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Extraction and Nanoencapsulation of Moringa oleifera Leaf Extract and Evaluation of Its Chemical and Physical Properties

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ABSTRACT

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Biosensors represent one of the most innovative technologies developed in recent decades in the field of the food industry. By integrating biotechnology, materials engineering, and data science, these systems enable accurate, rapid, and cost-effective monitoring of food quality and safety. Biosensors are designed based on sensitive biological elements such as enzymes, antibodies, or DNA, allowing them to detect chemical compounds, pathogens, and contaminants at very low concentrations. The present study reviews the theoretical foundations, historical development, and technological advancements of biosensors in the food sector, and analyzes their applications in areas such as microbial contamination detection, raw material quality control, supply chain monitoring, and the development of smart packaging systems. Advances in nanotechnology, micro-systems, artificial intelligence, and the Internet of Things (IoT) have significantly enhanced the sensitivity of biosensors and enabled their integration into intelligent monitoring networks. Despite advantages such as high accuracy, low cost, and real-time performance, several challenges remain, including biological stability, commercialization, and industrial standardization. The future of this technology lies in its integration with digital systems, biocompatible materials, and sustainable production processes. Such an approach can accelerate the transition toward a smart, transparent, and safe food industry, contributing significantly to the achievement of global food security.

1- INTRODUCTION

In recent years, consumers' inclination toward functional foods—which, in addition to their nutritional value, offer health-promoting benefits—has increased dramatically. In this context, the use of natural compounds with antioxidant properties, such as plant extracts, as suitable alternatives to synthetic antioxidants has attracted considerable attention from researchers. *Moringa oleifera*, owing to its unique array of phytochemical compounds—including phenolic acids, flavonoids (such as quercetin and kaempferol derivatives), and vitamins—has long been regarded as one of the most valuable natural sources in the functional food and pharmaceutical industries. Recent studies employing advanced metabolomics analyses have confirmed the presence of key compounds such as quercetin-3-glucoside and chlorogenic acid in the leaf extract of this plant, which are directly associated with its notable antioxidant and anti-inflammatory activity [1]. However, the fundamental challenge in the commercialization pathway of these compounds is their high sensitivity to environmental factors such as oxidation, degradation at physiological pH of the gastrointestinal tract, and ultimately, their low improved stability and controlled oral release, which severely limits their clinical and nutritional efficacy [2].

To overcome these limitations, novel formulation engineering approaches, such as nano emulsification followed by dry encapsulation, have been proposed as efficient strategies for the stabilization, protection, and targeted delivery of plant extracts. Among these, oil-in-water (O/W) nano emulsions have attracted considerable attention due to their relative simplicity of industrial-scale production, high optical clarity, and remarkable ability to enhance the apparent solubility of lipophilic compounds [3]. In this study, canola oil was selected due to its balanced fatty acid profile (low saturated fat, high oleic acid), suitable oxidative stability, low viscosity

(which facilitates nano emulsion formation), and neutral taste [4].

The production process of these nanocarriers typically involves the preparation of a coarse pre-emulsion followed by reduction of oil droplet size to below 100 nm through the application of intense shear forces by a high-pressure homogenizer. This method provides long-term physical stability of the emulsion by preventing phase separation and sedimentation [5]. However, liquid nano emulsions, due to their thermodynamic nature, are unstable against environmental stresses such as temperature fluctuations, light, and the presence of oxygen, and are prone to degradation. Therefore, converting the nano emulsion into a dry powder through encapsulation technology using a freeze-dryer is considered an ideal solution for significantly increasing shelf life, facilitating transportation, and maximizing protection of active compounds during storage [6]. The success of this process depends heavily on the selection of wall materials. In advanced research, the combination of proteins with prebiotic polysaccharides has shown highly promising results. Soy protein concentrate, as a wall material with strong emulsifying and film-forming properties, is capable of forming a resistant matrix structure. On the other hand, inulin, by creating a glassy matrix with a high glass transition temperature, prevents the collapse of the porous structure during drying, and gum Arabic, with its excellent emulsifying properties and high solubility in cold water, synergistically improves powder reconstitution stability and core protection [7, 8]. In the present study, a two-stage combined system was designed with the aim of improving the stability and controlled release of *Moringa oleifera* leaf extract. In the first stage, the extracted extract (lipophilic compounds in the oil phase and hydrophilic compounds in the aqueous phase and at the interface) is loaded into the oil phase of canola oil and converted into a nano emulsion under high pressure. In the next stage, the droplets of this nano emulsion are encapsulated using a wall composite consisting of soy protein concentrate, inulin, and gum Arabic via the freeze-drying method.

