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Ultrasound-Assisted Extraction and Spray-Drying Microencapsulation of *Moringa oleifera* Leaf Extract: Effects of Core–Wall Ratio and Drying Temperature on Powder Properties

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ABSTRACT

Moringa oleifera leaves contain a high level of bioactive compounds that possess strong antioxidant potential. However, their incorporation into food systems is currently limited due to their poor dispersibility and instability. This study investigated the combined application of ultrasound-assisted extraction (UAE) and spray-drying microencapsulation to produce stable powdered extracts of *Moringa Oleifera* leaves. Methanolic extracts obtained through UAE were encapsulated using maltodextrin as a wall material at different core-to-wall ratios (0.1:10, 0.2:10, and 0.3:10, w/w) and inlet air temperatures (140, 150, and 160 °C). The resulting powder was assessed for particle distribution size, color characteristics, encapsulation efficiency, morphology, moisture content, density, hydration, and hygroscopicity properties. The encapsulation efficiency varied between 52.6% and 74.6%, but the high efficiencies were seen at lower core loading ratios. Scanning electron microscopy revealed spherical microcapsules with slightly wrinkled surfaces, peculiar to spray-dried powders. The moisture content ranged from 3.1 5.4% while water activity remained below 0.55, which indicates good storage stability. Interestingly, the powders showed a high water-solubility index (>90 %), which is attributed to the hydrophilic nature of maltodextrin. Conclusively, the findings indicate that the UAE with spray-drying microencapsulation is an excellent method of converting *M. oleifera* leaf extract into a stable, highly soluble powder, which is physically stable and suitable for functional food applications. The identified processing conditions provide a practical basis for the incorporation of *M. oleifera* bioactives into numerous functional food formulations.

Keywords: Functional food ingredients, Microcapsules, *Moringa oleifera,* Core–wall ratio, Ultrasound-assisted extraction, Spray-drying encapsulation

Introduction

The leaves of *Moringa oleifera* Lam. are well known as a rich source of phenolic compounds, flavonoids, vitamins, and other antioxidant phytochemicals, thus attracting interest in their application as natural ingredients in food and dry formulations.[1,2] However, the direct use of *M. oleifera* leaf extracts in dry food products is limited by technological factors such as poor water dispersibility, high hygroscopicity, and stability during processing and storage.[3,4] These limitations support the importance of effective extraction and encapsulation methods to transform liquid plant extracts into physically stable, process-compatible powders.

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The ultrasound-assisted extraction (UAE) has become one of the effective methods to extract phytochemicals produced by plants under relatively mild conditions.[5] Acoustic cavitation generated in the UAE breaks down plant cell walls and increases the amount of solvent penetration, leading to improved mass transfer and more uniform extract suspensions with fewer particle aggregates.[6] This increased dispersion behaviour of extracts is of special significance in downstream drying operations as feed homogeneity affects droplet formation and drying dynamics. Recent literature identifies that *M. oleifera* leaves produce high phenolics in the UAE with a high-quality extract compared to the traditional method, thus justifying its adoption as an innovative extraction method in powder formulation research.[7,8] Spray drying is one of the most popular methods of reducing liquid extracts to stable powders because it is scalable and allows the properties of the particles to be controlled. Formulation variables (e.g., the type of wall material and core/wall ratio) and process conditions (e.g., the temperature of an inlet air) have a strong impact on the physicochemical properties of spray-dried powders.[9] Maltodextrin is an ideal carrier material used in spray drying due to its low-viscosity level at high solute content, extreme water solubility, and neutral sensory profile; all these characteristics allow easy homogenization of feed solutions and are effective in terms of atomization and drying. Nevertheless, low dextrose equivalent (DE) of maltodextrins has low barrier properties, so it may influence encapsulation efficiency and

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sensitivity to moisture.[10] In the context of powder engineering, the core-to-wall ratio and inlet temperature of the air during spray drying are decisive factors in the determination of encapsulation efficiency, the morphology of the particles, moisture level, water activity, bulk density, and the hydration-related properties. Inadequate wall material may lead to deposition of core solids on the surface of the wall, and too much carrier loading can cause a dilution of active components and changes in bulk properties. The inlet temperature affects the evaporation rates of droplets, diffusion rates inside the droplet, shrinkage on the surface of the droplets, and their subsequent structure.[11,12] These process property relationships have been well developed in the food powder science and underline the necessity to systematically optimize and characterize spray-dried plant extract powders.

Although the UAE and spray-drying microencapsulation methods have been applied individually to *M. oleifera* leaf extracts and other phytochemical-rich extracts, systematic evaluation of the combined effects of core–wall ratio and inlet drying temperature on the physicochemical and structural properties of encapsulated *M. oleifera* leaf extract powders remains limited. Moreover, existing studies sometimes extend interpretations to biological outcomes (e.g., bioavailability or controlled release) without direct experimental assessment, creating scope misalignment relative to measured endpoints.

