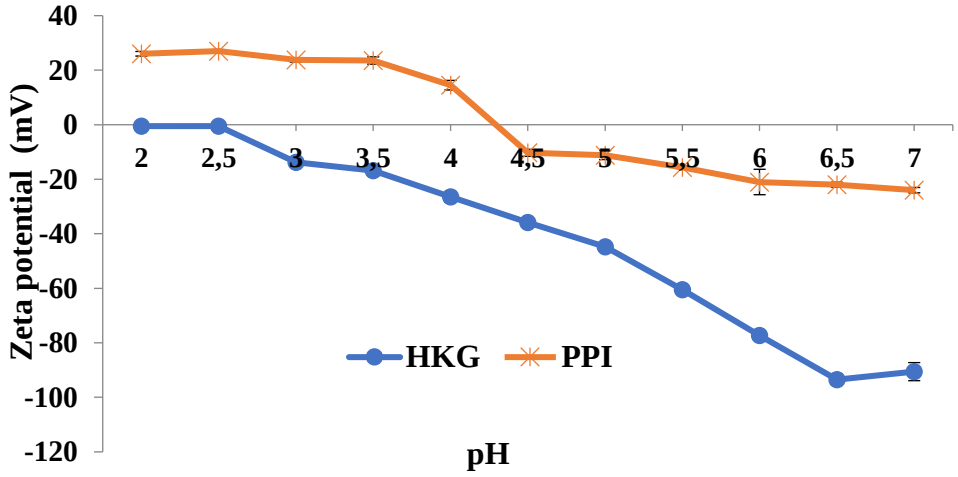

Figure 1. *Zeta potential of HKG and PPI dispersion as affected by pH.*

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Conversely, PPI exhibited a shift from a positive zeta potential of 26.03 mV at pH 2 to a negative potential of -24 mV at pH 7. Its isoelectric point (pI) around pH 4.3 indicates that the protein carries a positive charge at pH < pI and a negative charge at pH > pI due to the protonation and deprotonation of amine and carboxyl groups, respectively [15]. Electrostatic interactions between HKG and PPI are inferred to be significant, as indicated by the near-neutral charge at respective pH values of 2 and 4.3, suggesting potential for complex formation between the two macromolecules within the pH range of 4.3 to 2, aligning with findings by Kaushik et al. (2015) on the effective polyelectrolyte complex formation between gum and protein extracted from flaxseed within a similar pH range [16].

3.1.2. Evaluating Optimal pH and HKG-PPI mass ratio by turbidimetry

The influence of pH on the turbidity (absorbance) associated with HKG-PPI complex formation was investigated to determine the optimal pH value for maximum interaction between these polymers. This assessment aimed at identifying the pHmax, where the highest turbidity indicates maximal polymer interaction [8]. Complex formation was explored within the pH range of 4.3 to 2, based on preceding zeta potential findings.