The main objective of this study is a comprehensive investigation of the chemical and physical properties of the final powder, the extraction conditions and preparation of the phases, and a comprehensive investigation of the chemical and physical properties of the resulting final powder, in order to take an effective step toward the development of functional food additives with high shelf life and efficacy.

2- Materials and Methods

2-1. Materials and chemical reagents

Moringa oleifera leaves (voucher No. MO-2023-0150/71836) were prepared and used for extraction. The deep eutectic solvent (DES) was prepared from choline chloride and citric acid (1:1 molar ratio). Edible canola oil, soy protein concentrate (Merck, Germany), inulin, and gum arabic were used as wall materials. Other chemicals included Tween 80 surfactant, methanol, ethanol, Folin-Ciocalteu reagent, sodium carbonate, and DPPH radical.

2-2. Extraction of *Moringa oleifera* Leaf Extract

For extraction, 1 g of leaf powder was mixed with 10 mL of a deep eutectic solvent (DES) based on choline chloride-citric acid (1:1 molar ratio), and 30% v/v distilled water was added to reduce viscosity. The DES was prepared at 80 °C with stirring at 500 rpm for 30 min [9]. Ultrasound-assisted extraction was performed at a power of 20–40 W at a constant temperature of 50 °C for 30 min [10]. These conditions were selected based on preliminary experiments that maximized the total phenolic content. After centrifugation (1000 rpm, 10 min), the clear liquid phase was separated.

2-3. Evaluation Tests of the Extracted Extract

2-3-1. Antioxidant Activity Assay (DPPH)

The DPPH free radical scavenging capacity was measured by mixing 1 mL of extract, 1 mL of DPPH (0.1 mM), and 1 mL of methanol, followed by storage in the dark

for 30 min [11]. Absorbance was read at 517 nm. The inhibition percentage (% Inhibition) was calculated using equation (1) and compared with BHT:

$$\% \text{Inhibition} = (A_0 - A / A_0) \times 100$$

Where:

- % Inhibition = free radical inhibition percentage
- A_0 = absorbance of the control sample (containing 1 mL DPPH and 1 mL methanol)
- A = absorbance of the sample containing *Moringa oleifera* extract or standard antioxidant

In this assay, BHT was used as a positive control.

2-3-2. Determination of total phenolic content (TPC)

Total phenolic content was determined by the Folin-Ciocalteu method and expressed as milligrams of gallic acid equivalent per gram of dry extract (mg GAE/g DW) [12]. A standard curve was constructed with gallic acid (5.12–125 ppm) (equation: $y = 0.0125x + 0.021$), and absorbance was read at 765 nm.

2-3-3. Fourier-transform infrared spectroscopy (FTIR)

Thin discs were prepared from a mixture of dried extract and KBr, and spectra were recorded in the range of 4000–400 cm^{-1} with a resolution of 0.5 cm^{-1} [13]. The aim was to identify functional groups and chemical interactions. The raw FTIR spectrum can be provided as supplementary data.

2-4. Preparation and encapsulation of the extract nanoemulsion

2-4-1. Nanoemulsification with canola oil

The oil phase (canola oil, 5–10% w/v, oil-to-water ratio 5:95) and the aqueous phase

(distilled water and Tween 80 surfactant at 2–5% concentration) were prepared and mixed to form a pre-emulsion. This pre-emulsion was converted into a nanoemulsion with droplet diameters below 100 nm using a high-pressure homogenizer (150 MPa, 5 cycles) [14].