Therefore, the present study focuses explicitly on powder engineering and physical stabilization, rather than biological performance. It investigates the effects of different core-to-wall ratios and spray-drying inlet temperatures on encapsulation efficiency, particle morphology, moisture content, water activity, density, colour attributes, and hydration-related properties of maltodextrin-encapsulated *M. oleifera* leaf extract obtained via UAE. By clarifying the relationships between formulation variables, process conditions, and resulting powder characteristics, this work provides a practical physicochemical basis for the development of stable *M. oleifera*-based powdered ingredients for food applications.

Materials and Methods

Moringa oleifera samples and chemicals

Fresh *Moringa oleifera* leaves were collected in April 2017 at Queen Sirikit's demonstration farm (Yaring District, Pattani Province, Thailand), and a voucher specimen (QBG. No. 103322) was deposited at the herbarium of Queen Sirikit Botanic Garden, Chiang Mai, Thailand. After collection, the leaves were washed, subjected to freeze-drying, and pulverized into powder form. The sample was passed through a 60 mesh (250 µm) sieve, packed, and stored at 4 °C in airtight, light-protected containers to minimize oxidative degradation and remain relatively stable during long-term storage under controlled conditions. Food-grade maltodextrin with dextrose equivalence (D.E.) of 10-15 and 95% ethanol (food-grade reagent) was purchased from Scienfield Expertise PLT. (Selangor, Malaysia).

Preparation of Moringa oleifera leaf extract using UAE

UAE of dried *M. oleifera* leaf powder was conducted as follows: 10 g of the sample (powdered leaves) was extracted with 500 mL of 95% methanol using ultrasound-assisted extraction. The extraction was carried out in an ultrasonic bath at 40 °C for 30 minutes. The mixture was filtered, and the solvent was removed under reduced pressure in a rotary evaporator (EZ-2.3; Genevac Ltd., United Kingdom), and the resulting concentrate was stored in a tight-seal, light-protected container at −20°C until analyzed. The entire experiment was performed using a single batch of *M. oleifera* leaves to eliminate batch-to-batch inconsistency. The crude extract obtained after solvent removal was subsequently re-dissolved in food-grade ethanol prior to preparation of the spray-drying feed solution. This step ensured compatibility with the food-grade encapsulation process while preserving the phytochemical composition obtained during methanolic extraction.

Preparation of feed solution and encapsulation procedures

Feed emulsions were prepared by dissolving the maltodextrin in distilled water (ratio of 1:5 (w/w)) and allowing the solution to hydrate overnight with continuous magnetic stirring to ensure a complete dissolution. The previously obtained *Moringa oleifera* leaf extract was dissolved in food-grade ethanol at concentrations of 0.2, 0.4, and 0.6 % (w/v), then mixed with the maltodextrin solution at a 1:1 volume ratio. These mixtures produced feed formulations corresponding to core-to-wall ratios of 0.1:10, 0.2:10, and 0.3:10 (w/w).

A total volume of 100 mL of the solution was homogenized at 13500 rpm for 3 min (Ultra-Turrax, China) prior to spray drying. The spray drying was carried out using a laboratory spray dryer in which the feed solution was pumped into the drying chamber and atomized through a nozzle. Graded inlet temperatures of 140 °C, 150 °C, and 160 °C were evaluated while maintaining a constant feed flow rate. The resulting powders were collected and stored in airtight containers until further analysis. The drying process was carried out in triplicate according to the experimental parameters. Maltodextrin solution without extract was spray-dried as a control. The powder was retrieved from the collecting vessel below the drying cyclone chamber. The microencapsulated powders were weighed, and their yield efficiencies (%) were expressed as the ratio between the total amount of solids in the resulting powder and the total amount of solids in the feeding mixture.

Physicochemical characteristics of encapsulated powders

Tap density analysis

The tap density of each resulting powder was determined according to a published procedure. Briefly, 2 g of the microcapsule powder was weighed using a calibrated analytical balance (Mettler Toledo, Switzerland) and added to a 10 mL graduated measuring cylinder using a glass funnel. The measuring cylinder containing the sample was tapped for 1 min or until a constant volume was achieved. The tap density was calculated as the ratio of the powder mass to the volume occupied by the powder (g/cm^3).

Particle size of the microcapsules

The particle size distribution and the measurement of the average particle size of microcapsules were determined using a Malvern Scirocco 2000 particle size analyzer (Malvern Instruments, Worcestershire, U.K.). The assessments were conducted with the sample suspended in isopropanol with constant stirring. All measurement results were reported as averages of three replications.

