*Research article*

EFFECTS OF INLET TEMPERATURE AND WALL MATERIAL ON ENCAPSULATION YIELD, MORPHOLOGY AND CHEMICAL PROPERTIES OF SPRAY-DRIED *C. TERNATEA* FLOWER

Nurul Asyikin Md Zaki^{1,2✉}, Nur Suhanawati Ashaari³, Habsah Alwi^{1,2}, Syafiza Abd Hashib^{1,4}, Noorsuhana Mohd Yusof¹, Siti Fatma Abd Karim^{1,2}, Megawati⁵ and Ummi Kalthum Ibrahim^{1,2}

¹Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

²Food Process Engineering Research Group, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

³Malaysia Genome and Vaccine Institute (MGVI), National Institute of Biotechnology Malaysia (NIMB), 43000 Kajang, Selangor, Malaysia.

⁴Particle Engineering Technology, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia.

⁵Department of Chemical Engineering, Faculty of Engineering, Universitas Negeri Semarang, Gunungpati, 50229, Semarang, Indonesia.

✉Corresponding author: Nurul Asyikin Md Zaki, E-mail: asyikin6760@uitm.edu.my Mobile: +60162252587
ORCID 0000-0001-8264-8932

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ABSTRACT

C. ternatea, commonly known as blue pea flower, is a rich source of natural anthocyanins and other bioactive compounds with potential applications as natural colourants in food products. However, anthocyanins are sensitive to environmental and processing conditions, necessitating suitable protection during processing. This study investigated the effects of inlet temperature and wall material composition on the encapsulation yield, total anthocyanin content, morphology, and chemical profile of *C. ternatea* extract encapsulated by spray drying. Maltodextrin, arabic gum, and a combination of both wall materials were evaluated at inlet temperatures of 160, 180, and 200 °C. Total anthocyanin content was quantified using the pH differential method, particle morphology was examined using Field Emission Scanning Electron Microscopy (FESEM), and selected volatile and semi-volatile compounds were qualitatively identified using Gas Chromatography-Mass Spectrometry (GC-MS). The highest encapsulation yield (46.07%) and total anthocyanin content (27.47 mg/100 g encapsulated powder) were obtained using 10% maltodextrin at 160 °C. FESEM observations showed that wall material composition influenced particle morphology, while GC-MS analysis demonstrated differences in the chemical profiles among the formulations. Overall, the findings indicate that inlet temperature and wall material composition influence powder recovery, anthocyanin content, particle morphology, and chemical composition of spray-dried *C. ternatea* powder. Among the investigated conditions, 10% maltodextrin at 160 °C provided the most favourable combination of encapsulation yield and anthocyanin content

1. Introduction

The increasing demand for natural food colourants has intensified research interest in plant-derived pigments as alternatives to synthetic additives, driven by consumer concerns regarding food safety and regulatory restrictions. Anthocyanins are among the most widely studied natural pigments due to their attractive colour properties and associated antioxidant activity, which make them suitable for application in functional foods and beverages (Khoo et al., 2017). Nevertheless, anthocyanins are inherently unstable and susceptible to degradation during thermal processing and exposure to light, oxygen, and pH variations, limiting their direct incorporation into food systems (Laleh et al., 2006).

C. ternatea flower, commonly known as blue pea flower, is recognised as a rich source of polyacylated anthocyanins that impart an intense blue colour and demonstrate relatively higher colour stability compared to non-acylated anthocyanins from other plant sources (Suppadit, 2011; Muhammad Ezzudin & Rabeta, 2018). In addition to anthocyanins, *C. ternatea* flowers contain various bioactive compounds such as flavonoids, phenolic acids, and antioxidant-related constituents, contributing to their potential use as natural colourants with added functional value (Goh, 2022). Despite these advantages, the application of *C. ternatea* extracts in food processing remains challenging due to the thermal sensitivity and oxidative degradation of its bioactive components.

Microencapsulation has been widely employed to improve the stability, handling, and shelf life of thermally sensitive bioactive compounds. Among the available encapsulation techniques, spray drying is one of the most commonly used methods in the food industry due to its cost efficiency, continuous operation, and suitability for large-scale production (Haque et al., 2015). The effectiveness of spray drying is strongly influenced by processing parameters such as inlet temperature and the selection of encapsulating agents, which can affect powder