2-4-2. Nanoencapsulation by freeze-drying

The wall solution containing 40 g of a mixture of soy protein concentrate, inulin, and gum arabic (1:1:1 ratio) was dissolved in 200 mL of water and stirred at 40–60 °C. Then, 2 g of the nanoemulsion was added and dispersed with a homogenizer (8000–9500 ppm, 5 min) [15]. The final mixture was converted into powder using a freeze-dryer and stored at 20 °C.

2-5. Characterization of the nanoencapsulated powder

2-5-1. Encapsulation efficiency (%EE)

One milligram of powder was treated with absolute ethanol and ultrasound (20 kHz, two cycles of 10 min), then centrifuged [16]. Surface (unencapsulated) phenols were determined by the Folin-Ciocalteu method at 740 nm, and efficiency was calculated using equation (2):

$$\text{Encapsulation Efficiency (\%)} = \frac{W_2 - W_1}{W_2} \times 100$$

2-5-2. Release of phenolic compounds

Three grams of powder were mixed with 3 mL of phosphate buffer (pH = 7.0) for 90 min and then centrifuged [16]. The aqueous phase was measured, and the release percentage was calculated. In this formula, C1 is the percentage of encapsulated compounds in the external phase, and C2 is the percentage of encapsulated compounds in the internal phase. Note: This study only examined the initial release at a specific time point. Kinetic release modeling will be performed in future studies.

2-5-3. Zeta potential and particle size

Zeta potential and particle size were measured using a Zetasizer Nano ZS (Malvern, UK) and

DLS after diluting the samples (1:5) at 25 °C [18]. Measurement conditions: scattering angle 173°, 10 runs, 3 repeats each. The Span index was calculated from $D50/(D90 - D10)$. The polydispersity index (PDI) was 0.02 ± 0.15 for the free nanoemulsion and 0.03 ± 0.18 for the nanoencapsulated sample.

2-5-4. Surface morphology (SEM)

Powder morphology was examined by SEM after gold coating, and images were recorded [19]. The emulsion was first converted to powder by freeze-drying and then coated with gold. A minimum of 5 different fields of view were recorded and analyzed for each sample at 4000× magnification and a 5-micrometer scale.

2-6. Statistical analysis

For data analysis, SPSS version 19 was used. The normality of the data was checked using the Shapiro-Wilk test and homogeneity of variances using Levene's test ($p < 0.05$). One-way ANOVA and Duncan's post-hoc test were used to determine significant differences among means. ANOVA assumptions were met with the limited number of treatments (at the 5% probability level).

3-Results and Discussion

3-1. Extraction of *Moringa oleifera* leaf extract and total phenolic and antioxidant activity

The results obtained from evaluating different concentrations of the extract (50, 100, and 200 ppm) showed that the radical scavenging activity and total phenolic content increased significantly with increasing extract concentration ($p < 0.05$) (Table 1). The highest antioxidant activity ($68.01 \pm 1.8\%$) was observed at 200 ppm, while the lowest values were $35.71 \pm 1.2\%$ and 25.3 ± 0.9 mg GAE/g at 50 ppm. This indicates a strong correlation between TPC and antioxidant activity, which is consistent with previous findings on the presence of phenolic and flavonoid compounds [17, 18].

To achieve higher amounts of these bioactive compounds, this study employed ultrasound-

assisted extraction with a deep eutectic solvent composed of choline chloride and citric acid. This method, through cavitation phenomena, cell wall disruption, and increased mass transfer, facilitated the extraction of secondary metabolites [20]. The increasing trend of TPC from 25.3 to 87.5 mg GAE/g along with the increase in RSA from 35.71% to 68.01% confirms the efficiency of this green extraction method. DES, acting as both a hydrogen bond donor and acceptor, creates a network of hydrogen bonds that preserves polyphenols against hydrolysis, oxidation, and thermal degradation [21, 22]. The control sample at 50 °C also protected the extract against thermal degradation and preserved the biological

activity of compounds such as gallic acid and tannins [23].