Morphology of the microcapsule powder

The microstructure of spray-dried powder, including morphology and size measurements, was examined using a scanning electron microscope (SEM; SEMJSM5800LV, Japan). Powder samples were mounted on copper stubs and rendered conductive by coating with gold using a sputter coater. The SEM was operated at 30 kV, and the images were examined at 5000× magnification.

Microcapsules colour

The microcapsule colour measurements were reported in terms of CIE L^*, a^*, b^* (L^* = darkness to lightness, a^* = redness to greenness, and b^* = yellowness to blueness) using a colorimeter (Color Quest XE; Hunter Lab, USA) with an observer angle of 10°. The instrument was operated in Reflectance Specular Included (RSIN) mode (illuminant = D65/10; area view = 19.812 mm) and calibrated with a white tile before measurements. Approximately 3 g of microcapsules was placed into a sample holder and analyzed in triplicate.

Moisture content and water activity of microcapsules

The moisture content of the microcapsule powder (1 g) was determined using the oven-drying method and expressed as a percentage of weight loss after oven-drying (UNB-500; Memmert, Germany) at 105°C until a constant weight was achieved. The water activity of the samples was measured using a water activity analyzer (Aqua Lab Series 3 C.E.C.E., U.S.U.S.) after samples were stabilized at 25 ºC for 15 min. Analysis was done in triplicate.

Hygroscopicity of microcapsules

The hygroscopicity of the samples was measured using the method reported in the European Pharmacopoeia.[13] Briefly, 300 mg of powder was filled in a pre-weighted Petri plate and placed in a glass desiccator containing saturated NaCl solution for 24 h. The final mass of powder was determined using a calibrated analytical balance (Mettler Toledo, Switzerland). Percentage of increase in mass indicating the rate of water uptake at 25 - 27°C/76.5 – 78 % R.H.R.H. in 24 h was calculated and categorized as non-hygroscopic, slightly hygroscopic, moderately hygroscopic, and highly hygroscopic powder if the increase in the mass was below 0.2%, between ≥0.2% and <2.0%, between ≥2.0% and <15.0%, and ≥15%, respectively.

Water solubility index (WSI), water absorption index (WAI), and swelling capacity (SWC) of microcapsules

The microcapsule powder (1 g) was added to a pre-weighed 15 mL Falcon tube, followed by 12 mL of distilled water. The mixture was mixed vigorously using a vortex mixer for one minute and centrifuged at 3000 rpm for 15 minutes. The supernatant was poured into the pre-weighed glass dish and oven-dried at 105°C until a constant weight was reached. WSI was calculated based on the percentage of dried supernatant to the initial powder weight. WAI was expressed as the weight of the solid residue remaining after centrifugation divided by the amount of initial powder weight. SWC was calculated from the following equation: SWC = Weight of the residue/ [dry weight of sample x (1-WSI/100)].

Statistical analyses

All given parameters were tested in triplicate, and results were presented as mean ± S.D. Statistical analysis was performed using Statistical Package for the Social Sciences (SPSS 17.0 for Windows, SPSS Inc., Chicago, IL, USA) and Microsoft Office Excel 2010 (Windows version). One-way analysis of variance (ANOVA) followed by Duncan's New Multiple Range tests was performed to determine the significant differences among the treatments at a 95% confidence interval.

Results and Discussion

The current study assessed the effects of spray-drying conditions and formulation variables with regard to the physicochemical properties of microencapsulated *Moringa oleifera* leaf extracts. The findings illustrate that core-to-wall ratio and drying temperature had a great influence on the encapsulation efficiency, particle morphology, particle size distribution, and hydration characteristics of the resultant powders. These results indicate the necessity of the optimization of formulation parameters to obtain stable powdered plant extracts applicable in the utilization of functional foods.

The effects of the core to coating material ratios and inlet temperature on the yield and the microencapsulation efficiency are given in Table 1. The obtained products and encapsulation efficiency ranged from 5.52 to 7.53 g/100 mL and 52.58 to 74.56%, respectively.