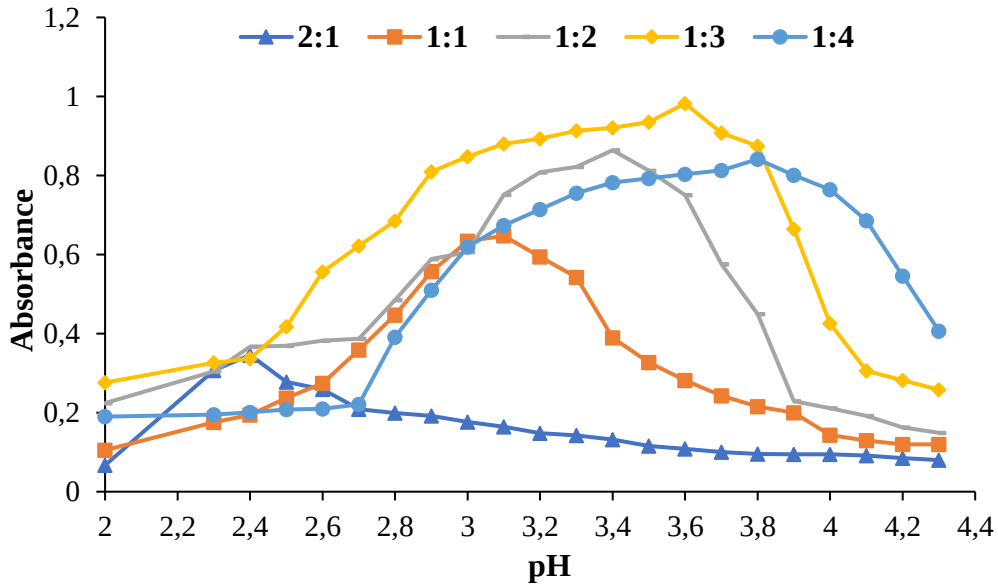

Figure 2. *Influence of HKG:PPI mass ratio and pH on absorbance of the HKG-PPI complex dispersion.*

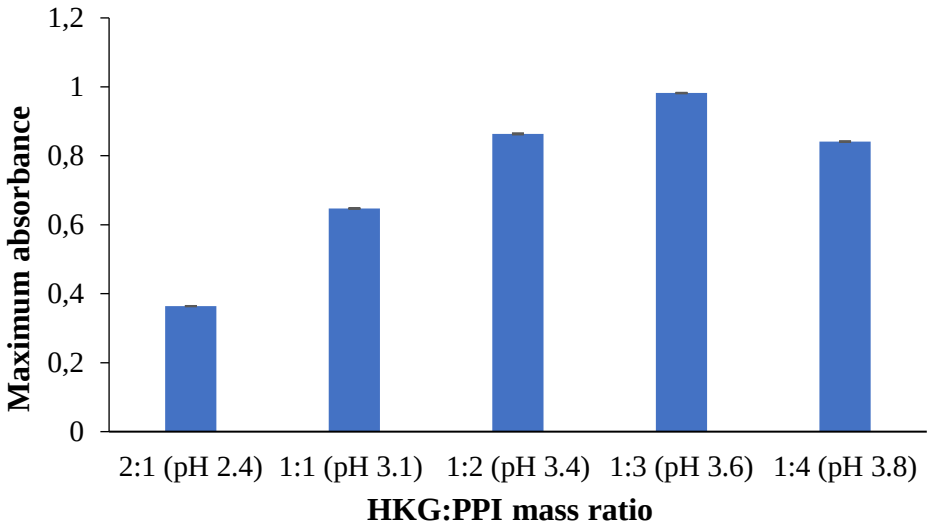

Figure 3. *Maximum absorbance of HKG-PPI dispersion of each HKG:PPI mass ratio at their optimal pH.*

Fig. 2 shows that the turbidity increased with decreasing pH, reaching a peak, then subsequently decreased, indicating a balance between the surface charges of PPI and HKG. The optimal pH (pHopt) for polyelectrolyte complex formation varied across the studied ratios, increasing with the protein concentration. Specifically, the optimal pH values corresponding to ratios of 2:1, 1:1, 1:2, 1:3, and 1:4 HKG: PPI were found to be 2.4, 3.1, 3.4, 3.6, and 3.8, respectively (Fig. 3), suggesting that increased PPI concentration leads to a higher optimal pH value for complex formation [17]. A notable decrease in maximum turbidity at higher polysaccharide concentrations was observed, attributed to reduced intra- and inter-polymer interactions and less effective light scattering by polysaccharide molecules compared to protein molecules, particularly at a ratio of 2HKG:1PPI. The maximum interaction between HKG and PPI, indicated by peak turbidity, was observed at a ratio of 1:3, beyond which protein excess likely leads to increased turbidity due to protein-protein interactions, shifting the optimal pH value higher [18], [19].

3.1.3. Determining optimal HKG-PPI mass ratio by recovery efficiency of the complex

The recovery efficiency is the mass of HKG-PPI complex obtained compared to the total mass of HKG and PPI used. Measurements of the recovery efficiency were conducted at pH values corresponding to maximum absorbance for various HKG:PPI ratios as identified in the previous section.