recovery, particle characteristics, and the chemical stability of the encapsulated compounds (Pui & Saleena, 2022). Maltodextrin and arabic gum are frequently used as wall materials because of their favourable solubility, film-forming ability, and compatibility with food applications. Maltodextrin has been reported to reduce stickiness and improve powder recovery during spray drying, whereas arabic gum provides favourable emulsification and encapsulation properties for bioactive compounds (Robert & Fredes, 2015). Several studies have investigated the spray drying of *C. ternatea* extracts, particularly in relation to physicochemical stability and antioxidant properties (Hamzah et al., 2013; Liew et al., 2020). However, fewer studies have simultaneously evaluated the effects of inlet temperature and wall material composition on multiple powder characteristics, including encapsulation yield, anthocyanin content, particle morphology, particle size distribution, and chemical profile. Particle morphology and size are important characteristics of spray-dried powders because they can influence properties such as flowability, rehydration behaviour, and susceptibility to oxidation, which are relevant to their subsequent application in food systems (Rezende et al., 2018). In addition to physical characterization, qualitative chemical profiling can provide complementary information on volatile and semi-volatile compounds present after spray drying. Gas Chromatography-Mass Spectrometry (GC-MS) has been used as a qualitative analytical technique for identifying such compounds in plant-derived materials, including *C. ternatea* extracts (Thakur et al., 2018).

Therefore, this study aimed to investigate the effects of inlet temperature and wall material composition on the yield, morphology, and chemical properties of spray-dried *C. ternatea* powder. Encapsulation yield and total anthocyanin content were determined to assess powder recovery and anthocyanin concentration, respectively. Particle morphology was examined using Field Emission Scanning Electron Microscopy

(FESEM), while particle size and size distribution were evaluated using dynamic light scattering (DLS). Selected volatile and semi-volatile compounds were qualitatively identified using GC-MS. By comparing maltodextrin, arabic gum, and their combination at different inlet temperatures, this study provides insight into how processing conditions influence powder recovery, anthocyanin content, particle characteristics, and the chemical profile of spray-dried *C. ternatea* powder.

2. Materials and methods

2.1. Materials

C. ternatea flower used in this study were obtained from a market in Klang Valley, Malaysia and stored at room temperature until usage. The encapsulating agents used are maltodextrin and arabic gum supplied by R&M, Malaysia.

2.2. Methods

2.2.1. Preparation of *C. ternatea* extract

The extraction procedure was adapted from the method described by Netravati et al. (2022), with some modifications. The present study employed a simplified distilled water extraction to preserve the natural profile of water-soluble anthocyanins and maintain food grade compatibility. The dried petals are coarsely shredded to increase the surface area for extraction. Approximately 10 g of dried petals (5% w/v) were mixed with 200 mL of distilled water in a Thermomix (Vorwerk, Malaysia) apparatus. The mixture was stirred at 60°C, 100 rpm, for 30 minutes to promote diffusion of anthocyanins into the solvent. After the extraction period, the mixture was passed through a clean filter cloth to remove insoluble plant material. The resulting filtrate, containing the anthocyanin-rich aqueous extract, was collected in amber bottles to minimise light exposure and stored at 4°C for 24 hours.

2.2.2 Preparation of carrier blend

The wall materials used in this study consisted of maltodextrin (MD) and arabic gum (AG) at three different formulations: MD 10%

(w/v), AG 10% (w/v), and MD 7.5% + AG 2.5% (w/v). Each formulation was prepared by accurately weighing the required amount of MD and AG and dissolving them in distilled water under continuous stirring at room temperature. Stirring was maintained for at least 30 minutes to ensure complete hydration of the arabic gum and full dissolution of the maltodextrin. After complete dissolution, the extract was mixed with the wall material solution at a fixed extract to encapsulating agent ratio of 1:2 (w/w). The mixture was homogenized using a high-speed homogenizer at approximately 10,000 - 12,000 rpm for 5 min to ensure uniform dispersion of anthocyanins within the carrier matrix and to obtain a stable feed emulsion suitable for spray drying. The feed mixture was filtered through a fine mesh ($\leq 150 \mu\text{m}$) to remove particulates that could block the spray dryer nozzle.

2.2.3. Encapsulation process by spray drying

Spray drying was carried out using a laboratory-scale spray dryer (SD-Basic, Lab Plant, UK), following the method described by Ramya et al. (2025) with slight modifications. The feed mixtures were spray-dried at three inlet air temperatures of 160, 180, and 200 °C, with a constant feed rate of 10 mL/min. The resulting powders were collected from the cyclone separator and immediately stored in airtight, opaque containers to minimise exposure to light, moisture, and oxygen prior to further analysis.

2.2.4. Encapsulation yield

The encapsulation yield expressed as a percentage of mass (% w/w) was determined by dividing the weight of the obtained microcapsule powder by the total weight of the primary solid matter. Encapsulation yields were calculated according to Equation (1).

$$\text{Encapsulation Yield} = \frac{\text{TW of Sample}}{\text{TW of Mixture}} \times 100\% \quad (1)$$

2.2.5 Determination of total anthocyanin content

The total anthocyanin content (TAC) of the spray-dried *C. ternatea* powder was determined using the pH differential method. The method is based on the reversible structural transformation of anthocyanins at different pH values, resulting in differences in absorbance between pH 1.0 and pH 4.5. Aliquots of each sample were separately mixed with 0.025 M potassium chloride buffer (pH 1.0) and 0.4 M sodium acetate buffer (pH 4.5). The absorbance of each solution was measured at 510 nm and 700 nm using a UV-Vis spectrophotometer.