The findings of this study are consistent with previous reports; Choudhary and colleagues (2021) confirmed the effectiveness of DES based on choline chloride and organic acids in the extraction of plant antioxidants [24]. Osorio-Tobón (2020) also showed that combining UAE with DES preserves the quality of phenolic compounds by reducing process time and temperature [25]. Overall, the combination of UAE and DES offers an optimal, sustainable, and efficient method for extracting phenolic compounds from *Moringa oleifera* leaves.

Table 1. Free radical scavenging and total phenolic content of *Moringa oleifera* extract

Extract concentration (ppm)	%RSA	Total phenolic content (mg GAE/g)
50	35.71 ± 1.2 ^a	25.3 ± 0.9 ^a
100	53.04 ± 1.5 ^b	51.25 ± 1.2 ^b
200	68.01 ± 1.8 ^c	87.5 ± 1.5 ^c

Results are expressed as mean ± standard deviation, and all experiments were performed in triplicate. Different superscript letters indicate statistically significant differences at the 5% level ($p < 0.05$).

3-1-2. FTIR analysis of the extract

The FTIR spectrum of the extracted extract (Figure 1) confirmed the presence of key functional groups of bioactive compounds: a broad and strong band in the region of 3200–3400 cm^{-1} corresponding to O-H stretching vibrations, indicating the presence of phenolic and flavonoid compounds (such as quercetin) and their antioxidant properties [26]. A peak observed at 1700–1720 cm^{-1} is related to C=O stretching of phenolic acids, and bands at 1600–1650 cm^{-1} confirm the presence of aromatic C=C rings in phenolic compounds [27]. It should be noted that FTIR only confirms the presence of specific functional groups and is not

a definitive method for identifying complete compounds; more complementary analyses such as LC-MS are required. The use of DES created a hydrogen-bonded network between choline chloride and citric acid, which provided a more suitable polar environment for the extraction of these compounds [28].

The peaks observed in the 3000–2500 cm^{-1} region (C-H stretching) indicate the absence of thermal degradation in the control sample at 50 °C [29]. Also, the bands in the 1300–1000 cm^{-1} region (C-O stretching) show that polysaccharides and glycosidic compounds are well extracted by DES [30]. These observations are consistent with the findings of Zheng et al. (2022) and Wu et al. (2020), who reported that DES in combination with UAE has superior performance compared to traditional solvents [31, 32]. Table 2 presents the main chemical

groups identified along with related compounds.

Table 2. Chemical functional groups of the extract extracted from the plant leaves *Moringa oleifera*

Wavenumber (cm ⁻¹)	Type of functional group	Type of vibration	Related compound
3200–3400	Hydroxyl group OH	Stretching vibration	Polyphenols, flavonoids, water
1700–1720	Carbonyl group C=O	Stretching vibration	Phenolic acids, coumarins
1600–1650	Aromatic C=C	Stretching vibration	Aromatic phenolic compounds
1000–1200	C-O-C / C-H	Bending	Sugars, glycosidic compounds

