



Enhancing Polyphenol Recovery and Stability in Lemon Myrtle (*Backhousia citriodora*) and River Mint (*Mentha australis*) in Herbal Tea Infusions Using Ultrasound-Assisted Extraction and Spray-Dried Microencapsulation

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Abstract

This study evaluated water-based ultrasound-assisted extraction (UAE) and spray-dried microencapsulation for producing phenolic-rich powders from Australian lemon myrtle (LM; *Backhousia citriodora*) and river mint (RM; *Mentha australis*). UAE was screened across time, amplitude and material-to-solvent ratio, with total phenolic content (TPC) used to identify the strongest tested condition. At 20 min, 30% amplitude and 1:20 m/v, method-development TPC was 25.10 ± 0.61 mg GAE/g for LM and 51.98 ± 4.28 mg GAE/g for RM. Applying these conditions to production materials, including a separately sourced commercial LM batch, yielded feed TPCs of 64.35 ± 2.72 and 37.67 ± 2.40 mg GAE/g, respectively. Spray drying with maltodextrin and maltodextrin–gum Arabic carriers gave production yields of 72.00–78.92% (LM) and 62.09–65.63% (RM), and process yields of 53.37–69.83% and 68.76–70.65%, respectively. RM showed higher TPC-based encapsulation efficiency (80.60–86.50%) than LM (59.71–68.02%), whereas LM powders had higher TPC (45.33–48.05 vs 24.25–25.63 mg GAE/g) and retention efficiency (68.8–74.9 vs 61.3–70.4%). Compound-specific encapsulation efficiency was approximately 78–85% for gallic acid in LM and 88–96% for rosmarinic acid in RM. Moisture ranged from 5.69 to 9.37%, while DPPH activity ranged from 3.31 to 10.52 mg TE/g for LM and 3.48–6.26 mg TE/g for RM. Powders had water activity of 0.42–0.47, solubility of 85.3–88.4%, Carr Index values of 39.69–46.73 and Hausner ratios of 1.66–1.88. Under the tested conditions, LM delivered greater phenolic density, while RM provided stronger proportional biomarker retention.

Keywords Ultrasound-assisted extraction · Spray drying · Microencapsulation · Polyphenols · Australian Native Foods · Gum Arabic

Introduction

Traditional herbal infusions are widely consumed for their flavour, aroma, and health-promoting properties (Huda et al., 2024). Much of this interest is linked to their polyphenol content, with many herbal infusions recognised as rich sources of dietary phenolic compounds (Chandrasekara & Shahidi, 2018). Polyphenols, including phenolic acids,

flavonoids and tannins, support antioxidant, anti-inflammatory and gut-modulatory activity, contributing to their nutritional and functional value (Abbas et al., 2017). However, polyphenol stability can be affected by extraction conditions and the processing steps used to formulate powders or ready-to-use herbal products (Debelo et al., 2020). As such, developing protocols that maximise retention of polyphenols during processing is critical to ensure both product quality and health benefits.

Australia possesses a rich flora of native aromatic and medicinal plants that are increasingly being incorporated into foods and beverages (Perry et al., 2026). Among them, lemon myrtle (*Backhousia citriodora*) and river mint (*Mentha australis*) are two promising herbal ingredients. Lemon myrtle is distinguished by its high citral content and strong lemon aroma, and it also contains a diverse array of phenolic

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acids and flavonoids (Saifullah et al., 2019). Previous studies have identified rutin, catechin, gallic acid, and quercetin among its major phenolic constituents, with demonstrated antioxidant and antimicrobial properties (Ali et al., 2024). River mint, traditionally used by Indigenous Australians for medicinal purposes, contains rosmarinic acid as a dominant phenolic compound, alongside chlorogenic acid, neoponcirin, and biochanin (Tang et al., 2016). These compounds contribute to antioxidant and anti-inflammatory potential, reinforcing the suitability of river mint and lemon myrtle as functional food ingredients. Despite their rich phytonutrient profiles, scientific evidence supporting optimised processing strategies for these plants remains limited, particularly with respect to polyphenol retention during extraction and spray drying.

Processing therefore plays a critical role in determining whether herbal infusions retain their phenolic composition and associated functional value. Heat, oxidation, and light exposure readily degrade phenolic compounds, resulting in loss of activity and reduced product quality (Renard et al., 2017). Conventional extraction techniques such as maceration, infusion, and decoction are often inefficient, time-consuming, and use volatile organic solvents (Chemat et al., 2020). Ultrasound-assisted extraction (UAE) has emerged as a green technology that enhances the recovery of phenolic compounds using shorter extraction times, reduced solvent consumption, and lower energy requirements (Tiwari, 2015). Acoustic cavitation, the underlying central mechanism of UAE, improves solvent penetration, disrupts plant cell walls, and accelerates mass transfer, resulting in improved yields compared to conventional methods (Panda & Manickam, 2019). Importantly, UAE can be performed with water as the solvent, making it highly suitable for food applications.

To use an herbal extract as a source for infusion tea, it first needs to be converted into a powder. Several commercial drying methods are available for this purpose, including freeze-drying, spray-drying, and microwave drying. Among these, spray-drying is often preferred because it is cost-effective, easy to operate, and produces fine powders.

However, the high temperatures involved in spray-drying can degrade or denature heat-sensitive bioactive compounds, particularly phenolic compounds. One way to overcome this limitation is through encapsulation, a process in which a protective coating is formed around sensitive bioactive ingredients. Although several encapsulation techniques exist, spray-drying is one of the most widely used microencapsulation methods and has shown strong potential for improving the stability of phenolic compounds in herbal infusions (Baltrusch et al., 2022; Liu et al., 2026; Medina-Torres et al., 2016). By encapsulating these compounds within hydrocolloid-based carriers such as maltodextrin and gum Arabic, spray drying improves stability against environmental stresses during packaging and storage as well as

enhances solubility and handling properties (Drosou et al., 2017). Previous research has demonstrated the suitability of spray drying for herbal infusions (Alaşalvar & Çam, 2019; Mazár et al., 2025); however, studies combining UAE with microencapsulation to maximise the extraction and retention of phenolic compounds in Australian native herbs remain unexplored. Moreover, systematic optimisation of direct UAE conditions for lemon myrtle and river mint is limited, where a single previous study employed indirect ultrasound extraction using a bath sonicator (Saifullah et al., 2021). Likewise, the effect of different wall materials on encapsulation efficiency and powder quality of phenolic-rich extracts of these Australian native herbs is unclear, where previous studies have primarily focused on the encapsulation of the oil fraction of lemon myrtle (Beikzadeh et al., 2020; Huynh et al., 2008). Therefore, addressing gaps surrounding water-based herbal infusions is critical for developing high-quality, shelf-stable herbal powders of Australian native plants, supporting their broader commercialisation in functional food markets.

This study uses UAE to recover phenolic compounds from lemon myrtle and river mint leaves, followed by spray drying with maltodextrin and maltodextrin–gum Arabic blends as carrier materials. The objectives were to (i) identify reproducible UAE parameters (extraction time, amplitude, and material-to-solvent ratio) for maximum polyphenol recovery, (ii) evaluate the influence of wall materials on encapsulation efficiency and physicochemical properties of the powders, and (iii) characterise the resulting powders in terms of yield, phenolic retention, and powder quality.

Materials and Methods

Materials

Fresh leaves of lemon myrtle (*B. citriodora*) were collected from the Bushfood Garden outside the Hartley Teakle Building, The University of Queensland, St Lucia campus (Brisbane, QLD, Australia) during spring (October 2024) and used for initial UAE method development due to their availability for the screening experiments. Following selection of the UAE parameters, commercial-grade organic lemon myrtle leaves sourced from Australian Native Products (Mareeba, QLD, Australia) were used to prepare the final feed extract for spray-drying trials, providing material representative of a commercially sourced ingredient. Oven-dried river mint (*M. australis*) leaves were obtained from NATIVE EXTRACTS Pty Ltd (Alstonville, NSW, Australia). Maltodextrin (dextrose equivalent [DE] 4–7), gum Arabic (food grade), Folin–Ciocalteu's phenol reagent (2 N), sodium carbonate ($\geq 99.7\%$), methanol ($\geq 99.9\%$), ethanol ($\geq 99.9\%$), gallic acid ($\geq 98\%$), rosmarinic acid

($\geq 98\%$), acetic acid ($\geq 99.7\%$, glacial), formic acid ($\geq 98\%$), Trolox ($\geq 97\%$), and DPPH (2,2-diphenyl-1-picrylhydrazyl) ($\geq 99.9\%$) were purchased from Sigma-Aldrich (St. Louis, MO, USA). All chemicals and reagents were analytical grade.

Processing of Australian Native Leaves

Fresh lemon myrtle leaves were washed with distilled water, drained, and dried in a DZ-2BCII Vacuum Drying Oven (Faithful Instrument, Hebei, China) at $50\text{ }^{\circ}\text{C}$ for 24 h. Dried leaves were ground using a Sunbeam 600 W Multi Food Processor LC5500 (Boca Raton, FL, USA) and passed through a $300\text{-}\mu\text{m}$ stainless steel ASTM mesh sieve to yield a consistent and uniform product for ultrasonic extraction. Commercially dried river mint leaves were separated from their stems, ground, and sieved according to the same method.