The absorbance difference was calculated using Equation (2) and the monomeric anthocyanin concentration was calculated as cyanidin-3-glucoside equivalents using Equation (3).

$$A = (A_{510} - A_{700})_{pH1} - (A_{510} - A_{700})_{pH4.5} \quad (2)$$

$$\text{Anthocyanins} \left(\frac{\text{mg}}{100 \text{ g}} \right) = \frac{A \times MW_{C3G} \times DF}{\epsilon} \times 100. \quad (3)$$

Where:

MW is the molecular weight of cyanidin-3-glucoside (449.2), ϵ is the molar absorptivity (26,900), and DF is the dilution factor.

2.2.6 Morphological characterisation by Field Emission Scanning Electron Microscope

The morphology of microparticles produced with various encapsulating agents was examined using a cold field emission scanning electron microscope (FESEM, HITACHI SU8010). The FESEM was employed at acceleration voltages ranging from 0.1kV to 30kV. The experiments employed a working distance of 1.5 mm – 30 mm, a resolution of 1.0nm, and a minimum calibration time of 10 nm. For the average particle size and particle size distribution studies, 100-200 microparticles were quantified individually from SEM micrographs. FESEM procedure was adapted from (Rezende et al., 2018).

2.2.7 Particle size and size distribution analysis

The particle size and size distribution of the spray-dried *C. ternatea* powder were determined using dynamic light scattering (DLS) with a Zetasizer Nano ZS (Malvern Instruments, Malvern, UK), with a measurement range of 0.3 nm to 10.0 μm . Sample preparation was adapted from Lee et al. (2016). Approximately 3 mg of spray-dried powder was dispersed in 20 mL of distilled water and vortexed for 20 s. The resulting suspension was filtered through a 0.45 μm syringe filter according to Sadiq et al. (2023) and allowed to equilibrate for 1 h prior to analysis. Measurements were performed at room temperature using refractive indices of 1.38 for the sample and 1.33 for the dispersant. Each sample was measured in triplicate. The mean particle size was expressed as the Z-average diameter, while particle size distribution was represented by the polydispersity index (PDI) (Lee et al., 2016).

2.2.8. Gas Chromatography-Mass Spectrometry (GC-MS) analysis

GC-MS analysis was performed to qualitatively identify volatile and semi-volatile compounds present in selected spray-dried *C. ternatea* powder samples. The analysis was used for qualitative compound identification and was not intended as a direct measurement of anthocyanin concentration. Sample preparation was adapted from Thakur et al. (2018). For each sample, 200 mg of spray-dried powder was dissolved in 2 mL of methanol and filtered through a 0.22 μm syringe filter prior to analysis. The GC-MS procedure was adapted from Ashaari et al. (2021). An aliquot of 1 μL of the prepared sample was injected into the GC-MS system using splitless injection mode. Separation was carried out using an HP-5MS capillary column (30 m $\times$ 0.25 mm internal diameter $\times$ 0.25 μm film thickness), with helium as the carrier gas at a flow rate of 1 mL/min. The oven temperature was programmed from 50 $^{\circ}\text{C}$ to 280 $^{\circ}\text{C}$ at a heating rate of 10 $^{\circ}\text{C}/\text{min}$. The mass spectrometer was operated in electron-impact ionisation mode at 70 eV. The inlet/transfer line and ion source

temperatures were maintained at 280 °C and 220 °C, respectively.

2.2.8. Statistical analysis

All measurements were performed in triplicate, where applicable, and the results were expressed as mean $\pm$ standard deviation. A two-way analysis of variance (ANOVA) was performed to determine the effects of inlet temperature and wall material formulation, as well as their interaction, on encapsulation yield and total anthocyanin content. When significant differences were detected, Tukey's HSD test was used for multiple comparisons among treatment combinations. Differences were considered statistically significant at $p \leq 0.05$.

3. Results and discussions

3.1. Encapsulation yield

Encapsulation yield reflects the efficiency of powder recovery during the spray drying process and is strongly influenced by both drying temperature and wall material composition. The encapsulation yields obtained under different spray drying conditions are summarised in Table 1. Statistical analysis using two-way ANOVA showed that inlet temperature had a significant effect on encapsulation yield ($p < 0.001$). Wall material formulation also significantly affected encapsulation yield ($p < 0.001$). A significant interaction between inlet temperature and wall material formulation was also observed ($p = 0.005$) indicating that the effect of drying temperature on encapsulation yield depended on the formulation of wall material.