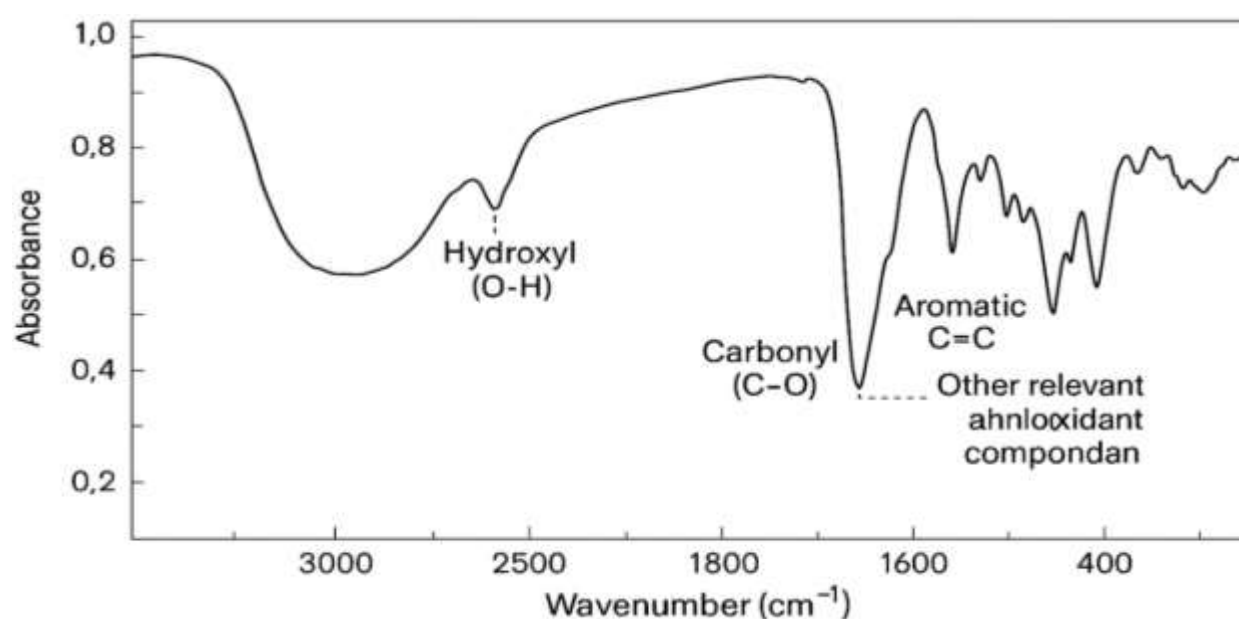


Figure 1. FTIR spectroscopy spectrum diagram of *Moringa oleifera* leaf extract

3-2. Encapsulation of Moringa extract

3-2-1. Physicochemical properties and nanoencapsulation efficiency

The data in Table 3 show that nanoencapsulation using the combined matrix of gum arabic, inulin, and soy protein concentrate had a significant effect ($p < 0.05$)

on all physicochemical parameters. The encapsulation efficiency (EE) reached $70.0 \pm 2.5\%$, indicating the high efficiency of the wall materials in entrapping phenolic compounds [33]. The release rate of phenolic compounds in the encapsulated sample ($20.0 \pm 1.5\%$) was significantly reduced compared to the free emulsion ($45.0 \pm 1.8\%$), indicating the creation of an effective physical barrier to control release and prevent premature oxidation [34, 35]. It

should be noted that this study only examined the initial release at a specific time (90 min), and kinetic release modeling will be performed in future studies. The zeta potential in the encapsulated sample reached -35.2 mV, which compared to -25.3 mV in the free emulsion, provides much higher electrostatic stability and prevents particle aggregation and clumping through stronger repulsion [36]. This increase in surface negative charge, consistent with the findings of Piacenza et al. (2018), is due to the presence of gum arabic with anionic functional groups at the interface [37]. The mean particle size decreased from 180 nm in the free emulsion to 98 nm in the encapsulated sample, mainly due to the action of the high-pressure homogenizer (150 MPa) in reducing oil droplet size and the role of inulin and gum arabic in rapidly stabilizing new surfaces [38]. The Span index also decreased from 0.70 to 0.45,

indicating a more uniform particle size distribution in the encapsulated system and a requirement for long-term colloidal stability [39]. The decrease in D50, D10, and D90 values (from 140, 180, and 220 nm to 80, 100, and 120 nm, respectively) confirms the success of the process in limiting the size distribution to smaller and more uniform droplets. This function is attributed to the dual role of inulin (forming a physical and protective matrix) and gum arabic (a natural emulsifier with high stabilization ability) [40, 41]. Also, canola oil with its high content of unsaturated and oleic fatty acids, as a carrier, helps protect phenolic compounds against oxidation [42]. Overall, the combination of DES-UAE with nanoemulsification and freeze-drying encapsulation provides a high-performance system for the protection and controlled release of phenolic compounds [43].

