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RESEARCH ARTICLE

Optimisation of spray-drying parameters for encapsulation of *Helicteres isora* L. extract

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Abstract

Helicteres isora L. (family Sterculiaceae) is a valuable herbal remedy and has been reported to exhibit remarkable hepatoprotective, antioxidant, hypolipidaemic, antibacterial and anticancer activities, underscoring its potential as a functional ingredient. However, despite its widespread use in traditional medicine, there is still limited scientific evidence to validate its bioactive compounds. In addition, the instant powder form of *H. isora* extract offers a convenient and stable formulation while retaining its hepatoprotective potential. Developing this preparation is essential to ensure standardised dosage, improved shelf life and wider applicability in therapeutic and nutraceutical products. In this study, the hydroethanolic extract of the plant was encapsulated using the spray drying method. The spray-drying experiments were conducted using the One-Factor-at-a-Time (OFAT) method with 4 varying extract concentrations (ranging from 5–20 °B), 4 different maltodextrin concentrations (5–20 % w/v), 4 different inlet temperatures (160–190 °C) and 4 different feed flow rates (555–1200 mL/h). The process yield (PY), encapsulation efficiency (EE) and physicochemical characteristics [total phenolic content (TPC), moisture content, hygroscopicity, water solubility index (WSI) and Carrs' index(CI)] of the exulting granules were examined. The results have shown that the encapsulation of *H. isora* extract by the spray-drying method with an extract concentration of 10 °B, maltodextrin concentration of 10 % w/v, feed flow rate of 750 mL/h and inlet air temperature of 170 °C produces the best quality product, while also achieving the highest encapsulation efficiency. These optimised spray-drying conditions, which produce powders with desirable physicochemical characteristics and efficient retention of bioactive constituents, establish the technological foundation for the subsequent formulation and production of instant *H. isora* tea.

Keywords: encapsulate; extract; *Helicteres isora*; maltodextrin; spray drying

Introduction

Helicteres isora L. is a medicinal plant that belongs to the Sterculaceae family, widely used in traditional medicine. The parts of the tree are used for the treatment of various ailments such as stomach issues, diarrhoea, dysentery, ulcers, measles, colds, poison, pimples, snake bites, worm infections and diabetes (1). It is widely distributed in most tropical countries of Asia, including India, Myanmar, Laos, China, Cambodia, Thailand and Vietnam. In Vietnam, it can also be found in provinces belonging to low and midland mountainous areas such as Lai Chau, Dien Bien, Hue and Dak Nong (2). The plant is known for its diverse bioactivities, including antioxidant, antimicrobial, wound-healing properties, anti-inflammatory, anticancer, antispasmodic, hepatoprotective and antiviral activities (3–8). The common active polyphenols include caffeic acid and p-coumaric acid. Especially, cucurbitacin B and isocucurbitacin B have been extracted from the roots of *H. isora* (9). Phenolic compounds extracted from *H. isora* have been demonstrated to possess significant antioxidant and antitumor activities. These bioactive compounds not only neutralise harmful free radicals, reducing oxidative stress, but also exhibit potential to inhibit the growth of various cancer cells, making them promising candidates for therapeutic applications (10). p-Coumaric acid has been evaluated for its protective effects against liver damage caused by toxic chemicals, such as acetaminophen, ethanol and fipronil (11, 12).

Phenolic chemicals are naturally unstable and susceptible to influences such as high temperatures, light exposure, pH fluctuations and oxidative or degradative enzymes, all of which may affect the structure of phenolic extracts. Therefore, in food as well as in pharmaceuticals, it is necessary to protect the active properties of polyphenols. In particular, encapsulation technology has emerged as a particularly effective approach for enhancing their stability and preserving functional properties. Numerous carriers can be used for the encapsulation of active ingredients, including gum Arabic, whey protein concentrate, gelatin, cyclodextrins and various plant-based polysaccharides. Among them, maltodextrin is a widely used

carbohydrate due to its low cost, easy solubility, colourlessness and mild sweetness. Several methods commonly used for encapsulation include coacervation, freeze-drying and spray drying. In this study, *H. isora* extract was encapsulated and spray-dried using varying *H. isora* extract concentrations, maltodextrin (DE15-20) concentrations, inlet temperatures and feed flow rate. The products were evaluated for their physicochemical characteristics, including total phenolic content (TPC), moisture content, hygroscopicity, water solubility index (WSI) and Carrs' index (CI).