Ultrasound-Assisted Extraction

Twelve experimental conditions ($3 \times 2 \times 2$ full-factorial screening design) were performed in triplicate using extraction time (10, 15, and 20 min), amplitude (20% and 30%), and solvent-to-material ratio (1:20 and 1:30, m/v) as independent variables, with phenolic content as the response variable (Table S1). Phenolic content was selected because this stage of the study focused on the bulk transfer of phenolic material from the plant matrix into the aqueous extract prior to downstream spray drying, rather than optimisation of individual phenolic compounds or antioxidant responses. Sonication was continuous and not pulsed, and conducted at room temperature with no temperature control. Prior to extraction, $5 \pm 0.01\text{ g}$ of leaf powder was weighed and dispersed in distilled water at the designated ratios (1:20 or 1:30 m/v). All formulations were prepared and extracted in triplicate using a Vibra-Cell™ VCX 750 ultrasonic processor (Sonics & Materials, Inc, Newtown, CT, USA) equipped with a titanium probe (10-mm diameter). Extractions were carried out in open, identical flat-bottomed plastic vessels (internal diameter 4 cm, height 16 cm), with the probe position kept constant to ensure reproducibility across samples. Specifically, the probe was immersed to 50% depth of the extraction solution. Extraction temperature was not independently controlled, and slurry temperature was measured immediately after each extraction using a mercury thermometer and reported as the endpoint temperature. Accordingly, endpoint temperature was treated as a process outcome reflecting ultrasound-induced heating rather than as an independently controlled extraction factor. Following extraction, all samples were centrifuged at 5000 rpm for 20 min at $20\text{ }^{\circ}\text{C}$ using a Heraeus Multifuge X1R (Thermo Fisher Scientific,

Waltham, MA, USA), the supernatant separated, and the final sample stored at $-80\text{ }^{\circ}\text{C}$ until further analysis.

Total Phenolic Content (TPC)

The total phenolic content (TPC) of the extracts was determined using the Folin–Ciocalteu (F–C) method optimised for 4 mL cuvettes according to a previous method (Nastasi et al., 2023). A gallic acid stock solution was prepared by dissolving 100 mg in 100 mL of deionised water, and working standards were prepared at 0, 25, 50, 100, 250, and $500\text{ }\mu\text{g/mL}$. The F–C reagent was diluted to 10% (v/v) with deionised water, and sodium carbonate was prepared at 7.5% (w/v). In cuvettes, $100\text{ }\mu\text{L}$ of standard or sample extract was combined with $1400\text{ }\mu\text{L}$ of FC reagent, reacted for 10 min under agitation in the dark, and then mixed with $1400\text{ }\mu\text{L}$ of sodium carbonate solution. The mixtures were incubated at ambient temperature in the dark for 2 h under agitation before measuring absorbance at 765 nm using a UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan). TPC values were calculated from the gallic acid calibration curve ($R^2 = 0.99$) and expressed as mg gallic acid equivalents (GAE) per g of dry sample.

Microencapsulation using Spray Drying

Stock solutions were prepared using a 5% w/v concentration of three carrier stocks: maltodextrin as a single carrier (100%), a combination of maltodextrin/gum Arabic (3:1), and maltodextrin/gum Arabic (1:1) (w/w). The ratios refer to the carrier blend and not the concentration of the stock. The stock solution were prepared as followed: each carrier stock was dry mixed using a Multi Reax orbital shaker (Heidolph Instruments, Schwabach, Germany), hydrated in 100 mL of distilled water at room temperature for 10 h under constant stirring using a magnetic stirring plate, and mixed with 100 mL of leaf extract. Before mixing with carrier stocks, the dry matter content of the leaf extract produced from UAE in the “[Ultrasound-Assisted Extraction](#)” section was measured using a freeze dryer (Christ Alpha 1–2 LD, Martin Christ, Osterode, Germany) for 24 h. The weights were compared before and after freeze-drying. The spray drying of herbal tea leaf extracts was conducted using a laboratory-scale Büchi B-290 mini spray dryer (Flawil, St. Gallen, Switzerland). The parameters for spray drying were maintained as follows: aspirator capacity at 97%, a flow rate of 2.7 mL/min controlled by a peristaltic pump, and an inlet temperature of $130\text{ }^{\circ}\text{C}$, while the outlet temperature was around $70\text{--}89\text{ }^{\circ}\text{C}$. The powders were transferred to screw cap containers, flushed with nitrogen to prevent oxidation of phenolic compounds, sealed with parafilm, and stored at $4\text{ }^{\circ}\text{C}$ until analysed.

Powder Characterisation

Product and Process Yield

The production yield was calculated to measure the concentration ratio of TPC in powder to the total concentration in the extract (Pashazadeh et al., 2021). Production yield was calculated according to Eq. (1):

$$\text{Production Yield (\%)} = \frac{\text{TPC of powder}}{\text{TPC of extract}} \times 100 \quad (1)$$

Process yield was calculated to investigate the spray drying process yield following the method by Cegledi et al. (2022), according to Eq. (2):

$$\text{Process Yield (\%)} = \frac{M_p}{M_d + M_c} \times 100 \quad (2)$$

where M_p represents the mass (g) of the obtained powder, M_d is the amount of dry matter (g) present in the extract volume used for drying, and M_c refers to the mass (g) of the carrier material added to the extract prior to spray drying.

Total and Surface Phenolic Content (SPC) of Powder Samples

The TPC was measured as described above, with modifications to the extraction protocol of the phenolic compounds from the microencapsulated powders. Briefly, 200 ± 0.1 mg of powder was dispersed in 2 mL of ethanol/acetic acid/water (50:4:8, v/v/v), vortex-mixed for 1 min, sonicated in an ultrasonic bath (Soniclean 160TD, Mektronics, Seven Hills, NSW, Australia) for 20 min, and centrifuged at 5000 rpm and 20 °C using a Heraeus Multifuge X1R (Thermo Fisher Scientific, Waltham, MA, USA). Surface phenolic content (SPC) was determined according to the method of Cilek et al. (2012) with modifications. Briefly, 200 ± 0.1 mg of powder was dispersed in 2 mL of ethanol/methanol (50:50, v/v), vortex-mixed for 1 min, and centrifuged at 5000 rpm and 20 °C for 20 min using the same centrifuge parameters. The resulting supernatant was filtered through 0.45 µm syringe filters (AF3–3107–52, Phenomenex, Torrance, USA) prior to analysis.

Encapsulation Efficiency (EE)

The encapsulation efficiency (EE) is used to assess the ability of the carrier material to protect the phenolic compounds within the powder particles. It was calculated based on the SPC:TPC ratio as defined by Cilek et al. (2012) and according to Eq. (3):

$$EE (\%) = \frac{TPC - SPC}{TPC} \times 100 \quad (3)$$

where TPC represents the quantity of phenolic compounds in the powder (mg GAE/g), while SPC refers to the amount of unprotected phenolic compounds present in the external environment (mg GAE/g). The EE calculation indicates the percentage of phenolic compounds entrapped within the wall material and a higher EE (%) value signifies better protection for the powder.

Retention Efficiency (RE)

Retention efficiency (RE) was determined to evaluate the proportion of phenolic compounds retained in the final powder relative to the initial feed extract as described by Gayathry and John (2024) and according to Eq. (4):

$$RE (\%) = \frac{TPC_{\text{powder}}}{TPC_{\text{feed}}} \times 100 \quad (4)$$

Loading Capacity (LC)

Loading capacity (LC) was determined to quantify the phenolic compounds incorporated into the spray-dried powder relative to its total mass. LC complements EE and RE by describing the “payload” of the microencapsulates. The entrapped phenolics (EP) were first calculated from the difference between TPC and SPC, according to Eq. (5):

$$EP = TPC - SPC \quad (5)$$

where EP is the number of phenolics protected inside the carrier wall (mg GAE g⁻¹ powder).

The LC was then calculated as the entrapped phenolics per gram of carrier material used in the formulation, following the approach by Cegledi et al. (2022), with minor adjustments in terminology, according to Eq. (6):

$$LC = \frac{EP}{M_p} \quad (6)$$

where M_p is the mass of recovered powder (g). LC is expressed as mg GAE g⁻¹ powder.

Moisture Content, Water Activity, and Colour Analysis

The moisture content of the powders was determined according to AOAC Official Method 925.10. Briefly, 2 ± 0.01 g of sample was dried in an oven at 105 °C until a constant weight was achieved. The loss in weight was measured after drying, following standard gravimetric procedures. Water activity (a_w) was measured at room temperature using a water activity meter (aWLife, WATER

ACTIVITY ANALYSER, Steroglass, San Martino in Campo, Perugia, Italy) after a two-point calibration below and above the a_w of the samples. Colour parameters (L^* , a^* , b^*) of the powders were evaluated using a Chroma Meter CR-400 Konica Minolta (Sakai, Osaka, Japan) after calibration with the supplied white calibration plate (CR-A43). Derived colour indices were calculated from CIELAB values as follows, using the equations outlined by Pathare et al. (2013):

Browning Index (BI) was calculated according to Eqs. (7–8):

$$x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \quad (7)$$

$$BI = 100 \times \frac{(x - 0.31)}{0.172} \quad (8)$$

Whiteness Index (WI) and Yellow Index (YI) were calculated according to Pathare et al. (2013) using Eqs. (9–10):

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (9)$$

$$YI = \frac{142.86 \times b^*}{L^*} \quad (10)$$

Chroma (C^*) and Hue angle (h°) were determined using Eqs. (11) and (12) respectively:

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (11)$$

$$h^\circ = \arctan\left(\frac{b^*}{a^*}\right) \quad (12)$$

Bulk Density, Tapped Density, Carr Index, and Hausner Ratio

The bulk density was assessed by gently pouring the powder into a 10-mL graduated cylinder without applying any pressure. The volume and weight of the powder were recorded, and the bulk density was calculated by dividing the weight by the corresponding volume. Subsequently, the same graduated cylinder was manually tapped consistently for 5 min at a rate of 1 tap per 5 s on a flat surface to allow the powder to settle for measuring the tap density. After tapping, the reduced volume was recorded and used to calculate the tapped density. According to the study by Saifullah et al. (2016), flowability indices were calculated as follows using Eqs. (13–14). The Carr Index (CI) expresses compressibility, and the Hausner Ratio (HR) reflects interparticle friction. Together, these indices provide complementary information about powder flowability.

$$\text{Carr Index (\%)} = \frac{\text{Tapped density} - \text{Bulk density}}{\text{Tapped density}} \times 100 \quad (13)$$

$$HR = \frac{\text{Tapped density}}{\text{Bulk density}} \quad (14)$$

Water Solubility and Swelling Capacity

The water solubility (WS) and swelling capacity (SWC) were determined as described by Ahmed et al. (2010) with minor modifications. A 10% (w/v) powder dispersion was prepared in water, vigorously mixed and incubated at 37 °C for 1 h, followed by centrifugation (4000 rpm, 10 min, 4 °C) using a Heraeus Multifuge X1R (Thermo Fisher Scientific, Waltham, MA, USA). The supernatant was transferred to a pre-weighed aluminium dish, and the residue was weighed after oven-drying at 105 °C for 24 h. The WS was calculated as the percentage of total dry solids in the original measured sample, using Eq. (15).

$$\text{Water Solubility (\%)} = \frac{W_s}{W_0} \times 100 \quad (15)$$

where W_s is the weight of the dried supernatant and W_0 is the weight of the original sample.

$$\text{Swelling capacity (\%)} = \frac{W_r}{W_0 \times \left(1 - \frac{W_s}{W_0}\right)} \times 100 \quad (16)$$

SWC was calculated based on the weight of the solid pellet remaining after centrifugation using Eq. (16). where W_r is the weight of the insoluble sample.