Table 1. Encapsulation yield and total anthocyanin content of *C. ternatea* powder

Sample	Temperature (°C)	Ratio	Encapsulation Yield (%)	Total Anthocyanin Content (mg/100 g)
S1	160	10% MD	46.07 $\pm$ 2.02 ^a	27.47 $\pm$ 4.04 ^a
S2	160	10% AG	37.38 $\pm$ 3.96 ^{ab}	25.38 $\pm$ 1.82 ^a
S3	160	7.5% MD + 2.5% AG	32.78 $\pm$ 5.67 ^{bc}	18.45 $\pm$ 2.69 ^{ab}
S4	180	10% MD	41.59 $\pm$ 0.67 ^{ab}	9.09 $\pm$ 5.89 ^{bc}
S5	180	10% AG	42.76 $\pm$ 6.04 ^{ab}	3.34 $\pm$ 3.46
S6	180	7.5% MD + 2.5% AG	25.06 $\pm$ 5.68 ^c	9.54 $\pm$ 1.21 ^{bc}
S7	200	10% MD	25.05 $\pm$ 2.71 ^c	14.03 $\pm$ 1.99 ^b
S8	200	10% AG	32.51 $\pm$ 3.94 ^{bc}	9.35 $\pm$ 3.71 ^{bc}
S9	200	7.5% MD + 2.5% AG	24.19 $\pm$ 2.74 ^c	8.60 $\pm$ 4.00 ^{bc}

Values are expressed as mean $\pm$ standard deviation ($n = 3$). Different superscript letters indicate significant differences among treatment combinations according to Tukey's HSD test at $p < 0.05$

At an inlet temperature of 160 °C, the highest encapsulation yield was achieved using 10% maltodextrin, as shown by Sample S1 (46.07 $\pm$ 2.02%), followed by 10% arabic gum in Sample S2 (37.38 $\pm$ 3.96%) and the mixed wall material formulation in Sample S3 (32.78 $\pm$ 5.67%). The superior performance of maltodextrin at lower inlet temperature may be attributed to its low viscosity, high solubility, and effective film-forming ability, which promote rapid crust formation around droplets

and reduce material loss due to wall deposition during spray drying. The encapsulation performance and morphological characteristics observed in this study are generally consistent with previously reported findings on spray-dried anthocyanin systems. The higher encapsulation yield obtained using maltodextrin at moderate inlet temperature is in agreement with earlier studies reporting improved powder recovery and reduced wall deposition when maltodextrin is used as the

primary encapsulating agent (Robert & Fredes, 2015; Pettinato et al., 2017). Maltodextrin has been widely reported to promote rapid film formation and reduce stickiness during spray drying, which supports the higher encapsulation yield observed in the present study.

Increasing the inlet temperature to 180 °C resulted in a slightly lower encapsulation yield for the maltodextrin-based sample, while the arabic gum formulation exhibited a comparable yield of $42.76 \pm 6.04\%$. At higher temperatures, increased thermal stress may enhance surface stickiness and particle rupture, particularly for formulations containing mixed wall materials, as reflected by the significantly lower yield observed for Sample S6 ($25.06 \pm 5.68\%$). At 200 °C, a further decrease in encapsulation yield was observed for most formulations, particularly S7 and S9, which showed significantly lower yields compared with S1. High inlet temperatures are known to accelerate moisture evaporation, which may cause particle deformation, surface cracking, and adhesion to the drying chamber wall, thereby reducing powder recovery. These findings indicate that moderate inlet temperature combined with maltodextrin as the encapsulating agent provides favourable conditions for achieving higher encapsulation yield.

3.2. Total anthocyanin content (TAC)

The total anthocyanin content (TAC) of the spray-dried *C. ternatea* powders was significantly affected by both inlet temperature and wall material formulation. As depicted in Table 1, the highest TAC was recorded for Sample S1 (27.47 ± 4.04 mg/100 g), whereas the lowest value was observed for Sample S5 (3.34 ± 3.46 mg/100 g). Overall, samples produced at 160 °C showed higher TAC than those produced at 180 and 200 °C. Two-way ANOVA confirmed that inlet temperature

significantly affected TAC ($p < 0.001$), and wall material formulation also showed a significant effect ($p < 0.05$). Meanwhile, the interaction between inlet temperature and wall material formulation was also significant ($p = 0.05$). Tukey's HSD test further showed that S1 and S2 were among the treatment combinations with the highest TAC.