Materials and Methods

Chemicals

Maltodextrin DE15-20 was procured from Qinhuangdao Lihua Starch Co., Ltd. (Hebei, China). Ethanol was procured from VN-Chemsol Co., Ltd. (Ho Chi Minh City, Vietnam). Gallic acid and Folin & Ciocalteu were obtained from Sigma – Aldrich (St. Louis, USA).

Preparation of the extract

Helicteres isora were harvested from Dak Nong province (Vietnam). The voucher specimens (VST 2023-239) were deposited and identified by the Department of Botanical Museum at the Institute of Life Sciences, Vietnam. The stems and leaves of *H. isora* were washed, cut and dried at 50 °C to 15 % humidity. The dried material was then crushed to a particle size of 0.25 mm. *Helicteres isora* was extracted using 70 % ethanol as a solvent for 24 hr at room temperature through maceration. The extract was stored at -20 °C (13). In addition, the initial total phenolic and p-Coumaric acid contents in the extract were determined. The results showed the total phenolic content (202.07 ± 1.21 mg GAE/g) and p-Coumaric acid content (0.15 ± 0.00 mg/g) in the hydroethanolic extract of *H. isora* (14, 15).

Encapsulation by spray drying

Helicteres isora extract was combined with a carrier solution (maltodextrin) and spray-dried using a mini SD-Basic spray dryer (LabPlant, UK). A peristaltic pump was used to feed the liquid into the spray dryer. During the production of the dry powder extract, the inlet temperature, feed flow rate and atomization pressure were kept constant. The dry powder was collected in a cyclone (16). A one-factor-at-a-time approach was used for experiments, with variations in *H. isora* extract concentration, maltodextrin concentration, inlet temperature and feed flow rate.

Effect of extract concentration on the characteristics of *Helicteres isora* instant powder

Different *H. isora* extract concentrations (5, 10, 15 and 20 °B) were used to prepare the encapsulation. Conditions for the spray dryer were kept constant, including a maltodextrin concentration of 10 %, an inlet temperature of 180 °C, a feed flow rate of 555 mL/h and an atomization pressure of 3 bar. The optimal parameter was selected by comparing different values of the instant powder, such as process yield (PY) (%), encapsulation efficiency (EE) (%), TPC (mg GAE/g), moisture content (%), hygroscopicity (g/100g), WSI (%) and CI (%).

Effect of maltodextrin (drying carrier agent) concentration on the characteristics of *Helicteres isora* instant powder

The optimal *H. isora* extract concentration for drying was selected for the subsequent experiments. Maltodextrin concentrations of 5, 10, 15 and 20 % (w/v) were utilised for encapsulation. Conditions for the spray dryer were kept constant, including an inlet temperature of 180 °C, a feed flow rate of 555 mL/h and an atomization pressure of 3 bar. The optimal parameter was selected by comparing different values of the instant powder, such as PY (%), EE (%), TPC (mg GAE/g), moisture content (%), hygroscopicity (g/100g), WSI (%) and CI (%).

Effect of inlet temperature on the characteristics of *Helicteres isora* instant powder

The optimal *H. isora* extract and maltodextrin concentrations were selected for the subsequent experiments. Different inlet drying temperatures (160, 170, 180 and 190 °C) were examined, with the feed flow rate of 555 mL/h and the atomization pressure was 3 bar, respectively. The optimal conditions were selected by comparing different values of the instant powder, such as PY (%), EE (%), TPC (mg GAE/g), moisture content (%), hygroscopicity (g/100g), WSI (%) and CI (%).

Effect of feed flow rate on the characteristics of *Helicteres isora* instant powder

The optimal *H. isora* extract concentration, maltodextrin concentration and an inlet temperature were used in this experiment. Different feed flow rate (555, 750, 990 and 1200 mL/h) was examined. Atomization pressure was set to 3 bar. The optimal conditions were determined by comparing different values of the instant powder, such as PY (%), EE (%), TPC (mgGAE/g), moisture content (%), hygroscopicity (g/100g), WSI (%) and CI (%).