Determination of ζ -potential and pH Measurements

The zeta (ζ) potential was measured using a Nano ZS Zeta-sizer (ZS90, Malvern Instruments Ltd., UK). Powder dispersions of 0.1% w/v were loaded into capillary cells and equilibrated at 25 °C before measurement. The pH was measured by reconstituting the powder in a 5% w/v dispersion before measurement using a pH meter (pH Cube, Model CUBESZ, TPS, Brendale, Australia).

2-Diphenyl-1-picrylhydrazyl (DPPH) Radical Scavenging Activity

The antioxidant activity of the microencapsulated powders was evaluated using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity assay, performed as described by Nenadis et al. (2007) with modifications. Extraction of powder samples was conducted according to the “Total and Surface Phenolic Content (SPC) of Powder

Samples” section. Extracts (100 μL) were mixed with 900 μL of 100 μM DPPH solution, mixed and incubated in darkness for 30 min, and the absorbance was measured at 517 nm (Shimadzu UV-1800, Shimadzu Corporation, Kyoto, Japan), using 100% methanol as reference. Blank samples were prepared using 100% methanol, and a standard curve using Trolox (0–1000 $\mu\text{g}/\text{mL}$) was prepared. Results are expressed as mg Trolox equivalents (TE)/g.

Field Emission Scanning Electron Microscopy (FE-SEM) Imaging

Field-emission scanning electron microscopy (FE-SEM) was employed to examine the morphology and surface topography of the powders. The particles were dispersed onto double-sided carbon tape mounted on an SEM stub. Prior to imaging, the samples were coated with a 15-nm platinum layer using a Quorumtech 150TS platinum sputter coater (Quorum Technologies, Lewes, United Kingdom) under Argon gas. Finally, the samples were imaged using a JEOL 7100 FE-SEM (JEOL Ltd., Tokyo, Japan) with a voltage set at 3 kV and with a probe current of 8 pA.

Phenolic Compound Quantification using LC–MS/MS

Targeted phenolic compound profiling was conducted on a Waters ACQUITY™ I-Class UPLC (Binary Solvent Manager + Sample Manager FTN) coupled to a Xevo™ TQ-S micro-triple–quadrupole mass spectrometer (Waters Corporation, Milford, MA, USA) according to the method by Ekanayake et al. (2025) with no modifications. Separation was achieved on an ACQUITY™ Premier BEH C18 column (2.1 $\times$ 150 mm, 1.7 μm) maintained at 30 °C. The mobile phases were Milli-Q water containing 0.1% formic acid (A) and methanol containing 0.1% formic acid (B), delivered at 0.20 mL min^{-1} . The gradient increased from 20 to 98% B over 10 min, was held for 3 min, and then returned to 20% B for re-equilibration, giving a total run time of 16 min. Samples were injected at 1.0 μL . Detection was performed in negative electrospray ionisation mode using multiple reaction monitoring. External mixed-standard calibration curves ranged from 0.25 to 20.0 mg L^{-1} and showed coefficients of determination greater than 0.99.

Statistical Analysis

Ultrasound runs were conducted in triplicate for each experimental condition, with technical triplicates performed for TPC determination. All spray-drying runs were performed in duplicate. Powder properties were determined in technical duplicate for the individual spray drying runs, with the exception of moisture content, water activity, and colourimetric parameters, which were analysed in triplicate. Results

are expressed as mean $\pm$ standard deviation. One-way analysis of variance (ANOVA), followed by Tukey’s multiple-comparisons post hoc test, was performed using IBM SPSS Statistics (version 29.0.1.0; IBM Corp., Armonk, NY, USA). Statistical significance was defined as $p < 0.05$.

Contour plots for TPC and endpoint slurry temperature were generated in Python (v3.11) (Rossum, 2009) using pandas (v2.2) (McKinney, 2010), NumPy (v1.26) (Harris et al., 2020), SciPy (v1.11) (Virtanen et al., 2020), and Matplotlib (v3.8) (Hunter, 2007). For each ratio, TPC and endpoint temperature for LM and RM were modelled as a function of time and amplitude. A regular 30 $\times$ 30 grid was constructed across the experimental factor ranges, and intermediate values between design points were interpolated by cubic interpolation. Contour maps were rendered with 30 levels. A single global colour scale was applied for endpoint temperature surfaces, while TPC surfaces were scaled independently. The interpolated surfaces were used exclusively for visual representation of trends within the experimental data, and no extrapolation beyond the tested parameter space was performed.

Results and Discussion

Establishing UAE Parameters for Phenolic Recovery

The first stage of this study focused on establishing ultrasound-assisted extraction (UAE) experimental conditions for recovering phenolic compounds from lemon myrtle (LM) and river mint (RM) leaves. This was necessary to define a reliable extraction baseline before subsequent spray-drying and microencapsulation trials. The parameters evaluated were extraction time, sonication amplitude, and material-to-solvent ratio because these variables are known to influence cavitation intensity, solvent penetration, mass transfer, and the release of phenolic compounds from plant tissues (Siddiqui et al., 2025). Endpoint temperature was also recorded as a process outcome. Total phenolic content (TPC) was used as the primary response variable to identify extraction conditions that maximised phenolic recovery.

Across LM and RM infusions, increasing sonication time (10–20 min) and amplitude (20–30%) improved TPC, while the 1:20 (m/v) ratio outperformed 1:30 (m/v) under equivalent conditions (Fig. 1A–D). The highest-performing tested condition for both LM and RM was 20 min, 30% amplitude, 1:20 (m/v). These UAE parameters yielded 25.10 ± 0.61 mg GAE/g for LM and 51.98 ± 4.28 mg GAE/g for RM using leaf material for method development.

The beneficial effect of longer sonication time in increasing phenolic recovery in the present study has also been observed with indirect UAE of LM using a bath sonicator (Saifullah et al., 2021), and direct UAE of *Mentha piperita*

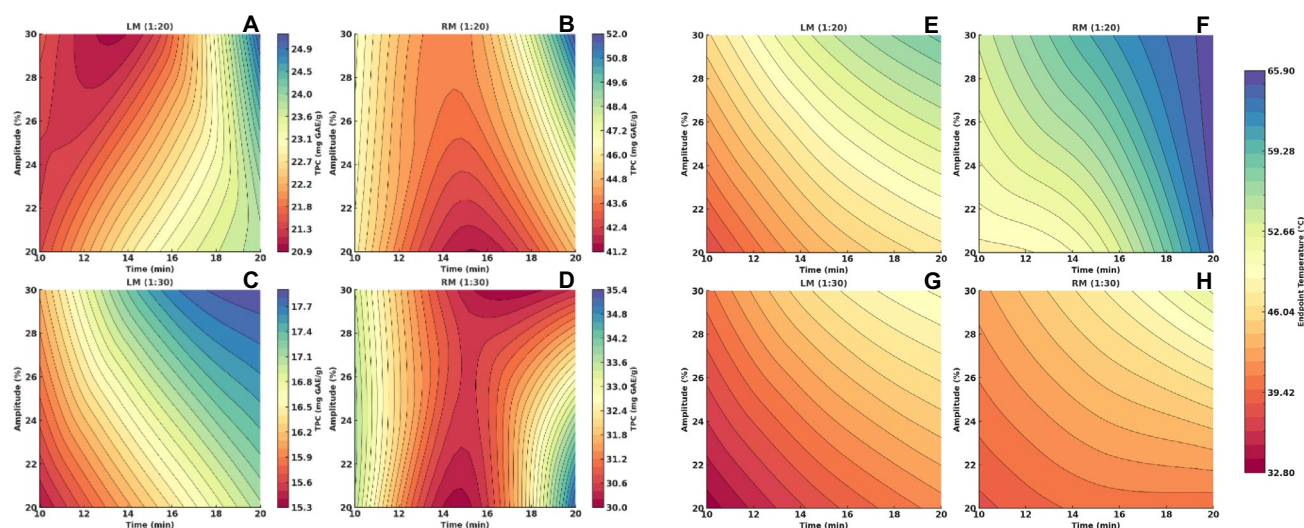


Fig. 1 Two-dimensional interpolated contour plots showing total phenolic content (TPC) and endpoint slurry temperature during ultrasound-assisted extraction of lemon myrtle (LM) and river mint (RM). Panels show the effects of extraction time (10–20 min) and sonication amplitude (20–30%) at material-to-solvent ratios of 1:20 and 1:30 (w/v). TPC is shown for (A) LM at 1:20, (B) RM at 1:20, (C) LM at 1:30, and (D) RM at 1:30. Endpoint slurry temperature is shown for (E) LM at 1:20, (F) RM at 1:20, (G) LM at 1:30, and (H)

RM at 1:30. Colour intensity represents the mean TPC or endpoint slurry temperature interpolated between the measured experimental combinations for descriptive visualisation within the tested parameter space. Endpoint temperature was not independently controlled and is presented descriptively to illustrate ultrasound-induced heating under the tested conditions. No extrapolation beyond the tested experimental conditions was performed

(peppermint) using a probe sonicator (Sobti et al., 2023). In addition, a positive correlation between higher amplitude and increased TPC was also consistent with these studies (Saifullah et al., 2021; Sobti et al., 2023).