The strong effect of inlet temperature is consistent with the thermal sensitivity of anthocyanins. Trirahayu et al. (2025) similarly reported that increasing inlet temperature during spray drying reduced the total anthocyanin content of *C. ternatea* powder. Higher thermal exposure can accelerate anthocyanin degradation through structural transformation and oxidation, resulting in lower measurable pigment content. Wall material formulation also influenced TAC, which agrees with previous findings that carrier composition affects anthocyanin stability. Lourith and Kanlayavattanukul (2020) reported improved stability of *C. ternatea* anthocyanins when protected by biopolymeric wall systems containing maltodextrin and gum arabic. Multisona et al. (2023) also highlighted the importance of maltodextrin, arabic gum, and mixed carrier systems in preserving *C. ternatea* anthocyanins during encapsulation. In addition, Mariano et al. (2025) showed that different proportions of maltodextrin and gum arabic influenced the physicochemical and bioactive properties of spray-dried *C. ternatea* powder.

3.3. Morphological characteristics

The morphological characteristics of the spray-dried *C. ternatea* powders were examined using Field Emission Scanning Electron Microscopy (FESEM) to evaluate the influence of wall material composition on particle structure and surface properties. Representative FESEM micrographs of samples produced at an inlet temperature of 160 °C are shown in Figure 1.

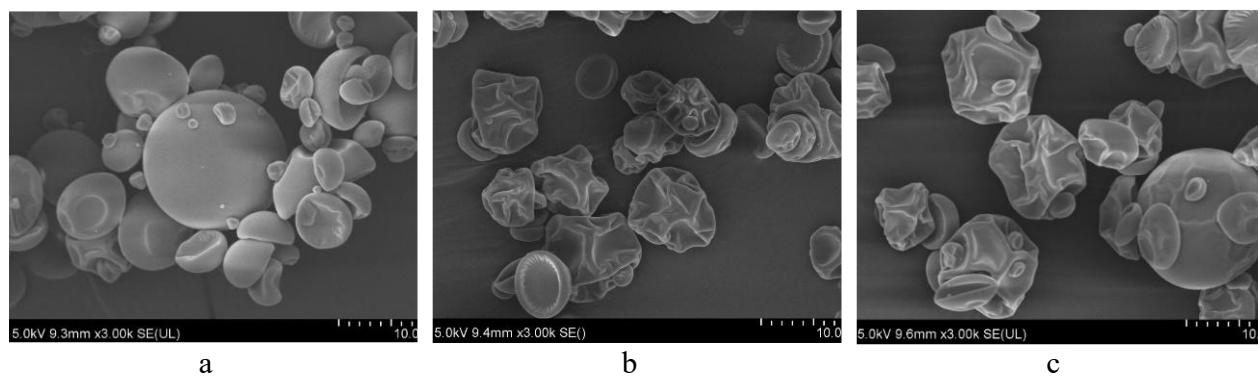


Figure 1. FESEM image of (a) Sample S1, (b) Sample S2, (c) Sample S3, of spray-dried *C. ternatea* powders at 160 °C with 3000X magnification

Particles encapsulated with 10% maltodextrin (Sample S1) exhibited predominantly spherical to near-spherical shapes with smooth and continuous surfaces. This morphology suggests effective encapsulation, where rapid film formation of maltodextrin around the droplets resulted in structurally stable particles. Smooth particle surfaces are generally associated with improved flowability and reduced exposure of bioactive compounds to external oxidative conditions. The spherical particle morphology with smooth surface characteristics observed for maltodextrin-encapsulated powders is also consistent with FESEM observations reported for spray-dried plant extracts and anthocyanin-rich materials (Rezende et al., 2018; Balci-Torun & Ozdemir, 2021).

In contrast, particles encapsulated with 10% arabic gum (Sample S2) displayed noticeable surface shrinkage and irregular deformation. The observed morphological collapse may be attributed to slower crust formation and higher hygroscopicity of arabic gum, which can lead to structural contraction during moisture removal. Such surface irregularities may increase susceptibility to oxidation and reduce powder stability during storage. The surface shrinkage and particle deformation associated with arabic gum-based formulations have been previously attributed to slower crust formation and higher hygroscopicity (Pui & Saleena, 2022), which aligns with the morphological features observed in this study. For the mixed wall

material formulation with 7.5% MD + 2.5% AG (Sample S3), particles exhibited intermediate morphological characteristics, showing partially smooth surfaces with slight shrinkage. This indicates that the presence of maltodextrin contributed to improved structural rigidity, while arabic gum influenced the drying behaviour and particle contraction.

The FESEM analysis demonstrates that maltodextrin produced more uniform and structurally intact microcapsules compared to arabic gum-based formulations. These morphological features are consistent with the higher encapsulation yield observed for maltodextrin and support its suitability as an encapsulating agent for producing stable anthocyanin powders.