Table 1: Effect of inlet air temperatures and different ratio of wall material (maltodextrin) and core material (*Moringa oleifera* leaf extract) on yields and yield efficiency of obtained microcapsules

Ratio of core material : wall material	Inlet temperatures (°C)	Outlet temperatures (°C)	Yield (g/100 mL)	Yield efficiency (%)
Control	140	105 ± 10	7.53 ± 0.08^{e}	74.56 ± 0.83^{c}
	150	113 ± 10	7.11 ± 0.44^{cde}	70.39 ± 4.40^{cd}
	160	120 ± 10	7.41 ± 0.26^{e}	73.38 ± 2.56^{c}
0.1:10	140	105 ± 10	6.89 ± 0.27^{bcde}	66.85 ± 2.57^{bcd}
	150	110 ± 10	7.20 ± 0.39^{de}	69.86 ± 0.38^{cd}
	160	120 ± 10	6.76 ± 0.57^{bcde}	65.67 ± 5.56^{bcd}
0.2:10	140	103 ± 10	5.56 ± 0.09^{a}	52.91 ± 0.89^{a}
	150	114 ± 10	6.00 ± 0.17^{abc}	57.13 ± 1.65^{ab}
	160	124 ± 10	5.91 ± 0.71^{ab}	56.30 ± 6.80^{ab}
0.3:10	140	104 ± 10	5.52 ± 0.28^{a}	52.58 ± 2.62^{a}
	150	114 ± 10	6.26 ± 0.29^{abcd}	59.58 ± 2.80^{abc}
	160	125 ± 10	5.76 ± 0.27^{ab}	54.83 ± 2.58^{a}

Inlet temperatures (T_{inlet}) and outlet temperatures (T_{outlet}) are expressed as mean ± SD (n = 3). The outlet temperature varied within an operational range of approximately ±10 °C depending on feed composition and drying dynamics. Yield and yield efficiency are expressed as mean ± SEM (n = 3). Mean values with different superscript letters in the same column are significantly different according to ANOVA followed by Duncan's New Multiple Range test ($p < 0.05$)

With increasing the content of UAE-MOL, both yield and the yield efficiency slightly decreased at 0.1:10 of UAE-MOL to maltodextrin and core to coating material of 0.2:10 and 0.3:10, respectively. The efficiency of encapsulation was between 52 and 75%, with efficiency increasing with lower core loading ratios. This trend can be attributed to a greater proportion of wall material being available, which can trap and shield the extract components in the drying matrix.[14,15] Under situations where core concentration is high compared to the wall material, the surrounding matrix can be inadequate to fully enclose the bioactive compounds and will partially be exposed on the surface, and its encapsulation ability will be reduced. The same trends have been described in spray-dried plant extract systems; whereby increasing core loading decreases the encapsulation efficiency because of a lack of sufficient wall material and because of high diffusion of solutes to the particle surface during the drying process. [16-20]

Figure 1 shows the morphological characteristics of microcapsules prepared by varying the ratio of core to coating material (0.1:10, 0.2:10, and 0.3:10) and the inlet temperatures (140°C, 150°C, and 160°C). The SEM photographs of the obtained maltodextrin microparticles with the UAE-MOL showed that the particles represent spherical and irregular microcapsules with smooth surfaces.

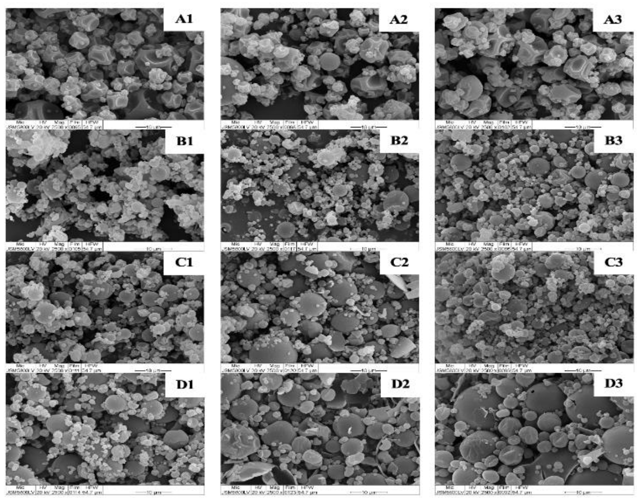

Figure 1: Scanning electron micrographs (5000X) represent morphology of *Moringa oleifera* leaf extract microcapsules achieved using maltodextrin as the wall material under the following ratios: 0:10 (w/w; A), 0.1:10 (w/w; B), 0.2:10 (w/w; C), and 0.3:10 (w/w; D) and spray dried at inlet air temperatures of 140°C (1), 150°C (2), and 160° (3)

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On the other hand, the non-spherical shape with concavities and wrinkles on the surfaces was noted from the control powder of maltodextrin without the core material, using these spraying conditions. The morphology of the particles was observed under scanning electron microscopy, where most of the particles were of a spherical shape with slightly wrinkled surfaces. It is a morphology typical of spray-dried powders manufactured by carriers of carbohydrates (e.g., maltodextrin). In the spray drying process, the atomized droplets are sprayed, and the moisture is quickly dried out, causing the droplets to form a solid crust on the surface.[21,22] During drying, the internal pressure of the vapour can lead to contraction or deform the shell of particles, producing the wrinkled surfaces in the micrographs. Surface deformation is also determined by the kinetics of drying, droplet chemistry, and the mechanical characteristics of the forming matrix.[23] The morphologies of similar particles have been reported extensively with respect to spray-dried bioactive compounds entrusted with maltodextrin and other polysaccharide carriers.[24,25]