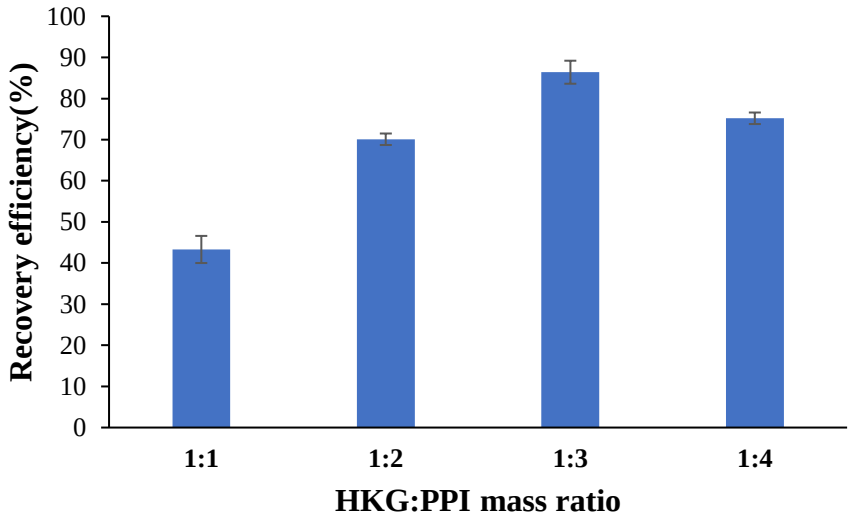

Figure 4. *Recovery efficiency of HKG-PPI complex as affected by the HKG:PPI mass ratio.*

As depicted in Fig.4, the 1:3 ratio exhibited the highest recovery efficiency, while the 1:1 ratio demonstrated the lowest. A recovery was not achievable for the 2:1 ratio. These findings correlate with the absorbance results from Figure 3, where the 1:3 ratio also showed the highest absorbance value, indicating optimal complex formation. The decreased recovery efficiency at higher HKG concentrations can be attributed to increased solution viscosity, which hinders complex formation, resulting in lower recovery efficiency [20]. This inefficiency arises due to imbalanced electrical charges leading to weaker electrostatic interactions when one of the biopolymers is in excess [11]. Consequently, the 1:3 HKG:PPI ratio was identified as optimal for complex formation.

In summary, pH and HKG:PPI ratios significantly influence the complexation between these two polymers. Following extensive evaluation, the 1:3 HKG:PPI ratio at pH 3.6 was determined to be most suitable for forming microencapsulation shells.

3.2. Microcapsule sizes in water

3.2.1. Effect of Homogenization Speed

Homogenization is a critical technique for creating emulsions in the food industry, notable for its cost-effectiveness and capability to generate ultrafine microcapsule droplets. Increasing homogenization speeds from 5000 to 9000 rpm significantly reduces microcapsule droplet size (Fig. 5) due to greater energy input, enhancing microcapsule droplet disruption [21]. At 5000 rpm, the mean microcapsule droplet size is approximately 20.81µm, contrasting sharply with the 15.05µm observed at 9000 rpm,

which also displays a more uniform size distribution, suitable for materials like vegetable oils. However, very high speeds can cause microcapsule droplet coalescence, forming large, multi-nucleated microcapsules, potentially compromising encapsulation effectiveness [22], [23].