Table 3. Evaluation of key physicochemical and functional parameters between free nanoemulsion and nanoencapsulated emulsion of *Moringa oleifera* leaf extract

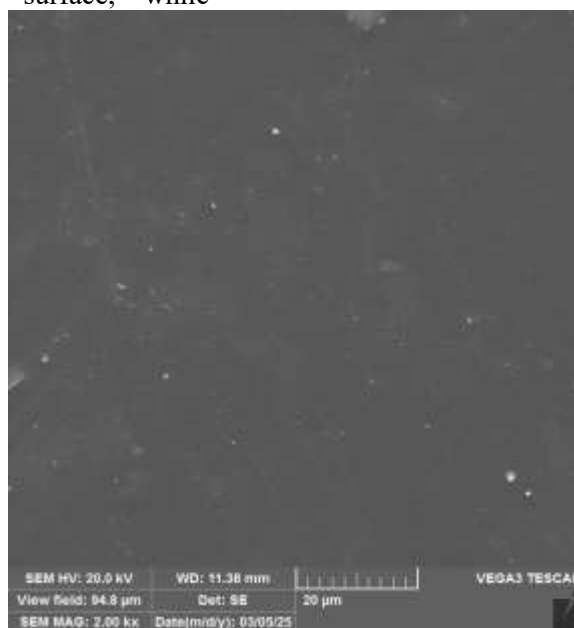
Parameters	Free emulsion	Encapsulated emulsion
Encapsulation efficiency (%)	—	70.0 ± 2.5^a
Release rate (%)	45.0 ± 1.8^b	20.0 ± 1.5^c
Zeta potential (mV)	-25.3 ± 1.2^b	-35.2 ± 0.8^a
Mean particle size (nm)	180 ± 5.0^b	98 ± 3.2^c
Span index	0.7 ± 0.05^b	0.45 ± 0.02^c
D10% (nm)	140 ± 3.4^b	80 ± 2.5^c
D50% (nm)	180 ± 4.0^b	100 ± 3.0^c
D90% (nm)	220 ± 5.0^b	120 ± 4.0^c
Loading efficiency (for 15% treatment)	—	7.5%

*Results are expressed as mean $\pm$ standard deviation, and all experiments were performed in triplicate. Different superscript letters indicate statistically significant differences at the 5% level.

3-2-2. Microstructural analysis of nanoemulsions (SEM)

Scanning electron microscopy images in Figure 2 show morphological differences between the two samples. The free emulsion (a) exhibited a non-uniform, irregular structure with extensive aggregates, indicating physical instability and absence of a protective layer [44]. In contrast, the encapsulated sample (b) displayed fully spherical particles with smooth, relatively porous surfaces and uniform distribution. This coherent network structure is the result of the successful blending of inulin and gum arabic around the oil core containing the extract during the freeze-drying process [45]. The semi-porous surface, while

creating a physical barrier against oxygen, allows controlled release of active compounds, consistent with the findings of Pieczykolan and Kurek (2019) regarding the integration of polymers in wall formation [46]. The absence of deep cracks in the walls indicates optimal drying conditions and appropriate wall material ratio. These features are fully consistent with the results of Span and particle size and confirm that encapsulation with the combined matrix, in addition to improving colloidal stability, provides more effective protection of bioactive compounds against destructive environmental factors [47, 48].