Endpoint temperatures recorded after sonication increased with both extraction time and amplitude (Fig. 1E–H). At the most intense condition (20 min, 30% amplitude), endpoint temperatures reached 58.3 °C for LM and 65.4 °C for RM, compared with approximately 33–38 °C at the mildest condition (10 min, 20%). This increase is consistent with heat generation arising from acoustic energy dissipation during high-intensity sonication (Ferraz & Silva, 2025). However, temperature was not independently controlled during the UAE, therefore, the thermal contribution cannot be separated from the effects of sonication time and amplitude. Increased temperature may have enhanced solvent penetration, diffusion and mass transfer and contributed to the higher phenolic recovery observed under the more intensive UAE conditions. Furthermore, only endpoint temperatures were recorded, and the temperature profile throughout sonication was not monitored. As such the UAE screening results should be interpreted as the combined response of the tested sonication conditions and their associated process heating, rather than as the isolated effects of time and amplitude. Importantly, the maximum temperature recorded was 65.4 °C which is favourable for UAE of phenolic compounds where it has been previously reported that degradation starts to occur quickly beyond 80 °C (Antony & Farid, 2022).

The findings support 20 min, 30% amplitude, and 1:20 (m/v) as a simple and reproducible, water-based UAE process for preparing phenolic-rich feed extracts of leaf powder for downstream spray drying. However, further optimisation could be conducted to maximise recovery using a larger test set with validation samples.

For the final extract feed solution that would be used to generate herbal infusion microencapsulates, fresh material of LM was sourced from a new organic supplier while the original source of RM was retained. After applying the selected UAE parameters listed above, a final yield of 64.35 ± 2.72 mg GAE/g (LM) and 37.67 ± 2.40 mg GAE/g (RM) was achieved. The higher TPC observed for LM compared to its optimisation set can be explained by biological and processing variability between harvests, including differences in supplier, collection lot, leaf maturity, and drying regime. Such factors are well known to influence phenolic content in herbal leaves, with seasonal and post-harvest conditions often driving significant variability in secondary metabolite levels of Australian native plants (Konczak et al., 2010).

Bench-Scale Spray Drying Performance: Production and Process Yield

Following the selection of UAE conditions for phenolic recovery, the next stage of the study evaluated whether the resulting LM and RM herbal extracts could be converted

into acceptable food powders using a spray-dried microencapsulation process with combinations of maltodextrin and gum Arabic as the wall material. The ratios selected were 3:1, 1:1, and 1:0 maltodextrin: gum Arabic.

Production yield was used to evaluate phenolic recovery following spray drying, based on TPC, while process yield was used to assess powder recovery relative to the total solids processed (Tontul & Topuz, 2017). These outputs are presented in Fig. 2. Across all wall material blends, production yields ranged from 72.00 to 78.92% for LM, while RM ranged from 62.09 to 65.63%. Process yields varied between 53.37–69.83% for LM and 68.76–70.65% for RM. It is

noted that the product and process yield of the RM powder has a smaller range in final percentage, regardless of wall material, whereas a greater range was observed for the LM powders.

It has been reported that a spray drying yield of over 50% is considered successful and that yields in the range of 50–75% are acceptable for bench-scale Buchi spray dryer systems (Gallo et al., 2015). The process yields obtained in the present study were comparable to those reported for spray-dried phenolic extracts from sugar maple leaves. In that study, mass-based microencapsulation yields of $62.86 \pm 0.73\%$ and $65.08 \pm 1.83\%$ were obtained for extracts

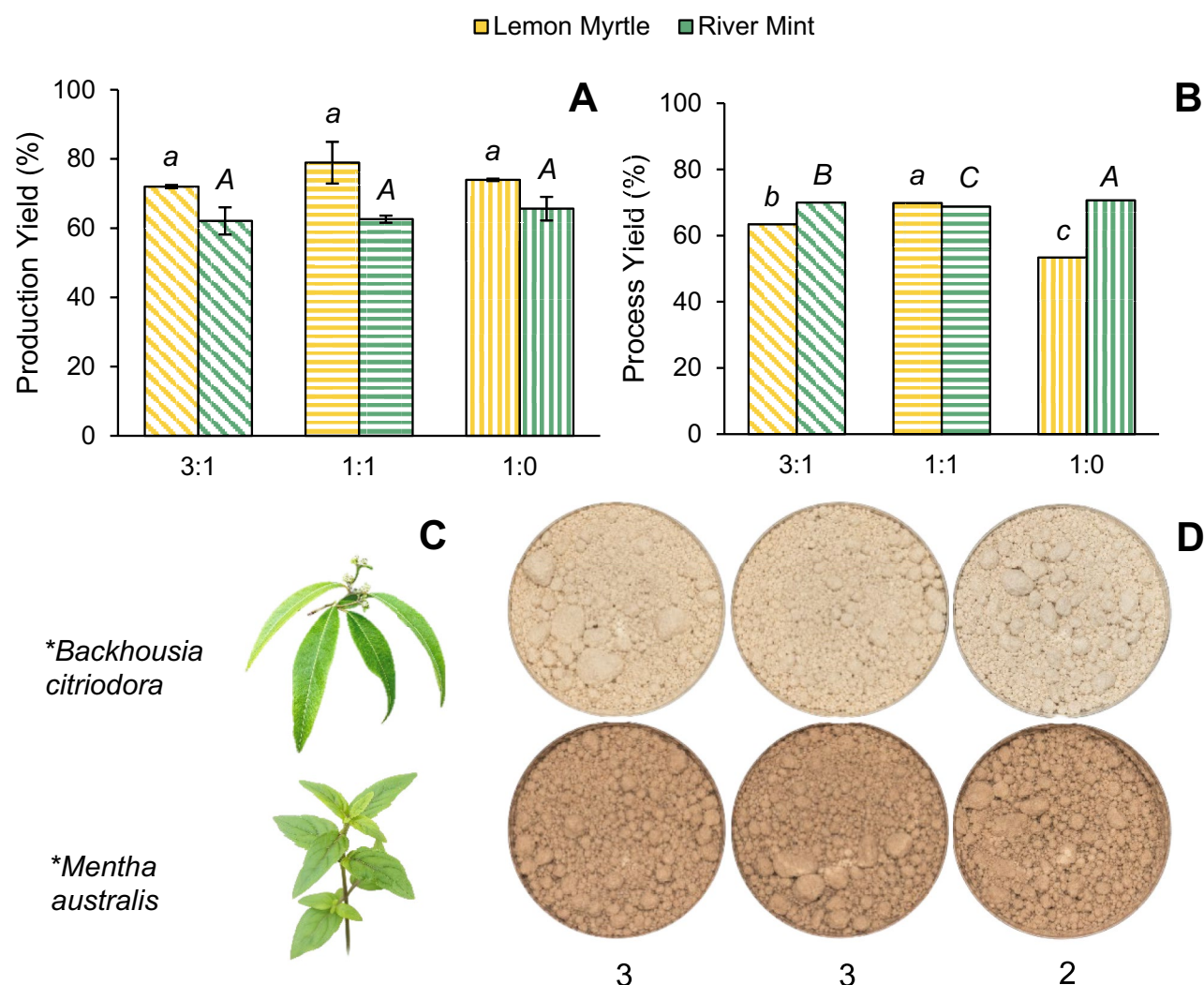


Fig. 2 Production and process yield of spray-dried lemon myrtle and river mint herbal infusions using different wall material ratios. (A) Production yield (%) of lemon myrtle and river mint powders prepared using maltodextrin:gum Arabic ratios of 3:1, 1:1, and 1:0. Values are presented as mean $\pm$ standard deviation. (B) Process yield (%) shown as a comparative bar charts across the same wall material ratios. (C) Pictures of lemon myrtle and river mint. (D) Pictures of powders produced from spray drying using different wall material

ratios (lemon myrtle top and river mint bottom). Different lowercase letters indicate significant differences among wall material ratios for lemon myrtle, whereas different uppercase letters indicate significant differences among wall material ratios for river mint, as determined using Tukey's post hoc test ($p < 0.05$). Error bars for Process Yield were negligible (less than 1% SD) and therefore not included in the figure

prepared using homogenisation combined with UAE and conventional maceration, respectively (Yeasmen & Orsat, 2024). These values fall within the process-yield range observed for LM in the present study, whereas RM produced slightly higher and more consistent process yields. It is expected that differences among the botanical systems will reflect variation in feed solids, extract composition, carrier interactions, and deposition losses during spray drying; however, these metrics provide a useful benchmark for phenolic-rich leaves. During spraying, some powder loss can be attributed to wall deposition and fines entrained in the exhaust filter (Bhandari et al., 2023). This can happen especially when sugars are present in the formulations (Baldelli et al., 2024; Keshani et al., 2015). Therefore, the yields achieved in the present study were satisfactory for bench-scale processing. The selected operating conditions (inlet temperature 130 °C, aspirator 97%, feed rate 2.7 mL/min) therefore provide a practical bench-scale baseline for reproducible powder production of Australian native leaf-water infusions.

Effect of Wall Material Composition on Total Phenolic Content Retention Metrics

Although the production and process yield results in Fig. 2 demonstrate that LM and RM extracts could be successfully converted into powders, these measurements don't describe phenolic retention within the carrier matrix. This distinction is important for leaf-derived herbal extracts, which contain diverse phenolic metabolite profiles that can differ in polarity, molecular size, and affinity for carrier materials (Chen et al., 2025). As total phenolic reducing content provides a measure for estimating the phenolic-rich reducing capacity of botanical materials and their potential nutraceutical relevance (Nastasi, 2025), encapsulation-related metrics based on this response were evaluated to determine how maltodextrin and gum Arabic wall material ratios influenced phenolic retention, surface localisation, and loading (Fig. 3). A quick performance summary of the phenolic retention metrics between species is presented in Fig. 3F.