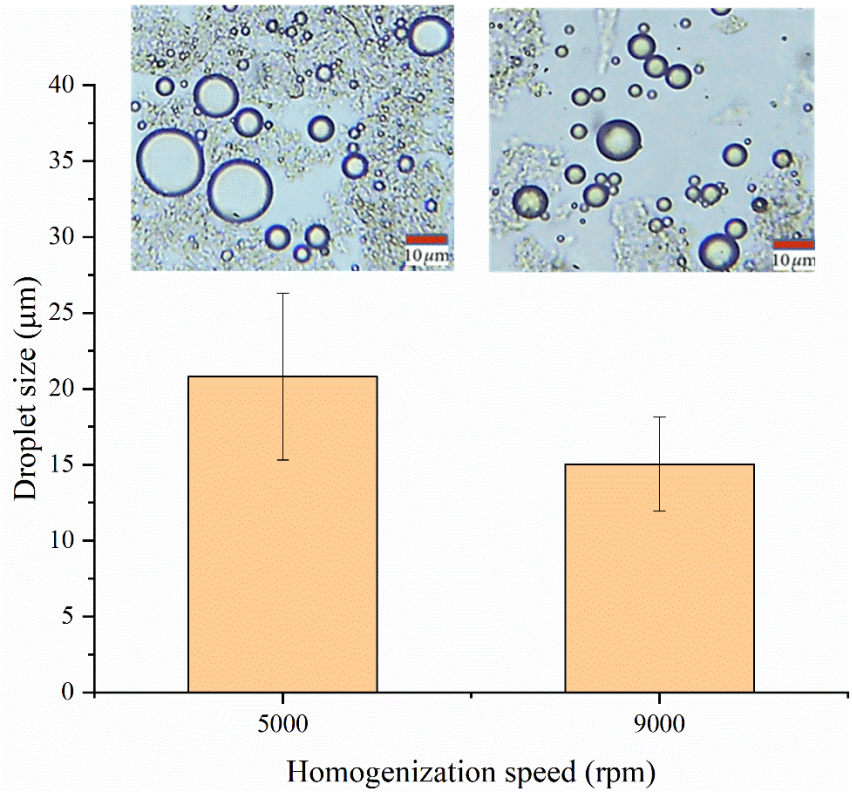

Figure 5. *Effect of homogenization speed on the microcapsule droplet sizes.*

3.2.2. Effect of emulsifier concentration

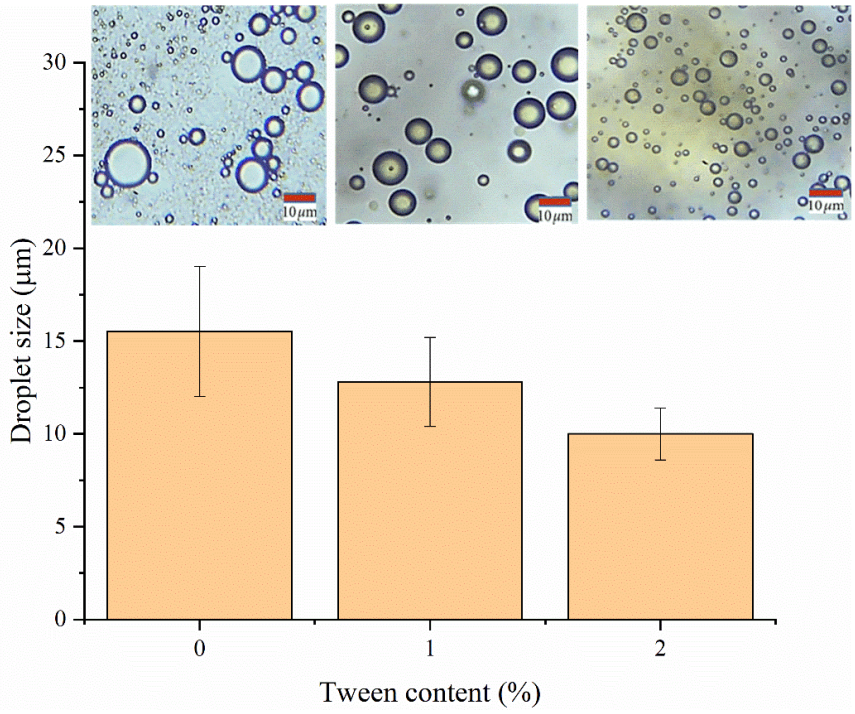

Figure 6. *Effect of Tween 80 content on the oil microcapsule droplet sizes after homogenization at 9000 rpm.*

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The study also investigates the effects of the emulsifier Tween-80 on microcapsule droplet size distribution. Increasing the emulsifier concentrations from 0% to 2% results in a decrease in mean microcapsule droplet size from 15.53 µm to 10 µm (Fig. 6), indicating that higher surfactant levels enhance stability and reduce surface tension during homogenization [24]. This effect is further exemplified by a reduced standard deviation in microcapsule droplet size, demonstrating a more consistent microcapsule droplet distribution.