Process yield

The process yield (PY) (%) of *H. isora* powder was calculated as the ratio of the dry mass of the powders obtained and the dry mass of *H. isora* extract and maltodextrin (17).

$$PY\ (\%) = \frac{Mp}{Mi} \times 100 \qquad \text{(Eqn. 1)}$$

Where,

Mp = Dry mass of powder

Mi = Dry mass of *H. isora* extract and maltodextrin

Encapsulation efficiency

The encapsulation efficiency (EE) (%) was calculated as the ratio between the phenolic content in the aqueous solution of dissolved powders and the phenolic content in the initial extract and carrier solution (18).

$$EE\ (\%) = \frac{\text{TPC recovered in powder}}{\text{TPC in powder}} \times 100 \qquad \text{(Eqn. 2)}$$

Total phenolic content

Total phenolic content was determined using the Folin-Ciocalteu method with slight modifications (14). Fifty microlitre of the sample solution was mixed with 250 µL of 10 % Folin-Ciocalteu reagent, followed by the addition of 200 µL of a 7.5 % Na_2CO_3. The mixture was kept stable for 120 min at room temperature. The optical density was measured at 740 nm. The phenolic content was expressed as milligram of gallic acid equivalent per gram of sample (mg GAE/g) using gallic acid as the standard.

Moisture content

The moisture content (%) of *H. isora* powder was determined gravimetrically by drying oven (Sanyo MOV212, Japan) at 105 °C to a constant mass, according to the Association of Official Analytical Chemists (AOAC) method 930.15 (19).

Hygroscopicity

Samples of each powder (approximately 2 g) were placed at 25 °C in a desiccator filled with NaCl saturated solution (relative humidity of 75.29 %). The hygroscopicity was measured after 7 days. Hygroscopicity was expressed as grams of absorbed water per 100 g of dry extract powder (20).

Water solubility index

The water solubility index (WSI) was evaluated via the method published (21). Hundred milligram of *H. isora* dry powder was mixed with 10 mL of water and then centrifuged at 3000 rpm for 10 min. The supernatant was collected, then dried at 105 °C and reweighed until a constant weight was achieved.

$$\text{WSI (\%)} = \frac{\text{Weight (g) dehydrate supernatant}}{\text{Weight (g) of the powder}} \times 100 \quad \text{(Eqn. 3)}$$

Carrs' index

Carrs' index (CI) quantifies the flowability and packing characteristics of powders. Five gram of powder was placed into a 25 mL graduated cylinder and the unsettled apparent volume (bulk volume) was read. The bulk density was determined by the mass of the particle per unit volume. The tapped density was measured by mechanically tapping until no measurable change in volume of a graduated cylinder (22).

$$\text{CI (\%)} = \frac{\text{(tapped density - bulk densi-}}{\text{tapped density}} \times 100 \quad \text{(Eqn. 4)}$$

Statistical analysis

All analyses were done in triplicate. Data were expressed as mean ± SD and analysed by one-way ANOVA using Statgraphics Centurion 19 software. Statistical significance between groups was defined as $p < 0.05$.

Results

Effect of extract concentration on the characteristics of spray-dried *Helicteres isora* powder

The impact of varying extract concentrations (5, 10, 15 and 20 °B) on the characteristics of *H. Isora* spray-dried powder is presented in Table 1 and Fig. 1. These extract concentrations affected several physicochemical properties of the spray-dried powders, including process yield, encapsulation efficiency, total phenolic content and moisture content.

Process yield

Table 1 shows that the process yield was highest at 5 °B (51.77 ± 1.39 %) but slightly declined to 49.23 ± 1.21 % at 10 °B. Further increase in concentration to 15 and 20 °B resulted in more substantial decreases in yield (41.20 ± 0.79 % and 25.98 ± 0.69 %, respectively), likely due to the increased viscosity of the feed solution. Higher viscosity can impede atomization and promote wall deposition, thereby reducing the amount of powder recovered.

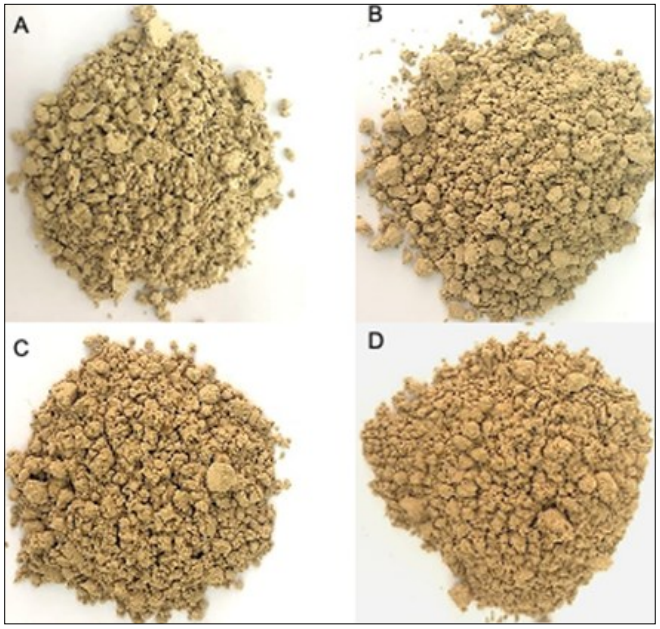

Fig. 1. The instant powder formed with different extract concentrations (with a maltodextrin concentration of 10 %, inlet temperature of 180 °C, a feed flow rate of 555 mL/h): (A) 5 °B, (B) 10 °B, (C) 15 °B, (D) 20 °B.