Encapsulation efficiency (EE) differed strongly between species, ranging from 59.71 to 68.02% for LM and 80.60–86.50% for RM. RM powders consistently showed higher EE across all wall material combinations, indicating more effective incorporation of phenolic compounds within the carrier matrix. Despite this species-dependent difference, the 1:1 maltodextrin gum Arabic ratio produced the highest EE for both extracts. In comparison, a study by Saifullah et al. (2024) reported an EE of $99.19 \pm 0.03\%$ for freeze-dried LM extracts encapsulated with maltodextrin and gum Arabic; however, this higher value is likely influenced by the application of freeze-drying, which can produce very high EE for phenolic compounds due to reduced thermal and

evaporative stresses compared with spray drying (Laureanti et al., 2023). The improved EE observed in gum Arabic-containing formulations can be attributed to gum Arabic's film-forming capacity, high solubility, emulsifying properties, and proteinaceous fractions, which may collectively reduce outward diffusion of hydrophilic phenolics and enhance their retention during solvent evaporation in the spray-drying process (Laureanti et al., 2023).

Surface phenolic content (SPC), retention efficiency (RE), entrapped phenolics (EP) and loading capacity (LC) were used as complementary indicators of phenolic distribution and retention within the spray-dried powders (Fig. 3B–E). While EE describes the proportion of phenolics retained within the carrier matrix, SPC indicates the amount remaining on the particle surface, where compounds are more susceptible to oxidation and surface-mediated degradation. RE estimates the proportion of phenolics retained after drying, whereas EP and LC describe the protected phenolic content relative to the final powder and carrier material, respectively. SPC was consistently higher in LM powders than RM powders, with LM showing approximately three-fold greater surface-associated phenolics (Fig. 3C). The lowest SPC values occurred in the 1:1 formulations, indicating that higher gum Arabic content limited phenolic surface migration during the spray-drying process. RE ranged from 68.8 to 74.9% for LM and 61.3–70.4% for RM. EP and LC were highest in 1:1 powders, reaching 31.9–32.5 mg GAE/g powder and 23.5–24.0 mg GAE/g for EP respectively, while RM powders showed lower EP and LC values despite higher EE. From a total phenolic perspective, Fig. 3 shows that LM powders retained a higher overall phenolic load than RM powders, despite lower encapsulation efficiency. However, this bulk response should not be assumed to reflect the behaviour of individual phenolic compounds. To examine this compound-level behaviour, gallic acid and rosmarinic acid were assessed as species-relevant biomarkers in the following section.

Retention Performance of Biomarkers: Gallic acid and Rosmarinic acid

The functional value of herbal tea powders depends not only on total phenolic content, but also on the retention and final loading of key phenolic biomarkers after processing (Sinija et al., 2007). For LM and RM, gallic acid and rosmarinic acid were quantified using LC–MS/MS because they represent relevant marker compounds and major phenolic constituents associated with these botanical sources (Saifullah et al., 2019; Tang et al., 2016). Their encapsulation behaviour is shown in Fig. 4, together with predicted physico-chemical properties generated using structure–function relationship models (Daina et al., 2017).

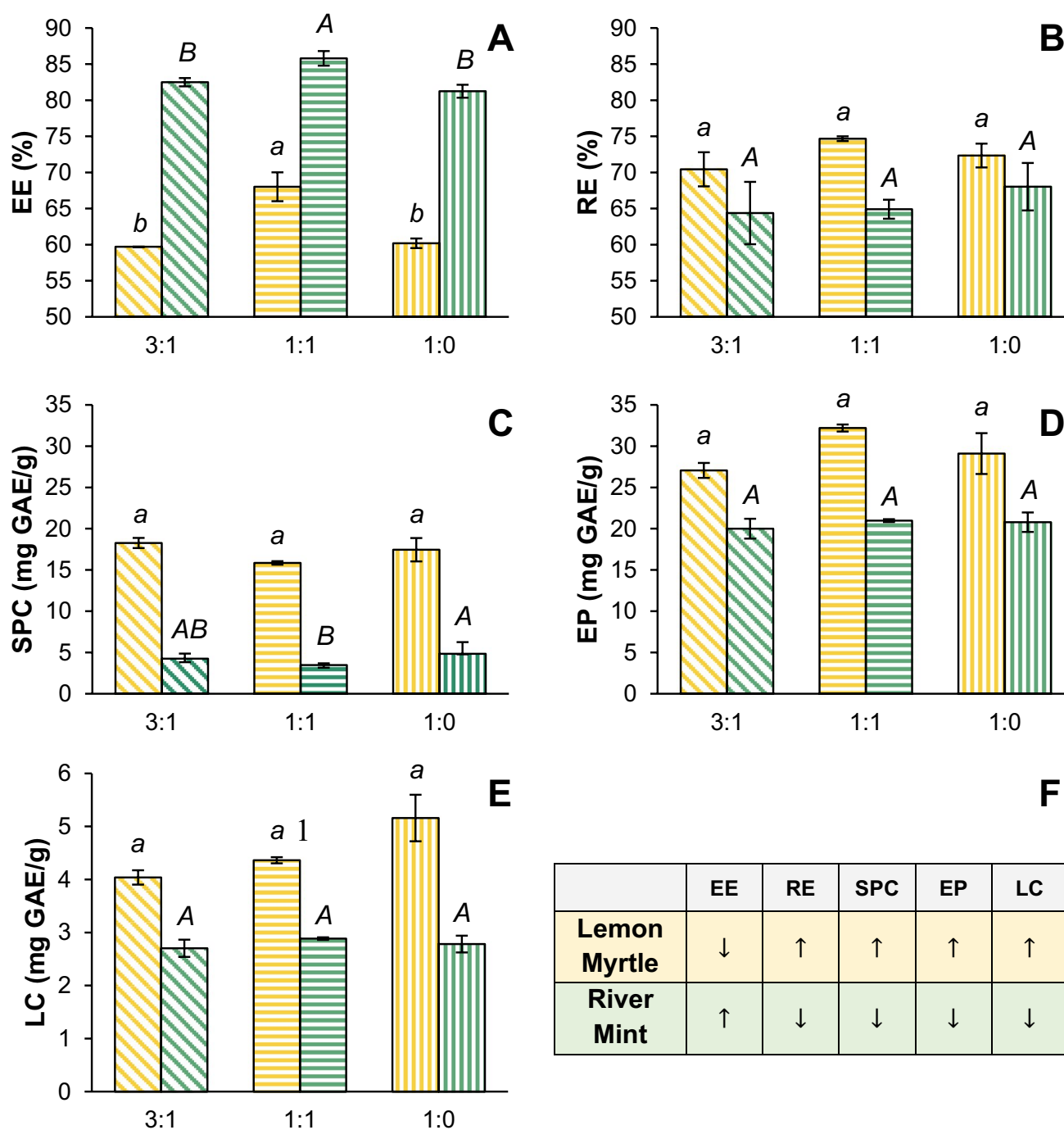


Fig. 3 Phenolic retention and encapsulation performance of spray-dried lemon myrtle (yellow) and river mint (green) herbal infusions. Effect of maltodextrin: gum Arabic wall material ratio on (A) encapsulation efficiency (EE), (B) retention efficiency (RE), (C) surface phenolic content (SPC), (D) encapsulated phenolics (EP), (E) loading capacity (LC) of spray-dried lemon myrtle and river mint powders, and (F) performance summary. Wall material ratios are pre-

sented as 3:1, 1:1 and 1:0 maltodextrin: gum Arabic. Values are presented as mean $\pm$ standard deviation. Within each panel, different lowercase letters indicate significant differences among wall material ratios for lemon myrtle, whereas different uppercase letters indicate significant differences among wall material ratios for river mint, as determined using Tukey's post hoc test ($p < 0.05$)

Gallic acid and rosmarinic acid both showed high compound-specific EE, demonstrating that spray drying retained a large proportion of each marker compound within the

powder matrix (Fig. 4A and B). However, the two compounds differed substantially in their formulation response. Gallic acid EE in LM ranged from approximately 78–85%,

with the maltodextrin-only formulation producing the highest retention. In contrast, rosmarinic acid EE in RM was higher overall, ranging from approximately 88–96%, with the 1:1 maltodextrin:gum Arabic formulation producing the strongest EE response. This pattern supports a specific role for gum Arabic in improving the proportional retention of rosmarinic acid, likely through stronger carrier–compound interactions. Rosmarinic acid has greater molecular size, polarity, and conformational flexibility than gallic acid (Fig. 4G and H), providing more potential sites for hydrogen bonding and interaction with carbohydrate- and proteinaceous domains in gum Arabic (Kanakidi et al., 2022). Gallic acid, as a smaller hydroxybenzoic acid, was retained most effectively in the maltodextrin-only matrix, suggesting that its encapsulation was less dependent on the additional emulsifying and interfacial properties of gum Arabic (Xiao et al., 2022).

Importantly, although EE is useful for assessing the proportional retention of compounds of interest during encapsulation, it doesn't reflect the final phenolic concentration of the powder. Although, rosmarinic acid showed higher EE than gallic acid, the EP and LC were greater for gallic acid in LM (Fig. 4C–F). The maltodextrin-only LM formulation produced the highest gallic acid EP and LC, reaching approximately 31% EP and 5.5 mg GAE/g LC. By comparison, rosmarinic acid EP and LC in RM remained much lower, with the highest values in the maltodextrin-only formulation reaching approximately 2.1% EP and 0.29 mg GAE/g LC. Therefore, the LC of gallic acid in LM was approximately an order of magnitude higher than the LC of rosmarinic acid in RM. This is a meaningful formulation outcome because LC reflects the amount of primary bioactive agent delivered per unit mass of powder, whereas EE only describes proportional retention relative to the starting material. It is noted that the gallic acid LC determined by LC–MS/MS was similar to, but lower than, the TPC of the LM powder. This may occur as a result of the non-specificity and analytical limitations of the TPC assay (Nastasi, 2025). This further demonstrates the value of biomarker-specific quantification for assessing the retention of key phenolic compounds in encapsulated powders and the need to move beyond reliance of the TPC assay for calculating powder performance metrics.

In practical terms and for nutraceutical product development, this means that the LM maltodextrin-only powder may provide greater singular bioactive-compound delivery per gram of powder, whereas the RM 1:1 formulation may be more effective where proportional retention of rosmarinic acid is the primary objective.