The powder prepared from maltodextrin was significantly lighter than the UAE-MOL microcapsules. The negative *a** values and the positive *b** values of all samples indicated that the colours of the samples were green and yellow. The green color of microparticles was more observed than the maltodextrin powder, as noted in the negative *a** value of -0.45 ± 0.05 to -1.28 ± 0.04. Furthermore, coating UAE-MOL with maltodextrin caused a more yellow colour, possibly due to the colour of the core material added (Table 2).

Table 2: Color parameters of the microcapsules containing *Moringa oleifera* leaf extract prepared by different inlet air temperatures (T_{inlet}) and ratio of core material and wall material (maltodextrin)

Ratio Core/wall (w/w)	Inlet temperatures (°C)	*L**	*a**	*b**
Control	140	94.60 ± 0.32^{d}	-0.26 ± 0.05^{f}	3.35 ± 0.07^{a}
	150	94.31 ± 0.27^{d}	-0.20 ± 0.05^{f}	3.15 ± 0.03^{a}
	160	95.02 ± 0.18^{d}	-0.22 ± 0.04^{f}	3.13 ± 0.04^{a}
0.1:10	140	90.53 ± 0.19^{c}	-1.28 ± 0.04^{a}	11.47 ± 0.29^{b}
	150	90.63 ± 0.23^{c}	-1.24 ± 0.05^{a}	11.28 ± 0.09^{b}
	160	90.51 ± 0.21^{c}	-1.15 ± 0.04^{a}	11.42 ± 0.09^{b}
0.2:10	140	86.58 ± 0.66^{b}	-0.84 ± 0.08^{c}	15.89 ± 0.24^{d}
	150	86.85 ± 0.26^{b}	-0.92 ± 0.03^{bc}	15.42 ± 0.14^{c}
	160	86.88 ± 0.06^{b}	-0.98 ± 0.02^{b}	15.75 ± 0.10^{cd}
0.3:10	140	83.92 ± 0.14^{a}	-0.52 ± 0.03^{e}	16.20 ± 0.15^{d}
	150	83.78 ± 0.13^{a}	-0.45 ± 0.05^{e}	18.38 ± 0.25^{e}
	160	84.63 ± 0.34^{a}	-0.66 ± 0.06^{d}	19.11 ± 0.07^{f}

The parameters are presented as mean ± SEM (n = 3). Mean values with same superscript letter are not significantly different according to ANOVA followed by Duncan's New Multiple Range test ($p < 0.05$)

The influence of the ratio of UAE-MOL to maltodextrin and inlet temperatures used with these encapsulation procedures on particle size and particle size distribution is presented in Table 3 and Figure 2, respectively. Using the ratio of core material to wall material at 0.1:10 and the inlet temperatures of 150 and 160°C, the particle distribution curves of the microcapsules were monomodal. Similarly, the microparticles prepared from the ratio of UAE-MOL to maltodextrin at 0.2:10 and the inlet temperatures of 140 and 150°C tended to be also monomodal. At the core material to wall material ratio of 0.3:10, the tendency of the particle distribution curve of the samples was bimodal or multimodal. The span values that indicated the width of the UAE-MOL microcapsules' size distribution ranged from 0.84 to 1.65. The particle size of UAE-MOL microcapsules ranged from 27.86 to 222.49 µm for the surface-area mean ($D_{3,2}$) and from 35.15 to 340.25 µm for the volume-moment mean ($D_{4,3}$). These variations can probably be associated with the variations in the droplet formation and atomisation dynamics during spray drying. The feed formulations with relatively constant viscosity and solid content are likely to achieve similar droplet breakup during atomisation and therefore, lead to smaller distributions of the particle sizes. Conversely, increased extract content can enhance the viscosity of the feed and encourage anomalous droplet fragmentation or part droplet coalescence during the drying procedure.