Lastly, the interaction between HKG, PPI, and Tween-80 in safflower oil emulsions reveals the critical role of surfactants. Surfactants not only stabilize emulsions by adsorbing at the oil-water interface but also prevent coalescence, ensuring the formation of stable emulsions. This finding underscores the necessity of surfactants in maintaining emulsion stability and optimizing microcapsule droplet size, albeit acknowledging that excessive surfactant use can increase costs and alter physical properties.

3.3. Encapsulation efficiency of safflower oil

The encapsulation efficiency of safflower oil was investigated across various shell-to-core ratios (1:1, 2:1, 4:1, 6:1, 8:1) with a homogenization speed of 9000 rpm and 2% Tween addition (Fig. 7).

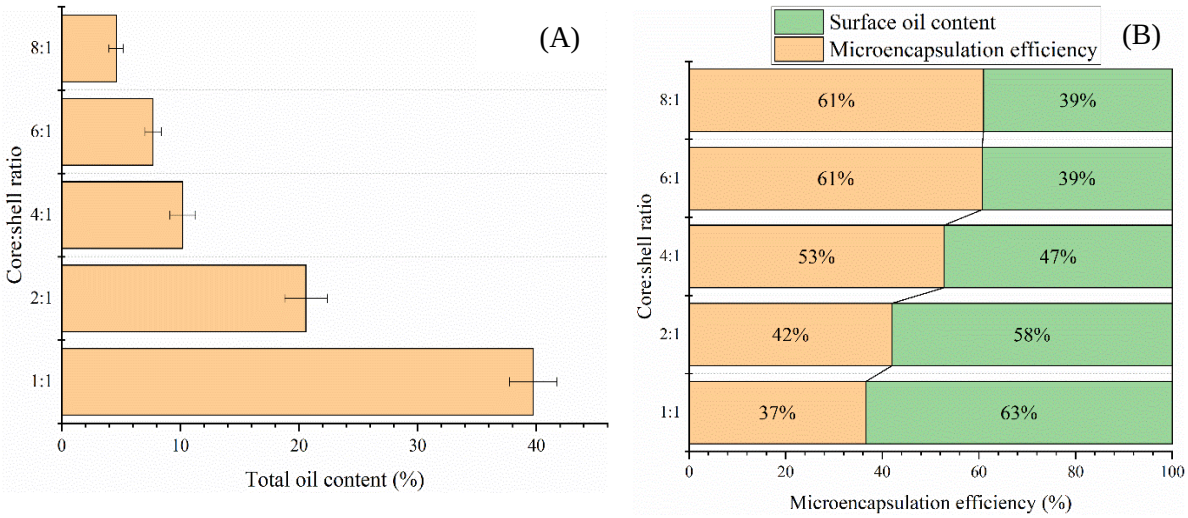

Figure 7. *Effects of core:shell mass ratio on the oil content in microcapsules (A) and the microencapsulation efficiency of the oil (B).*

Increasing the shell-to-core ratio from 1:1 to 1:8 resulted in a 1.6-fold increase in efficiency (Fig. 7B), indicating that a larger shell formation effectively encapsulates the core. This finding aligns with Nori et al. (2011), who noted a 1.1-fold increase in encapsulation efficiency of propolis with a doubled shell amount [10]. The efficiency at 6:1 and 8:1 ratios showed no significant difference, suggesting a 6:1 ratio as more suitable for safflower oil encapsulation to avoid overly thick shells and diminished oil content (Fig 7A), which could adversely affect the microcapsule's properties, including oil release capabilities. Therefore, we chose the 6:1 shell-to-core ratio for further experiments in comparing the characteristics of microcapsule powders obtained by different drying techniques.

3.4. Properties of microcapsule powders as affected by drying techniques

3.4.1. Morphology

Scanning Electron Microscopy (SEM) images (Fig. 8) reveal distinct morphological differences among samples dried by different methods.

Convective drying resulted in a denser structure, while both vacuum and freeze-dried samples exhibited a porous nature with the presence of tiny holes, particularly pronounced in the FD samples, which showed a more expanded and porous structure compared to the more angular morphology of the OD and VD samples. Convective drying tends to produce a tightly packed structure with significant shrinkage, whereas vacuum drying mitigates some of the disadvantages associated with hot air drying,

such as uncontrolled moisture removal and potential structural damage at high temperatures (40-60°C) deemed appropriate to limit these effects [25]. Freeze-drying, involving initial freezing followed by sublimation under reduced pressure, reduces surface tension forces, leading to a porous and fragile structure [26].