Powder Functionality

The physical functionality of the spray-dried powders was evaluated to determine their suitability as reconstitutable herbal powders. In addition, TPC and DPPH activity were

used to assess the nutraceutical density of the final dried products as indicators of reducing and scavenging activity respectively. While phenolic retention is central to their functional value as a nutraceutical product, practical product performance also depends on the stability, appearance, handling behaviour, and aqueous reconstitution properties of the powder system. Therefore, moisture content and a_w provide indicators of storage stability, colour parameters reflect visual quality and potential pigment-related changes, and density and flowability describe how the powders may behave during filling, transport and consumer use (Bhandari et al., 2023; Quek et al., 2007; Suhag et al., 2024). Regarding reconstitution, zeta potential, electrophoretic mobility, conductivity, and pH describe the charge behaviour and dispersion environment of the powders in water (Fang et al., 2007), while water solubility and swelling index capture the extent to which the dried matrix dissolves, hydrates, or expands upon contact with water.

These measurements are relevant for herbal powder systems because phenolic compounds and carrier materials can differ in solubility, ionisable functional groups, and interaction behaviour which may influence the uniformity and stability of the reconstituted powders in a beverage system (Cano-Sarmiento et al., 2018). The physicochemical, flow, and reconstitution properties of the spray-dried powders are presented in Table 1.

Values are presented as mean $\pm$ standard deviation. *LM*, lemon myrtle; *RM*, river mint. Formulation ratios refer to maltodextrin: gum Arabic wall material ratios. *Aw*, water activity; *TPC*, total phenolic content; *GAE*, gallic acid equivalents; *DPPH*, 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity; *TE*, Trolox equivalents. *L**, lightness; *a**, red–green coordinate; *b**, yellow–blue coordinate; *C**, chroma; *Hue*, hue angle; *BI*, Browning index; *WI*, Whiteness index; *YI*, Yellowness index. Zeta potential, electrophoretic mobility, conductivity and pH were measured after powder reconstitution in water. Carr Index and Hausner ratio were calculated from bulk and tapped density and used as indicators of powder flowability. Different lowercase letters indicate significant differences among wall material ratios for lemon myrtle, whereas different uppercase letters indicate significant differences among wall material ratios for river mint, as determined using Tukey's post hoc test ($p < 0.05$).

Moisture, Stability, and Reconstitution in a Beverage Model

Moisture content differed between wall material formulations, with maltodextrin-only powders recording the lowest values for both species. LM moisture increased from 5.69% in the 1:0 formulation to 9.37% and 8.78% in the 1:1 and 3:1 formulations, respectively, while RM powders ranged

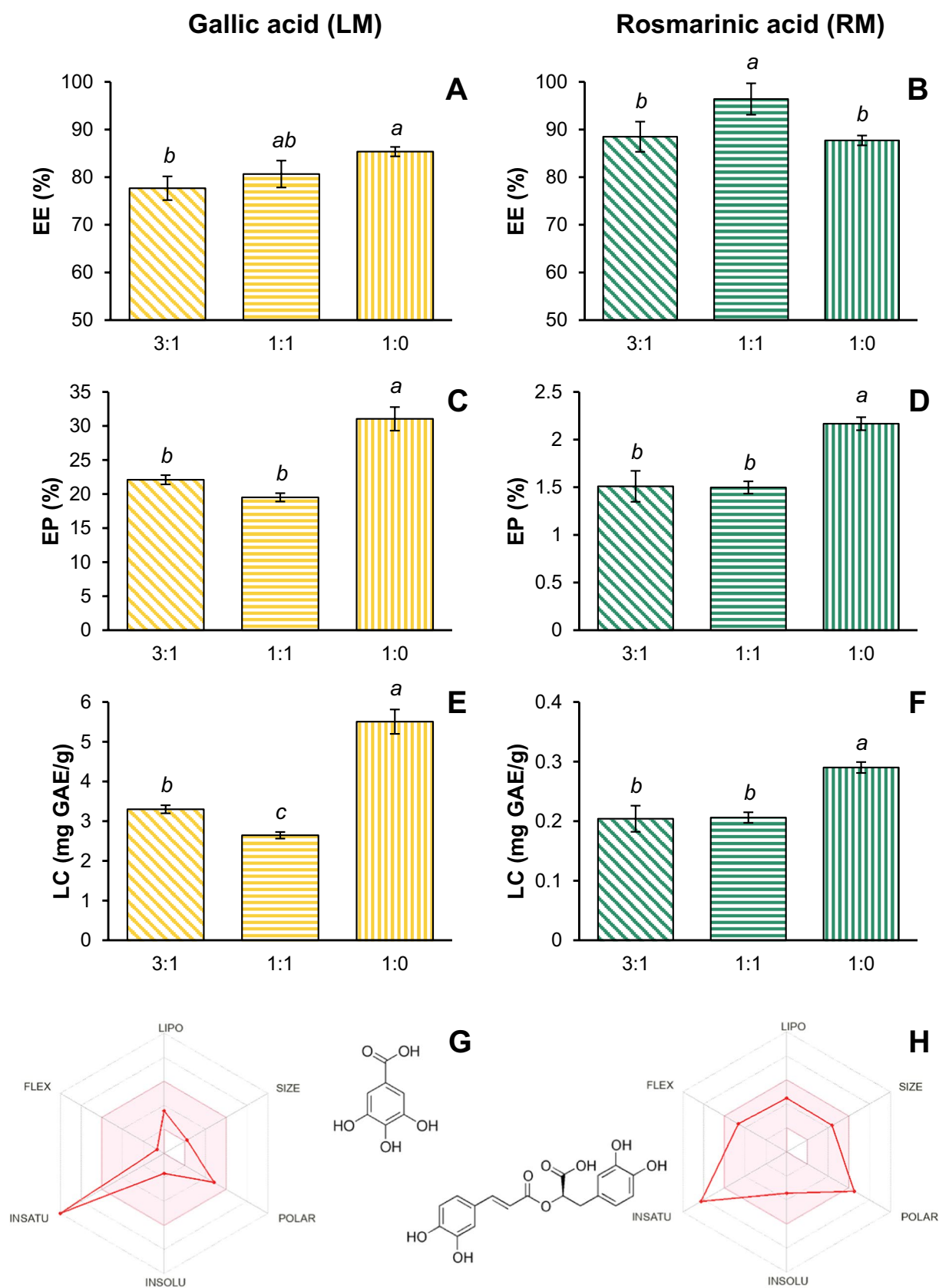


Fig. 4 Compound-specific retention and predicted physicochemical properties of gallic acid and rosmarinic acid in spray-dried lemon myrtle and river mint powders. Compound-specific encapsulation responses were evaluated for gallic acid in lemon myrtle (LM) and rosmarinic acid in river mint (RM) powders produced using maltodextrin Arabic wall material ratios of 3:1, 1:1 and 1:0. (A, B) Encapsulation efficiency (EE), (C, D) entrapped phenolics (EP), and (E, F) loading capacity (LC) of gallic acid and rosmarinic acid, respectively. Values are presented as mean $\pm$ standard deviation. (G, H) SwissADME bioavailability radar plots and molecular structures of gallic acid and rosmarinic acid, respectively, showing predicted physicochemical space across lipophilicity (LIPO), size (SIZE), polarity (POLAR), insolubility (INSOLU), saturation (INSATU), and flexibility (FLEX). The pink region represents the optimal physicochemical range defined by the SwissADME model. Within each panel, different lowercase letters indicate significant differences among wall material ratios for lemon myrtle and river mint, as determined using Tukey's post hoc test ($p < 0.05$)

from 8.06% in the 1:0 formulation to 9.14–9.23% in the gum Arabic-containing blends (Table 1). These results suggest that gum Arabic increased water retention in the final powders, most likely due to its hydrophilic polysaccharide structure and greater water-binding capacity (Al-Hamayda et al., 2023). Despite these differences in moisture content, a_w remained low across all samples, ranging from 0.42 to 0.47. These values are below the commonly accepted threshold of 0.60 for microbial proliferation (Syamaladevi et al., 2016), indicating that all powders produced in this study may be suitable for long-term storage in sealed plastic packaging (Shishir et al., 2017).

The moisture contents observed in the present study were higher than those reported for spray-dried phenolic extracts from sugar maple leaves, where maltodextrin–gum Arabic microparticles contained 3.87–4.38% moisture (Yeasmen & Orsat, 2024). Yeasmen and Orsat (2024) associated maltodextrin–gum Arabic carriers with effective moisture control, whereas gum Arabic-containing formulations in the present study retained more moisture than the corresponding maltodextrin-only powders. This difference indicates that the influence of gum Arabic on residual moisture is also dependent on the botanical matrix and may also be affected by feed-solids composition, carrier-to-extract ratio, atomisation behaviour, and drying conditions.

The reconstitution properties of the spray-dried powders were evaluated to determine their suitability for beverage-style solubilisation. Water solubility was high across all formulations, ranging from 85.3 to 88.4%, indicating that the powders were largely dispersible in water despite differences in species and wall material ratio. These values were slightly lower than the 89.80–92.05% reported for spray-dried sugar maple leaf microparticles (Yeasmen & Orsat, 2024), but still indicate a high degree of aqueous reconstitution. Swelling capacity showed greater variation, ranging from 274–309% for LM to 281–386% for RM. The higher swelling capacity of the RM 1:0 formulation may reflect greater hydration

and matrix expansion of the maltodextrin-rich system when combined with RM extract solids (Kanakidi et al., 2022; Marchev et al., 2021; Xiao et al., 2022), although this response was reduced in gum Arabic-containing formulations. These results show that the powders did not simply dissolve as low-molecular-weight solids but also underwent hydration and structural expansion during reconstitution.