Table 3: Particle size analysis of microcapsules prepared by different inlet air temperatures and ratio of wall material (maltodextrin) and core material (*Moringa oleifera* leaf extract)

Ratio Core/wall (w/w)	Inlet temperatures (°C)	*Particle Size Parameters (µm)**		
		$D_{[4,3]}$	$D_{[3,2]}$	Span
Control	140	1391.22 ± 7.41^{d}	1348.97 ± 8.15^{c}	0.44 ± 0.01^{a}
	150	1365.72 ± 7.64^{d}	1320.66 ± 8.57^{c}	0.46 ± 0.01^{a}
	160	1349.92 ± 25.00^{d}	844.54 ± 283.37^{b}	0.53 ± 0.03^{a}
0.1:10	140	81.85 ± 5.42^{ab}	54.57 ± 7.22^{a}	1.62 ± 0.04^{d}
	150	91.11 ± 0.83^{ab}	60.33 ± 3.79^{a}	1.20 ± 0.02^{bc}
	160	55.32 ± 1.32^{ab}	45.85 ± 3.75^{a}	0.84 ± 0.18^{ab}
0.2:10	140	105.25 ± 12.89^{ab}	84.52 ± 16.31^{a}	1.07 ± 0.12^{bc}
	150	95.13 ± 2.98^{ab}	46.41 ± 7.53^{a}	1.65 ± 0.15^{d}
	160	324.25 ± 77.60^{c}	222.49 ± 86.95^{a}	1.39 ± 0.36^{cd}
0.3:10	140	135.29 ± 17.21^{b}	117.16 ± 17.75^{a}	1.06 ± 0.11^{bc}
	150	340.25 ± 8.20^{c}	206.98 ± 63.00^{a}	1.05 ± 0.14^{bc}
	160	35.15 ± 6.99^{a}	27.86 ± 5.92^{a}	1.30 ± 0.20^{cd}

Results are presented as mean ± SEM (n = 3). Mean values with different superscript letters within each column are significantly different according to ANOVA followed by Duncan's New Multiple Range test ($p < 0.05$). *$D_{[3,2]}$; The surface area means (Sauter mean diameter): $D_{[4,3]}$; The volume moment means (De Brouckere Mean Diameter)

The effects may produce both smaller primary populations and larger secondary ones, resulting in larger or bimodal particle size distributions. Up to now, it has been observed in spray-drying research of plant extracts and materials rich in polyphenols that feed composition has a very strong effect on atomisation behaviour and particle formation mechanisms. [26, 27] The apparent particle size of the control maltodextrin powder had a value that was exceptionally large compared to the extract-loaded microcapsules. A probable cause of this discrepancy is that measuring particle agglomeration occurs instead of varying primary particle formation. It is known that maltodextrin powders are highly hygroscopic and may be characterized by a strong inter-particle cohesion that encourages the development of agglomerates during laser diffraction.[28] Conversely, the integration of solids of plant extracts into the encapsulated formulations can lead to a decrease in cohesive forces between the particles, thus generating smaller values of the measured particle sizes. The same agglomeration effects in the analysis of the particle size of carbohydrate-based powders have been observed in earlier studies.[29-31]Water activity and moisture content are important parameters that determine the stability of spray-dried powders and shelf life. In the current research, the microencapsulated powders were rather dry, with the moisture content and water activity not higher than 0.55, which indicated excellent physical stability and low resistance to microbial growth during storage. As given in Table 4, various core/coating ratios and the inlet temperatures also affected the microparticle powders' physicochemical characteristics. In this study, the tap densities of UAE-MOL microcapsule powders tended to decrease as the inlet temperatures increased, ranging from 0.18 to 0.40 g/cm^3. Among the tested microparticles, the sample with a core: wall weight ratio of 0.2:10 and dried at 140 °C exhibited the highest tap density.

Table 4: Physicochemical properties of *Moringa oleifera* leaf extract microcapsules prepared by different inlet air temperatures (T_{inlet}) and ratio of core material and wall material (maltodextrin)