3.4. Particle size and size distribution

The mean particle size and polydispersity index (PDI) of the spray-dried *C. ternatea* powders varied with inlet temperature and wall material formulation as shown in Figure 2. The smallest particle size was observed for S1 containing 10% maltodextrin at 160 °C (35.47 nm), whereas S7 containing the same wall material at 200 °C exhibited the largest particle size (188.79 nm). A marked increase in particle size with increasing inlet temperature was particularly apparent for the maltodextrin formulation, while the arabic gum formulations showed comparatively smaller variations across the investigated temperatures.

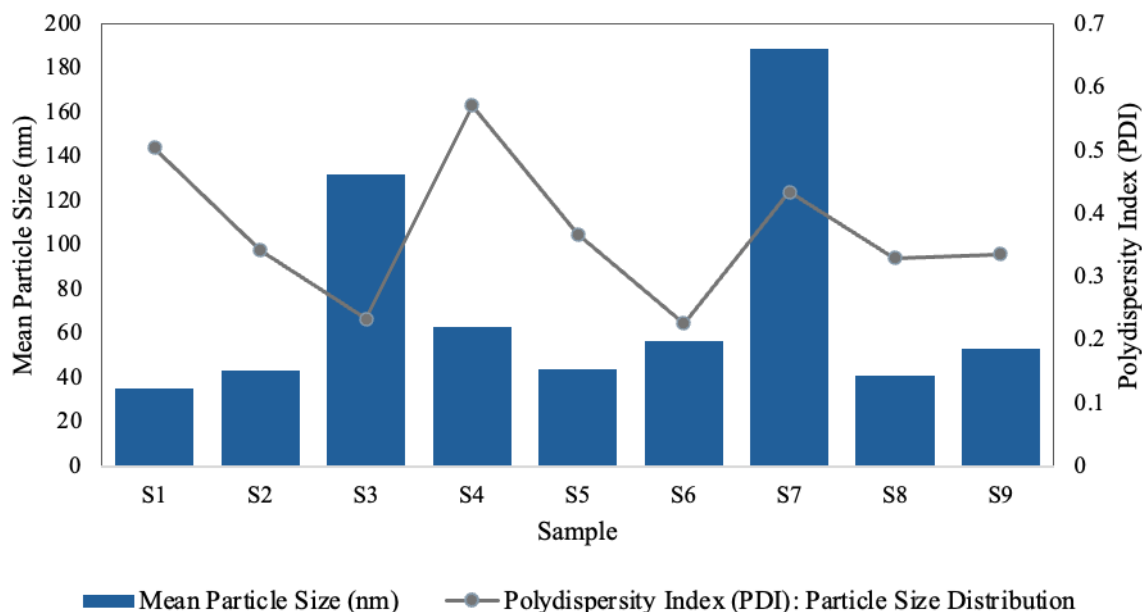


Figure 2. Mean particle size (Z-average) and polydispersity index (PDI) of spray-dried *C. ternatea* powders under different inlet temperatures and wall material formulations

The effect of carrier composition on the particle size of spray-dried *C. ternatea* powder has also been reported by Mariano et al. (2025). They observed particle sizes ranging from approximately 121 to 199 nm and reported smaller particles in formulations containing higher proportions of maltodextrin. The authors attributed this behaviour partly to the lower viscosity of maltodextrin-containing feed solutions, which may favour the formation of smaller droplets during atomisation. Previous studies on microencapsulated *C. ternatea* have similarly demonstrated that the type and proportion of coating material can influence particle size and morphological characteristics (Multisona et al., 2023).

In this study, the increase in particle size of the maltodextrin formulation from 160 to 200 °C suggests that inlet temperature also influenced particle formation. Higher drying temperatures can accelerate moisture evaporation and promote rapid crust formation, which may alter particle expansion, shrinkage, and aggregation during drying. Similar effects of processing conditions and carrier

composition on the particle characteristics of spray-dried anthocyanin-rich powders have been reported for other plant materials (Hoang et al., 2024; Hay et al., 2025).

The polydispersity index (PDI) ranged from 0.227 to 0.572, indicating differences in the width of particle size distribution among the formulations. The lowest PDI was observed for S6 (0.227), followed closely by S3 (0.234), both containing the mixed maltodextrin–arabic gum formulation. This suggests a comparatively narrower particle size distribution for these samples. In contrast, S4 exhibited the highest PDI (0.572), indicating a broader and more heterogeneous particle population. The DLS results indicate that both processing temperature and wall material composition contributed to differences in particle size and size distribution of the reconstituted spray-dried powders. The variation observed among formulations further supports the importance of carrier selection and drying conditions in determining the physical characteristics of spray-dried *C. ternatea* powder.