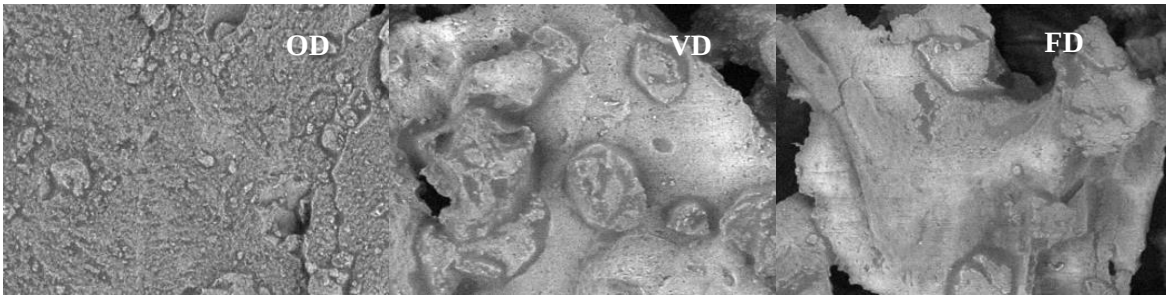

Figure 8. *SEM micrographs of oven-dried (OD), vacuum-dried (VD), and freeze-dried (FD) microcapsules.*

3.4.2. Color

Color measurements (Table 1) indicated variations across drying methods, with freeze-dried samples (FD) exhibiting the highest lightness (L*) values, suggesting minimal color degradation due to low-temperature processing that inhibits oxidation and chemical reactions. The redness (a*) and yellowness (b*) values also varied, with convective drying resulting in darker tones due to prolonged exposure to oxygen and heat, facilitating non-enzymatic browning reactions [27].

Table 1. *Color characteristics and appearance of microcapsule powders.*

	OD	**VD**	**FD**
L*	70.53±0.61^{a}	80.99±0.56^{b}	82.19±0.51^{c}
a*	6.76±0.82^{b}	4.71±0.11^{a}	4.11±0.6^{a}
b*	16.89±0.61^{b}	13.11±0.19^{a}	12.5±0.48^{a}
Appearance			

3.4.3. Solubility

The solubility of microencapsulated powders varies with temperature and pH, with significant differences observed across drying methods (Table 2). Solubility increased with temperature but decreased as pH increased, indicating a complex interplay between these factors and the microencapsulation process. Freeze-dried samples (FD) exhibited the highest solubility across all temperatures, attributed to the preservation of porous structures and hydrophilic proteins during the drying process, which facilitates water penetration and solubility. In contrast, convective and vacuum-dried samples showed lower solubility, possibly due to damage to these porous structures and partial denaturation of proteins at higher drying temperatures.

The solubility was highest in acidic conditions (pH 2) and lowest at pH 6, suggesting that the presence of hydrogen ions disrupts the complex's structure, facilitating increased solubility through the breakdown of polymer chains and preventing their interaction [28].

3.4.4. Oxidative stability of encapsulated safflower oil

The oxidative stability of encapsulated safflower oil was assessed through accelerated oxidation at 105 °C, using the ferric thiocyanate method to measure peroxide formation during the initial stages of

oxidation. Results in Fig. 9 indicated that non-encapsulated safflower oil (control) exhibited a steeper increase and highest absorbance values, signifying rapid oxidation and increased peroxide formation compared to encapsulated samples. Encapsulated oils reached maximum absorption at significantly delayed times (21 h for OD, 24 h for VD, and 30 h for FD compared with 15 h for control), demonstrating the protective effect of microencapsulation against oxidation, with freeze-drying showing the greatest efficacy.