Ratio (w/w)	T_{inlet} (°C)	Tap density (g/cm^3)	Water activity (a_w)	Moisture content (%)	Moisture absorbed (g)	Hygroscopicity (%)	Water solubility index (%)	Water absorption index (g/g)	Swelling capacity (g/g)
Control	140	0.39 ± 0.01^{ef}	0.38 ± 0.01^{bc}	1.69 ± 0.11^{a}	0.02 ± 0.00^{abc}	7.19 ± 0.42^{cd}	93.09 ± 0.10^{bcd}	0.04 ± 0.01^{abc}	0.60 ± 0.10^{ab}
	150	0.47 ± 0.00^{g}	0.33 ± 0.00^{a}	0.99 ± 0.211^{a}	0.03 ± 0.00^{c}	8.06 ± 0.70^{d}	93.83 ± 0.06^{d}	0.04 ± 0.01^{ab}	0.65 ± 0.11^{ab}
	160	0.46 ± 0.01^{g}	0.36 ± 0.01^{b}	1.32 ± 0.24^{a}	0.02 ± 0.00^{abc}	7.16 ± 0.36^{cd}	93.80 ± 0.04^{d}	0.03 ± 0.01^{a}	0.49 ± 0.07^{a}
0.1:10	140	0.37 ± 0.01^{e}	0.38 ± 0.01^{cd}	3.95 ± 0.06^{bc}	0.02 ± 0.00^{abc}	6.64 ± 0.50^{bcd}	92.36 ± 0.05^{abc}	0.05 ± 0.00^{abcd}	0.68 ± 0.01^{ab}
	150	0.32 ± 0.01^{cd}	0.43 ± 0.00^{e}	3.38 ± 0.31^{b}	0.02 ± 0.00^{abc}	6.97 ± 0.87^{cd}	93.73 ± 0.24^{d}	0.05 ± 0.00^{abcd}	0.84 ± 0.07^{ab}
	160	0.30 ± 0.01^{c}	0.44 ± 0.01^{ef}	3.14 ± 0.16^{b}	0.02 ± 0.00^{abc}	6.66 ± 0.25^{bcd}	93.46 ± 0.02^{cd}	0.06 ± 0.02^{bcde}	0.89 ± 0.33^{ab}
0.2:10	140	0.40 ± 0.00^{f}	0.47 ± 0.00^{g}	3.36 ± 0.10^{b}	0.02 ± 0.00^{bc}	7.17 ± 0.75^{cd}	92.34 ± 0.12^{abc}	0.05 ± 0.00^{abcd}	0.64 ± 0.03^{ab}
	150	0.38 ± 0.01^{ef}	0.45 ± 0.00^{f}	3.90 ± 0.35^{bc}	0.02 ± 0.00^{bc}	5.42 ± 0.59^{abc}	92.57 ± 0.13^{abc}	0.07 ± 0.00^{bcde}	0.87± 0.04^{ab}
	160	0.32 ± 0.01^{cd}	0.39 ± 0.00^{d}	4.01 ± 0.27^{bc}	0.02 ± 0.00^{bc}	5.50 ± 0.32^{abc}	94.05 ± 0.58^{d}	0.05± 0.01^{abcd}	0.79± 0.14^{ab}
0.3:10	140	0.32 ± 0.01^{d}	0.50 ± 0.00^{h}	4.57 ± 0.37^{cd}	0.01 ± 0.00^{a}	4.74 ± 0.52^{ab}	92.20 ± 0.09^{ab}	0.07 ± 0.01^{cde}	0.86 ± 0.06^{ab}
	150	0.23 ± 0.01^{b}	0.52 ± 0.01^{i}	5.40 ± 0.51^{e}	0.01 ± 0.00^{a}	4.68 ± 0.96^{a}	91.43 ± 0.08^{a}	0.08 ± 0.01^{e}	0.94 ± 0.10^{b}
	160	0.18 ± 0.01^{a}	0.44± 0.01e^{f}	5.10 ± 0.17^{de}	0.01 ± 0.00^{a}	4.41 ± 0.46^{a}	92.56 ± 1.03^{abc}	0.07± 0.00^{de}	0.96 ± 0.19^{b}

The parameters are presented as mean ± SEM (n = 3). Mean values with same superscript letter are not significantly different according to ANOVA followed by Duncan's New Multiple Range test ($p < 0.05$)

The estimated water activity and moisture content for all powders were found to be between 0.38 and 0.52 and 3.14% to 5.40 % (dry basis), respectively. The increase in UAE-MOL content tended to raise water activity levels and moisture content of the obtained microcapsules. The values obtained for moisture absorption of the powders varied from 0.01 to 0.02 g, and their hygroscopicity was calculated to be 4.41 to 6.97 g absorbed water per 100g solids. Among these, the samples prepared from a core per wall weight ratio of 0.3:10 possessed low hygroscopicity values ranging from 4.41 to 4.74%. The low moisture levels obtained are a result of the high inlet air temperatures employed in spray drying, which favour fast solvent evaporation of atomised droplets. Also, maltodextrin has a fairly high glass -transition temperature and low hygroscopicity relative to most other carbohydrate carriers, which can be used to develop stable amorphous structures that restrict water uptake.[32]