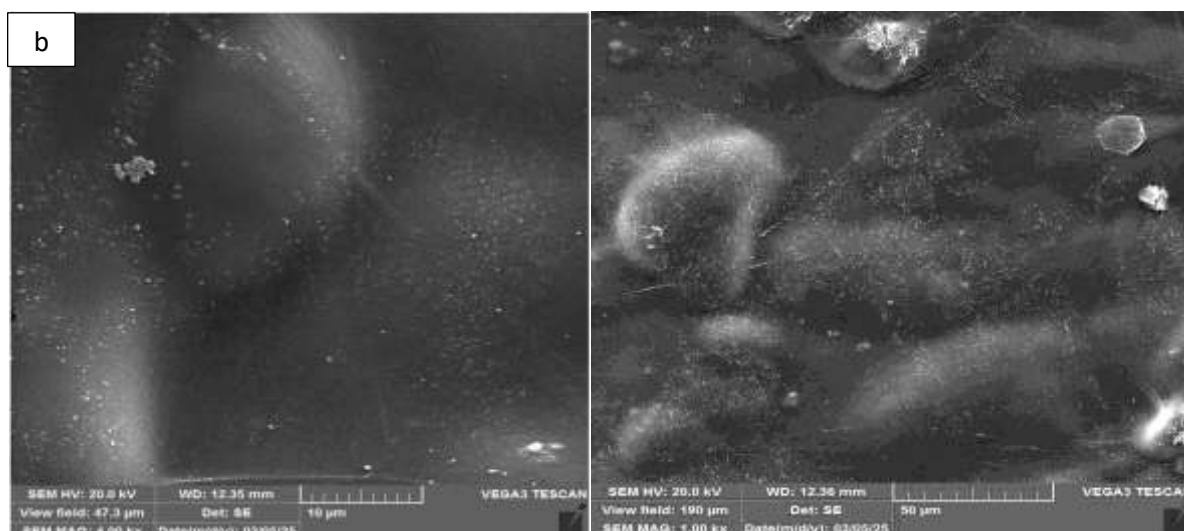


Figure 2 – Scanning electron microscope (SEM) images of the microstructure of a) free nanoemulsion of *Moringa oleifera* leaf extract and b) microencapsulated nanoemulsion with a composite wall of inulin and gum arabic (magnification $\times 4000$, scale bar 5 μm)

Figure 2 – Scanning electron microscope (SEM) images of the microstructure of a) free nano emulsion of *Moringa oleifera* leaf extract and b) microencapsulated nano emulsion with a composite wall of inulin and gum Arabic (magnification $\times 4000$, scale bar 5 μm)

4- Conclusion

In this study, an integrated and stepwise approach including green extraction with DES and ultrasound, nanoemulsification with canola oil, and freeze-drying nanoencapsulation with a combined matrix of soy protein concentrate-inulin-gum arabic was designed and implemented to stabilize and enhance the efficacy of *Moringa oleifera* leaf extract. The results demonstrated the success of this strategy from various aspects. DES based on choline chloride-citric acid (1:1 molar ratio) in combination with ultrasound (50 °C, 20–40 W) led to the extraction of an extract with high phenolic content (87.5 mg GAE/g) and considerable antioxidant activity (68.01% DPPH). FTIR analysis also confirmed the structural integrity of key functional groups of bioactive compounds. These results demonstrate the high efficiency of the DES-UAE method as a green and sustainable technology for extracting phenolic compounds from *Moringa* leaves. In the next step, the use of canola oil as a lipophilic phase (with 0.95% oil-to-water ratio) and a high-pressure homogenizer (150 MPa, 5 cycles) with Tween 80 surfactant enabled the formation of a nanoemulsion with a particle size below 100

nm. Encapsulation of this nanoemulsion with the combined matrix of soy protein concentrate-inulin-gum arabic (1:1:1 ratio) by freeze-drying significantly improved all physicochemical parameters. Nanoencapsulation, while achieving appropriate efficiency (70%), led to a significant reduction in particle size (from 180 to 98 nm), increased surface charge (zeta potential from -25.3 to -35.2 mV), and more uniform particle distribution (Span decrease from 0.70 to 0.45). More importantly, controlled release (decrease from 45% to 20%) showed that the wall matrix is capable of preventing premature release of phenolic compounds and ensuring long-term protection. SEM images also confirmed the formation of spherical and integrated particles with desirable surfaces, which was fully consistent with DLS data. It should be noted that in this study, bioavailability tests, simulated gastrointestinal digestion, and release kinetic models were not performed and are suggested for future studies.

In summary, this study showed that the integration of three novel technologies including DES-UAE, nanoemulsification with canola oil, and freeze-drying encapsulation with a protein-polysaccharide wall can synergistically address the challenges related to instability and achieve improved stability and

controlled release of *Moringa* extract. The resulting nanoencapsulated powder, with high antioxidant activity, desirable physicochemical stability, and controlled release capability, is an ideal candidate for enriching functional food products and developing herbal drugs with high efficiency. Future research can focus on evaluating the long-term stability of this system in real food matrices, investigating release kinetics, and bioavailability in simulated gastrointestinal models.