3.5. Chemical profile by GC-MS

GC-MS analysis was used to qualitatively identify volatile and semi-volatile compounds present in the spray-dried *C. ternatea* powder prepared using different wall material formulations. The comparison presented in

Table 2 and Figure 3 focused on Samples S1, S2, and S3 produced at an inlet temperature of 160 °C, as this temperature produced the highest total anthocyanin contents among the investigated drying conditions.

Table 2. Gas Chromatography Mass Spectrometry (GCMS) analysis for Sample S1, S2 and S3 of spray-dried *C. ternatea* powder at 160 °C

Compound Name (Formula)	S1 Component Area	S1 Area %	S2 Component Area	S2 Area %	S3 Component Area	S3 Area %
2-Furanmethanol (C ₅ H ₆ O ₂)	22947051.68	14.16	ND	ND	81500625.71	15.79
1,2-Cyclopentanedione (C ₅ H ₆ O ₂)	7664022.25	4.73	1630232.57	5.20	15887108.84	3.08
Maltol (C ₆ H ₆ O ₃)	2257618.17	1.39	ND	ND	12814765.12	2.48
4H-Pyran-4-one, 2,3- dihydro-3,5-dihydroxy-6- methyl- (C ₆ H ₈ O ₄)	9944055.81	6.14	422573.70	1.35	29713226.43	5.76
5-Hydroxymethylfurfural (C ₆ H ₆ O ₃)	11087894.88	6.84	ND	ND	54553965.17	10.57
Tetradecanoic acid (C ₁₄ H ₂₈ O ₂)	2013610.15	1.24	ND	ND	1293264.01	0.25
Tris(1,3- dichloroisopropyl)phosphate (C ₉ H ₁₅ Cl ₆ O ₄ P)	2251598.64	1.39	1161433.30	3.71	4516628.97	0.88
Dimethylsulfoxonium formylmethylide (C ₄ H ₈ O ₂ S)	ND	ND	2639058.82	8.42	ND	ND
2-Hydroxy-gamma- butyrolactone (C ₄ H ₆ O ₃)	ND	ND	1096376.55	3.49	ND	ND
Pentanal (C ₅ H ₁₀ O)	ND	ND	3529846.33	11.26	ND	ND
2(3H)-Furanone, dihydro-4- hydroxy- (C ₄ H ₆ O ₃)	ND	ND	531464.96	1.69	ND	ND
4-Vinylphenol (C ₈ H ₈ O)	ND	ND	1001998.58	3.19	ND	ND
2,4-Di-tert-butylphenol (C ₁₄ H ₂₂ O)	ND	ND	ND	ND	3419335.35	0.66