Following dispersion in water, zeta potential, electrophoretic mobility, conductivity and pH were measured to assess the charge behaviour and aqueous dispersion environment of the powders (Table 1). All reconstituted powders produced negatively charged dispersions, although the magnitude of zeta potential differed between species and wall material systems. Gum Arabic-containing LM formulations showed substantially more negative zeta potential values than the maltodextrin-only formulation. Because zeta potential reflects the electrical properties of the particle–water interface, these differences provide indirect evidence of the wall material exposed at the particle surface (Předota et al., 2016). The more negative values of the gum Arabic-containing formulations are consistent with greater surface exposure of anionic gum Arabic components. This greater surface charge can be attributed to the anionic carboxyl groups of gum Arabic, which increase electrostatic repulsion in the reconstituted dispersion, whereas maltodextrin is comparatively neutral and contributes limited charge stabilisation (Dickinson, 2003). RM powders showed more consistently negative zeta potential values across the three wall material ratios.

Phenolic and Antioxidant Density of the Final Powders

TPC and DPPH activity were expressed per gram of powder to assess the nutraceutical density of the final dried products. LM powders had higher TPC values than RM powders, ranging from 45.33–48.05 mg GAE/g compared with 24.25–25.63 mg GAE/g for RM (Table 1). This higher final phenolic density should be interpreted in the context of the starting feed extracts, which contained 64.35 ± 2.72 mg GAE/g for LM and 37.67 ± 2.40 mg GAE/g for RM. Accordingly, the greater TPC of the LM powders primarily reflects their higher initial phenolic load and should not be interpreted as superior encapsulation performance. DPPH activity did not follow the same pattern as TPC. The highest DPPH value was observed in LM 3:1, despite this formulation not having the highest TPC. RM powders also showed measurable antioxidant activity, with the RM 1:0 formulation recording higher DPPH activity than the RM 1:1 formulation despite similar TPC values. From a product-development perspective, the higher initial phenolic content of the LM feed translated into powders with greater final phenolic density per gram, whereas RM powders showed stronger proportional encapsulation performance and rosmarinic acid retention. Furthermore, higher TPC per gram

Table 1 Physicochemical properties of spray-dried lemon myrtle and river mint powders produced with different maltodextrin: gum Arabic ratios

Parameters	LM 3:1	LM 1:1	LM 1:0	RM 3:1	RM 1:1	RM 1:0AQ
Stability and Reconstitution-related Properties						
Moisture (%)	8.78 ± 0.46a	9.37 ± 0.22a	5.69 ± 0.40b	9.23 ± 0.46A	9.14 ± 0.43A	8.06 ± 0.38B
Water activity (aw)	0.46 ± 0.01a	0.47 ± 0.01a	0.47 ± 0.01a	0.46 ± 0.01A	0.43 ± 0.01B	0.42 ± 0.01B
Water Solubility (%)	85.6 ± 2.8a	85.7 ± 2.6a	86.9 ± 1.2a	85.3 ± 4.0A	85.6 ± 4.2A	88.4 ± 1.3A
Swelling Capacity (%)	309 ± 53a	274 ± 35a	281 ± 37a	281 ± 37A	314 ± 73A	386 ± 74A
pH	4.87 ± 0.02a	4.89 ± 0.02a	4.82 ± 0.05a	5.45 ± 0.03B	5.31 ± 0.02C	5.31 ± 0.02A
Zeta Potential (mV)	−21.43 ± 2.68b	−22.10 ± 1.14b	−4.17 ± 0.34b	−24.37 ± 2.67B	−21.87 ± 2.18B	−16.07 ± 0.93A
Mobility (μm cm/Vs)	−1.68 ± 0.21b	−1.73 ± 0.09b	−0.33 ± 0.03a	−1.90 ± 0.20B	−1.71 ± 0.017B	−1.26 ± 0.07A
Conductivity (mS/cm)	0.052 ± 0.001b	0.056 ± 0.001a	0.043 ± 0.001c	0.052 ± 0.001B	0.077 ± 0.001A	0.056 ± 0.001B
Phenolic and Antioxidant Content						
TPC (mg GAE/g)	45.33 ± 1.52a	48.05 ± 0.21a	46.55 ± 1.06a	24.25 ± 1.63A	24.45 ± 0.49A	25.63 ± 1.24A
DPPH (mg TE/g)	10.52 ± 0.76b	3.31 ± 0.30b	4.02 ± 0.29a	5.07 ± 0.72B	3.48 ± 0.05C	6.26 ± 0.16A
Colour Properties						
L*	92.19 ± 0.10b	92.03 ± 0.12b	93.00 ± 0.02a	77.37 ± 0.05B	76.63 ± 0.08C	78.51 ± 0.06A
a*	−0.33 ± 0.03a	−0.36 ± 0.01a	−0.28 ± 0.02a	3.54 ± 0.03B	3.73 ± 0.02A	3.11 ± 0.03C
b*	8.95 ± 0.03b	9.37 ± 0.06a	8.50 ± 0.03c	15.65 ± 0.05A	15.40 ± 0.01B	15.64 ± 0.05A
C*	8.96 ± 0.03b	9.38 ± 0.06a	8.50 ± 0.03c	16.04 ± 0.04a	15.85 ± 0.01b	15.94 ± 0.06ab
Hue (°)	177.89 ± 0.18a	177.80 ± 0.07a	178.15 ± 0.15a	12.75 ± 0.14B	13.60 ± 0.08A	11.25 ± 0.07C
BI	9.59 ± 0.07b	10.07 ± 0.05a	9.03 ± 0.05c	25.22 ± 0.03A	25.28 ± 0.03A	24.39 ± 0.12B
WI	88.12 ± 0.09b	87.69 ± 0.03c	88.98 ± 0.01a	72.26 ± 0.02B	71.76 ± 0.07C	73.24 ± 0.08A
YI	13.87 ± 0.06b	14.54 ± 0.08c	13.06 ± 0.04a	28.89 ± 0.07A	28.71 ± 0.06AB	28.45 ± 0.11B
Flow and Packing Properties						
Carr Index (%)	44.07 ± 1.79a	43.16 ± 1.20a	39.69 ± 1.73a	46.73 ± 1.88A	46.00 ± 8.49A	43.71 ± 4.19A
Hausner ratio	1.79 ± 0.08a	1.76 ± 0.04a	1.66 ± 0.05a	1.88 ± 0.05A	1.87 ± 0.29A	1.78 ± 0.14A
Bulk density (g cm ^{−3})	0.21 ± 0.00a	0.22 ± 0.00a	0.20 ± 0.01a	0.24 ± 0.03A	0.22 ± 0.00A	0.20 ± 0.01A
Tapped density (g cm ^{−3})	0.38 ± 0.02a	0.38 ± 0.01a	0.33 ± 0.01a	0.45 ± 0.07A	0.41 ± 0.06A	0.36 ± 0.01A

of powder and a stronger DPPH response was observed in the LM 3:1 formulation. RM powders, however, may offer advantages where encapsulation efficiency and retention of rosmarinic acid are the primary formulation targets (Fig. 4).

Colour Properties

Colour properties were influenced primarily by species rather than wall material ratio (Table 1). LM powders were lighter than RM powders, with L* values of 92.03–93.00 compared with 76.63–78.51 for RM. LM powders also had slightly negative a* values, indicating a weak green contribution, while RM powders had positive a* values of 3.11–3.73, indicating a greater red contribution. For both species, b* was the dominant colour axis, and a* was negative or close to zero. When a* values are low like this, C* values can be very similar to b* values (Table 1). LM powders had lower C* values

of 8.50–9.38, while RM powders had higher C* values of 15.85–16.04, implying greater colour saturation. The derived colour indices supported this species effect, with RM powders showing higher BI and YI values, and lower WI values, than LM powders. Wall material effects were comparatively minor, although maltodextrin-only powders had the highest L* values for both species, indicating slightly greater brightness in the absence of gum Arabic. These between-species colour differences likely reflect, at least in part, the inherent colour characteristics of the respective botanical extracts. As the colour of the feed extracts was not measured prior to spray drying, the relative contributions of initial extract colour, wall material composition and spray-drying effects cannot be separated from the present data. Accordingly, the colour measurements are interpreted as characteristics of the final powders rather than as evidence of processing-induced colour change.

Flow and Packing

Bulk density ranged from 0.20–0.22 g cm⁻³ for LM to 0.20–0.24 g cm⁻³ for RM, while tapped density ranged from 0.33–0.38 g cm⁻³ for LM to 0.36–0.45 g cm⁻³ for RM. RM powders had slightly higher tapped density, particularly in the 3:1 formulation. This may be explained by a greater particle rearrangement or packing after tapping. Flowability indices revealed “very very poor” flow behaviour across all formulations (Lebrun et al., 2012), with Carr Index values of 39.69–44.07% for LM and 43.71–46.73% for RM, and Hausner ratios of 1.66–1.79 and 1.78–1.88, respectively (Table 1). Although these properties limit the suitability of the powders for direct use as free-flowing instant powder products, they may still be appropriate for product formats where flowability is less critical, such as compressed tablets, pressed discs, sachet-based dosing, or formulations that

undergo further agglomeration or granulation (Bhandari et al., 2023; Mitchell et al., 2017).

Particle Morphology

Across both species, the powders contained irregular, collapsed particles with wrinkled surfaces, concave depressions and shell-like structures (Figs. 5 and 6). These features are typical of spray-dried maltodextrin and gum Arabic blends, and are commonly associated with rapid solvent evaporation, early crust formation and subsequent shrinkage of the particle wall during drying (Ferrari et al., 2013; Hay et al., 2025; Mehrli et al., 2025). At higher magnification, particles with visible diameters of approximately 1 µm were observed.