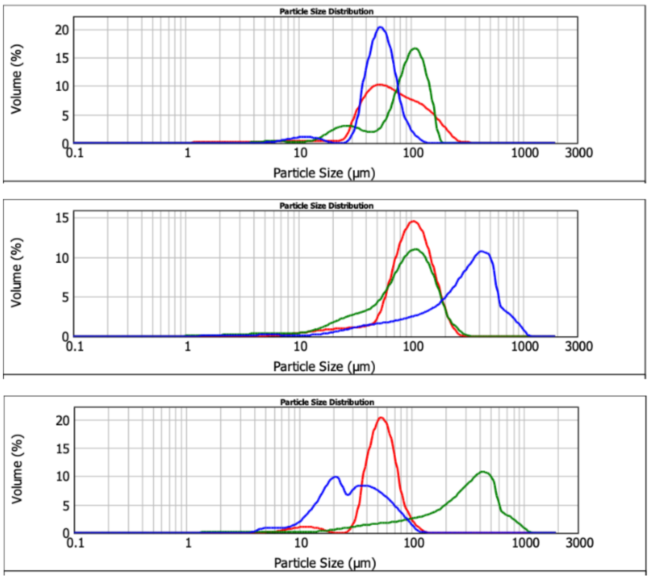

Figure 2: Particle size distribution for microcapsules of *Moringa oleifera* leaf extract achieved using maltodextrin as the wall material under the following ratios: 0.1:10 (w/w; red lines), 0.2:10 (w/w; green lines), and 0.3:10 (w/w; blue lines) and spray dried at inlet air temperatures of 140°C (A), 150°C (B), and 160° (C)

The functional benefits of the microencapsulation process could also be observed by the hydration qualities of the powders. Water solubility index (WSI), water absorption index (WAI), and swelling capacity, representing the microcapsule powders' dissolving ability, are presented in **Table 4**. Because of the high solubility of maltodextrin in water, the high WSI of 91.43-94.05% for UAE-MOL microcapsules was achieved. These values were found to be comparable to the coating material. The WAI of the samples was calculated to be 0.05 to 0.08 g/g and tended to be higher than that of the powder prepared from maltodextrin, whose WAI ranged from 0.03 to 0.04 g/g. A similar observation was found with the swelling capacity of UAE-MOL microcapsule powders. These values, which ranged from 0.64 to 0.96 g/g, were slightly higher than those of the coating material powder, which ranged from 0.49 to 0.65 g/g. The encapsulated powders showed high water solubility indices above 90%, whereas the non-encapsulated Moringa oleifera leaf powder had a much lower index. The insolubility of the raw leaf material is mainly related to the solubility of structural elements of the plant, which are insoluble, i.e., cellulose, hemicellulose, and lignin. On the other hand, the encapsulated powders have maltodextrin as the major constituent of the matrix, which is very soluble in water and easily dispersible in aqueous medium. This is the reason why much greater solubility values were seen with the spray-dried formulations. The enhanced solubility is a significant property of powdered functional ingredients meant to be incorporated into drinks and any other reconstituted foods.

The general physicochemical properties of the powders that were achieved in this research indicate that the ultrasound-assisted extraction followed by spray-drying microencapsulation would be an effective method in stabilising the extract of the Moringa oleifera leaves. Ultrasound extraction increases the extraction of phenolic compounds and other phytochemicals by disruption by cavitation on the plant tissues, and spray drying transforms the liquid extract into a powdered form that is stable. The maltodextrin structure that is created in the drying process not only serves to preserve the encapsulated compounds against environmental degradation but also enhances the handling, dispersibility, and storage attributes of the extract. Integrated processing approaches have been found to increase the stability of bioactive compounds found in different sources of plants.[33] Combined, the results of this paper reveal that the correct choice of the core-to-wall ratio and drying conditions is very important in defining the structural and functional characteristics of the spray-dried powders of the Moringa extract. Optimisation of these parameters can result in the generation of homogeneous microcapsules with preferred particle properties and water solubility to be utilised as functional ingredients in food preparations. The combination of ultrasound-assisted extraction and spray-drying microencapsulation, therefore, represents a promising strategy for improving the physicochemical stability and functional usability of plant-derived bioactive compounds

The limitation of the study lies in the fact that the study focused on the immediate physicochemical and structural properties of spray-dried *M. oleifera* leaf extract powders. No parameters like release kinetics, long-term storage properties, or biological efficacy were considered, and, therefore, inferences made are limited to the powder-engineering properties observed under the conditions of the experiment carried out. Another limitation of the study is that the optimization of spray-drying parameters used a simplified experimental design that mainly evaluated the individual effects of core-wall ratio and inlet drying temperature. The study did not utilize factorial design or response surface methodology to fully model potential non-linear and interaction effects between the variables. Future studies should apply response surface methodology to obtain a more comprehensive optimization of spray-drying conditions.

Conclusion

This study demonstrated that ultrasound-assisted extraction combined with maltodextrin-based spray-drying microencapsulation can effectively convert *Moringa oleifera* leaf extracts into stable powder ingredients. Core-to-wall ratio and inlet air temperature significantly influenced encapsulation efficiency, particle morphology, moisture content, density, and hydration properties of the powders. Lower core loading improved encapsulation efficiency, while higher drying temperatures promoted lower moisture content and reduced powder density. The resulting powders exhibited high water solubility due to the hydrophilic properties of maltodextrin. These findings provide useful insights for optimizing spray-drying parameters for the production of physically stable *Moringa* extract powders intended for functional food applications.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Declaration

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

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