Table 2. *Solubility of microcapsule powders as affected by drying techniques, temperatures, and pH.*

Factor	Solubility (%)		
	OD	VD	FD
Temperature (°C)			
37	2.36±0.2[a]	2.89±0.2[b]	4.86±0.27[c]
50	4.33±0.26[a]	5.09±0.23[b]	6.25±0.26[c]
70	5.77±0.35[a]	6.52±0.4[b]	7.76±0.25[c]
pH			
2	19.9±0.26[a]	21.24±0.56[b]	23.22±0.58[c]
4	10.11±0.32[a]	11.68±0.72[b]	14.42±0.54[c]
6	7.8±0.27[a]	8.85±0.61[b]	9.91±0.44[c]

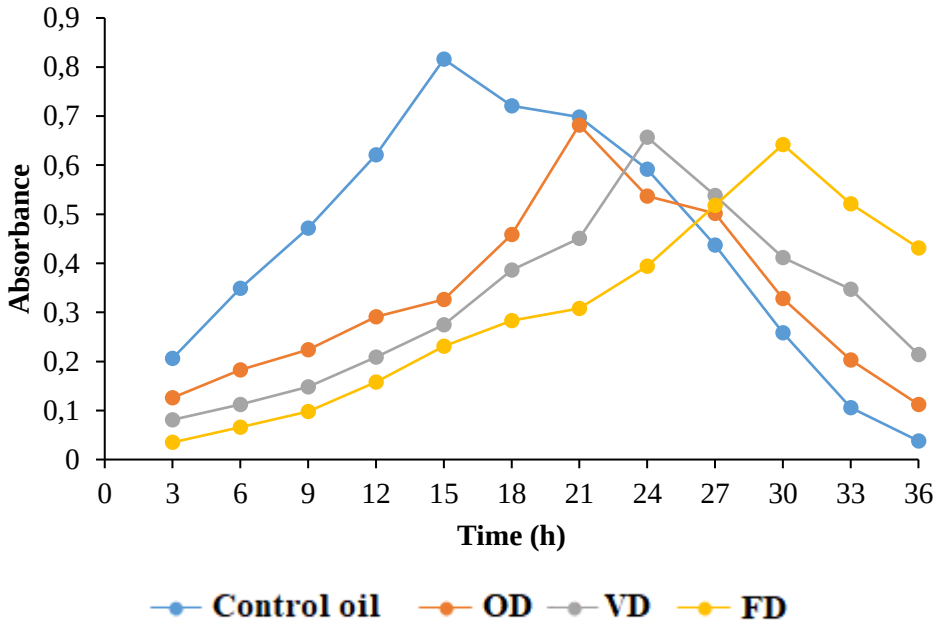

Figure 9. *Accelerated oxidative test of control oil and oil in microcapsules produced with different drying techniques.*

Microencapsulation effectively forms a barrier against oxygen, light, temperature, and moisture, limiting the oxidative degradation of fats. Among the drying methods, convective drying presented the highest rate of oxidation, likely due to the exposure of surface oil to oxygen, facilitating higher oxidation levels. Vacuum drying showed lower oxidation rates than freeze-drying, possibly due to the higher temperatures used in the process, which can partially promote oxidation despite the vacuum conditions [29].

In summary, the drying method significantly impacts the solubility and oxidative stability of microencapsulated safflower oil, with freeze-drying providing superior solubility and protective effects against oxidation. These findings underscore the importance of selecting appropriate drying techniques to enhance the functional properties of microencapsulated food ingredients.

4. Conclusions

The research presented in this manuscript provides comprehensive insights into the optimization of microencapsulation techniques for enhancing the solubility and oxidative stability of safflower oil using karaya gum and Lima bean protein isolate. The findings demonstrate that the choice of drying method significantly impacts the physical properties of the microencapsulated powder, with freeze-drying offering superior benefits in terms of morphology, color preservation, and protective effects against oxidation. Conversely, vacuum drying emerges as a balanced approach, effectively reducing moisture content while maintaining a desirable structure and color. Additionally, solubility variations with temperature and pH underscore the complex interplay between encapsulation materials and processing conditions, highlighting the importance of selecting appropriate drying techniques to optimize the functional properties of microencapsulated food ingredients. This study's implications extend to the broader application potential of microencapsulation in food science, particularly in enhancing the stability and usability of volatile or sensitive food components.

Acknowledgments

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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