Data Availability

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

Conflict of Interest

The authors declare no conflict of interest.

Authors Contributions

All authors reviewed and approved the final manuscript for submission.

5. References

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استخراج و نانوریزپوشانی عصاره برگ گیاه مورینگا اولیفر (Moringa oleifera) و بررسی ویژگی‌های شیمیایی و

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گیاه مورینگا اولیفر (Moringa oleifera Lam.) منبعی غنی از ترکیبات زیست‌فعال با خواص آنتی‌اکسیدانی برجسته است، اما کاربرد آن در صنایع غذایی و دارویی به دلیل ناپایداری و رهایش نامناسب با محدودیت‌هایی مواجه می‌باشد. هدف از این پژوهش، استخراج عصاره برگ مورینگا با استفاده از حلال یوتکتیک عمیق (Deep Eutectic Solvent, DES) به کمک امواج فراصوت (Ultrasound-Assisted Extraction, UAE)، سپس تهیه نانوامولسیون با روغن کانولا و در نهایت نانوریزپوشانی آن با ماتریکس ترکیبی پروتئین-پلی‌ساکارید به روش خشک‌کن انجمادی به منظور بهبود پایداری و عملکرد آنتی‌اکسیدانی بود. استخراج با حلال DES (کولین کلراید-اسید سیتریک با نسبت مولی ۱:۱) و امواج فراصوت (W 40-20) در دمای ۵۰ درجه سانتی‌گراد (بر اساس پیش‌آزمایش‌های اولیه) به مدت ۳۰ دقیقه انجام شد. نانوامولسیون روغن در آب با نسبت روغن به آب ۵:۹۵ (حجمی/حجمی) با استفاده از روغن کانولا و سورفکتانت Tween 80 و هموژنایزر پرفشار (۱۵۰ MPa، ۵ سیکل) تهیه و سپس با دیواره ترکیبی کنسانتره پروتئین سویا-اینولین-صمغ عربی (نسبت ۱:۱:۱) به روش خشک‌کن انجمادی ریزپوشانی گردید. عصاره و پودر نهایی از نظر محتوای فنولی کل (Total Phenolic Content, TPC)، فعالیت آنتی‌اکسیدانی (DPPH)، طیف‌سنجی مادون‌قرمز با تبدیل فوریه (FTIR)، راندمان ریزپوشانی (Encapsulation Efficiency, EE%)، پتانسیل زتا، اندازه ذرات (Dynamic Light Scattering, DLS) و مورفولوژی سطحی (Scanning Electron Microscopy, SEM) ارزیابی شدند. عصاره استخراجی در غلظت ۲۰۰ ppm دارای TPC معادل ۸۷.۵ mg GAE/g و مهار رادیکال DPPH به میزان ۶۸.۰۱٪ بود. طیف FTIR حضور موفق گروه‌های عاملی فنولی، فلاونوئیدی و کربوهیدراتی را تأیید کرد. فرآیند نانوریزپوشانی به‌طور معنی‌داری ($p < 0.05$) ویژگی‌های فیزیکوشیمیایی را بهبود بخشید: راندمان ریزپوشانی به ۷۰٪ رسید، اندازه ذرات از ۱۸۰ به ۹۸ نانومتر کاهش، پتانسیل زتا از ۲۵.۳ به ۳۵.۲ mV- افزایش و رهایش ترکیبات فنولی از ۴۵٪ به ۲۰٪ کاهش یافت. تصاویر SEM، ذراتی کروی، یکنواخت و بدون ترک‌خوردگی را در نمونه ریزپوشانی‌شده نشان داد. تلفیق استخراج سبب با نانوامولسیون‌سازی و ریزپوشانی انجمادی، سامانه‌ای کارآمد با پایداری فیزیکوشیمیایی بالا و رهایش کنترل‌شده ارائه می‌دهد که پتانسیل بالایی برای کاربرد در فرمولاسیون‌های غذایی فراسودمند و دارویی دارد.