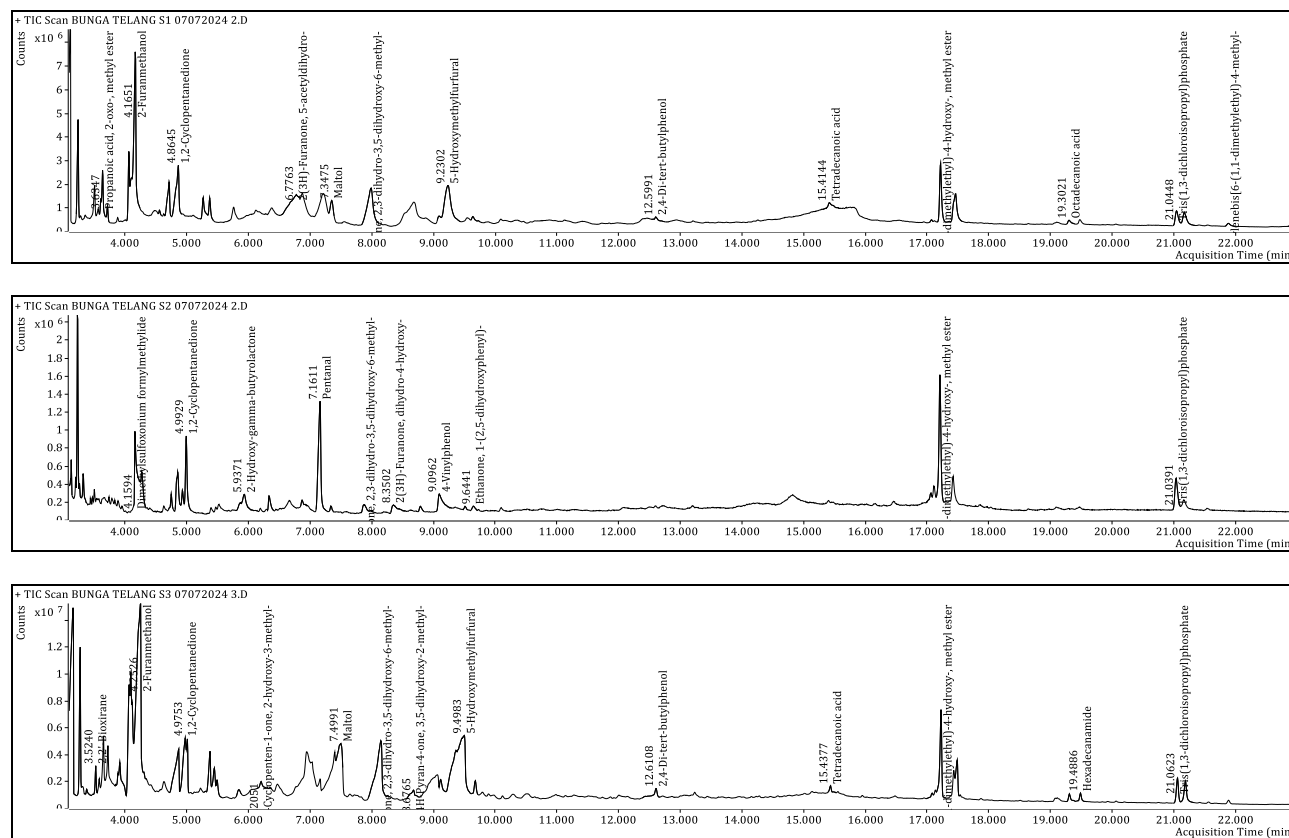


Figure 3. Chromatography diagram for (a) Sample S1, (b) Sample S2, (c) Sample S3 of spray-dried *C. ternatea* powders

Sample S1 showed several identifiable compounds, including 2-furanmethanol, 1,2-cyclopentanedione, maltol, 4H-pyran-4-one derivatives, 5-hydroxymethylfurfural, tetradecanoic acid, and tris(1,3-dichloroisopropyl) phosphate. Several of these compounds, particularly furans and pyranone derivatives, may originate from thermal transformation or degradation reactions involving carbohydrates during spray drying rather than representing intact anthocyanins. The presence of maltol, hydroxymethylfurfural, and related compounds may therefore reflect thermal processing of the extract and carrier matrix.

In contrast, Sample S2 exhibited a different chemical profile, with compounds including pentanal, dimethylsulfoxonium

formylmethylide, 1,2-cyclopentanedione, 4-vinylphenol, and 2(3H)-furanone, dihydro-4-hydroxy-. The occurrence of aldehydes and furan-related compounds may be associated with oxidation and thermal transformation pathways during drying. Differences in the relative abundance and type of detected compounds among the formulations suggest that wall material composition may influence the chemical environment of the spray-dried matrix.

Sample S3 showed a profile containing several compounds also detected in S1, including 2-furanmethanol, 1,2-cyclopentanedione, maltol, 4H-pyran-4-one derivatives, 5-hydroxymethylfurfural, tetradecanoic acid, and 2,4-di-tert-butylphenol. The similarity in several detected compounds

between S1 and S3 may be related to the presence of maltodextrin in both formulations, although the qualitative nature of the GC-MS analysis does not permit conclusions regarding compound retention or degradation kinetics.

The GC-MS results demonstrated that the spray-dried powders contained different qualitative profiles of volatile and semi-volatile compounds depending on the wall material formulation. These findings complement the total anthocyanin content analysis and FESEM observations by providing information on the chemical composition of the powders after spray drying. However, GC-MS was not used to quantify anthocyanins or to establish anthocyanin retention, and the detected compounds should be interpreted primarily as part of the broader chemical profile of the spray-dried powders.

4. Conclusions

This study demonstrated that inlet temperature and wall material composition influenced the properties of spray-dried *C. ternatea* powder. The highest encapsulation yield and total anthocyanin content were obtained at 160 °C, with the 10% maltodextrin formulation showing the highest values for both parameters. Statistical analysis confirmed that inlet temperature and wall material significantly affected encapsulation yield and total anthocyanin content. FESEM observations showed differences in particle morphology among the wall material formulations, with maltodextrin producing relatively smoother and more uniform particles at 160 °C. Dynamic light scattering analysis further demonstrated variation in particle size and size distribution across the drying conditions and formulations. GC-MS analysis identified differences in the qualitative profiles of volatile and semi-volatile compounds among the samples, although these results were interpreted as chemical profiling rather than direct evidence of anthocyanin retention or biological activity. Overall, an inlet temperature of 160 °C provided the most favourable condition for maintaining higher anthocyanin content and powder recovery. Among the investigated formulations,

maltodextrin showed favourable performance in terms of encapsulation yield, anthocyanin content, and particle morphology. These findings provide useful information for the development of spray-dried *C. ternatea* powder for potential food applications, although further evaluation of colour stability, antioxidant activity, storage stability, and other functional properties is recommended.

5. References

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