Differences between wall material ratios were apparent, although the overall morphology remained broadly similar across formulations. The 1:1 formulation appeared to contain

Fig. 5 Scanning electron micrographs of spray-dried lemon myrtle (LM) powders formulated with maltodextrin: gum Arabic at ratios 3:1, 1:1, and 1:0. Left column (A, C, E): LM — (A) 3:1, (C) 1:1, (E) 1:0 at ×2000 magnification. Right column (B, D, F): LM — (B) 3:1, (D) 1:1, (F) 1:0 at ×8000 magnification

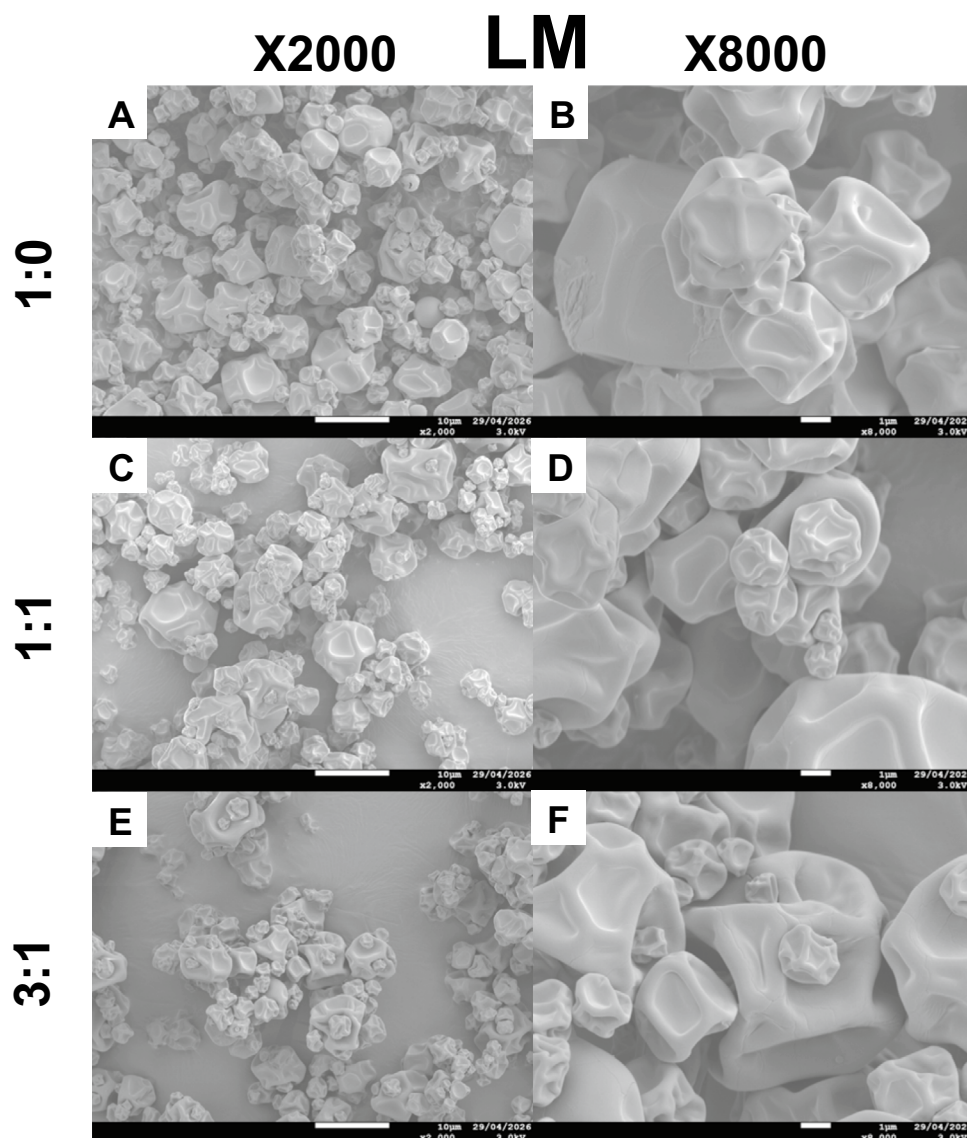
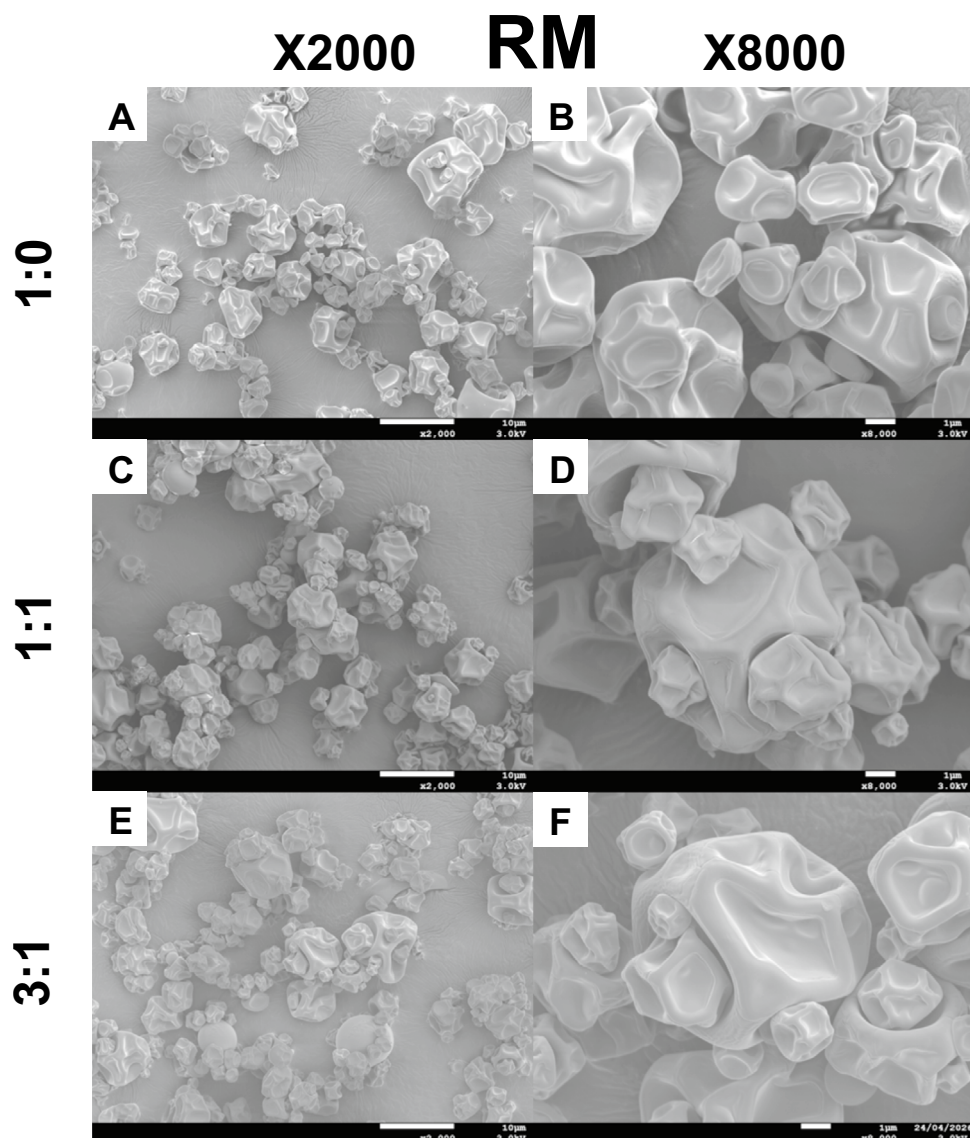


Fig. 6 Scanning electron micrographs of spray-dried river mint (RM) powders formulated with maltodextrin: gum Arabic at ratios 3:1, 1:1, and 1:0. Left column (A, C, E): RM — (A) 3:1, (C) 1:1, (E) 1:0 at $\times 2000$ magnification. Right column (B, D, F): RM — (B) 3:1, (D) 1:1, (F) 1:0 at $\times 8000$ magnification



more clustered particles, particularly for RM, while the maltodextrin-only powders showed more separated collapsed particles. The presence of collapsed and wrinkled particles may have contributed to differences in bulk and tapped density, while the more clustered appearance of the 1:1 formulation is consistent with their poorer flow behaviour. Interestingly, the same 1:1 formulation also produced the highest EE and lowest SPC (Fig. 6), revealing that the wall material ratio associated with more favourable phenolic encapsulation did not necessarily produce the most freely flowing powder.

Conclusion

This study demonstrates that water-based UAE combined with spray-dried microencapsulation can be used to produce phenolic-rich powders from lemon myrtle and river mint

herbal infusions. The selected UAE condition of 20 min, 30% amplitude and 1:20 material-to-solvent ratio provided a practical extraction baseline for generating feed extracts for downstream drying. Spray drying with maltodextrin and maltodextrin–gum Arabic wall systems produced powders with acceptable bench-scale process yields, low a_w , and high water solubility, supporting their potential use in reconstitutable herbal powder applications.

The results also show that phenolic encapsulation performance must be interpreted beyond encapsulation efficiency alone. RM powders achieved consistently higher encapsulation efficiency, including strong retention of rosmarinic acid, particularly when gum Arabic was included in the wall system. However, LM powders delivered higher TPC, greater EP content and substantially higher gallic acid loading per unit mass of powder. Under the conditions evaluated, LM powders contained higher final TPC and gallic acid loading,

although these outcomes were influenced by the higher phenolic content of the starting LM feed extract and should not be interpreted as evidence of superior encapsulation performance. In contrast, RM powders showed higher proportional encapsulation efficiency and strong retention of rosmarinic acid.

Wall material selection created a clear trade-off between phenolic protection and powder functionality. Gum Arabic-containing formulations improved encapsulation-related metrics and reduced surface phenolic exposure, but also increased moisture retention and did not improve flowability. Maltodextrin-only formulations produced powders with lower moisture and slightly brighter colour, although with weaker encapsulation performance. Across all formulations, the poor flowability indicates that further formulation or secondary processing would be required before their suitability for specific commercial delivery formats could be established.

This study was designed to establish a practical bench-scale framework for integrating water-based UAE with spray-dried microencapsulation of lemon myrtle and river mint extracts. Accordingly, the findings are specific to the tested extraction conditions, wall-material formulations, and drying parameters. Future work should evaluate longer-term storage stability, release behaviour, and process scale-up to support translation into commercial powder applications. In conclusion, the findings establish a processing framework for Australian native herbal powders and show that species choice, biomarker behaviour, and wall material composition should be matched to the intended functional and commercial product format.

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Data Availability Data is available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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