Encapsulation efficiency

Table 1 illustrates a different trend compared to process yield, reaching its maximum at 10 °B (41.12 ± 0.27 %), which was significantly higher than values at 5 °B (35.42 ± 0.56 %), 15 °B (29.39 ± 0.41 %) and 20 °B (18.26 ± 0.22 %). These findings suggest that 10 °B offers the most favourable core-to-wall material ratio, optimising phenolic compound entrapment while minimising surface deposition and thermal degradation that can occur at higher extract concentrations during spray drying.

Total phenolic content

Table 1 indicates that phenolic content increased significantly with extract concentration, with the maximum retention at 20 °B (96.97 ± 1.16 mg GAE/g). This high phenolic content at 20 °B can be attributed to the greater availability of phenolic compounds in the feed solution, providing a higher initial concentration of bioactive compounds for encapsulation. However, it is important to note that although total phenolic content increased, higher extract concentrations may also pose challenges such as reduced process yield and increased moisture content, which could compromise powder stability and flowability. Therefore, while 20 °B supports high phenolic retention, other processing parameters must be balanced to ensure overall powder quality.

Table 1. Effect of extract concentration (°B) on process yield, encapsulation efficiency, total phenolic content and physicochemical properties of spray-dried *H. isora* extract powder

Extract concentration (°B)	Process yield (%)	Encapsulation efficiency (%)	Total phenolic content (mg GAE/g)	Moisture content (%)	Hygroscopicity (g/100g)	WSI (%)	CI (%)
5	51.77 ± 1.39^{a}	35.42 ± 0.56^{b}	46.03 ± 0.73^{c}	4.56 ± 0.33^{c}	4.54 ± 0.35^{c}	87.33 ± 1.15^{a}	25.35 ± 1.20^{b}
10	49.23 ± 1.21^{b}	41.12 ± 0.27^{a}	85.60 ± 0.56^{b}	4.60 ± 0.28^{c}	5.79 ± 0.28^{b}	86.33 ± 0.58^{a}	24.34 ± 1.02^{b}
15	41.22 ± 0.79^{c}	29.39 ± 0.41^{c}	86.49 ± 1.20^{b}	5.40 ± 0.55^{b}	6.10 ± 0.11^{b}	83.00 ± 1.00^{b}	25.62 ± 1.49^{b}
20	25.98 ± 0.69^{d}	18.26 ± 0.22^{d}	96.97 ± 1.16^{a}	6.20 ± 0.26^{a}	6.81 ± 0.24^{a}	79.33 ± 1.15^{c}	28.90 ± 1.66^{a}
CD ($p < 0.05$)	**2.00**	**0.73**	**1.79**	**0.70**	**0.41**	**1.88**	**2.57**

Values are expressed as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences at $p < 0.05$ according to one-way ANOVA followed by Fishers' LSD test. CD: Critical Difference at $p < 0.05$.

Moisture content

Moisture content was lowest at 5 and 10 °B, while higher extract concentrations, particularly 20 °B, retained more moisture (6.20 ± 0.2 %), reflecting inefficient drying of more viscous feed solutions.

Water solubility index and carr's index

As shown in Table 1, WSI decreased with increasing extract concentration, from 87.33 ± 1.15 % at 5 °B to 79.33 ± 1.15 % at 20 °B. This reduction in solubility at higher solid concentrations may be attributed to the increased viscosity of the feed and potential surface deposition of insoluble compounds during drying. Conversely, CI values, which reflect powder flowability, increased with extract concentration. The lowest CI (24.34 ± 1.02 %) was observed at 10 °B, indicating better flow characteristics, while the highest CI (28.90 ± 1.66 %) was observed at 20 °B suggests a more cohesive and less free-flowing powder. These results imply that higher extract concentrations negatively impact both solubility and flowability, with optimal physical properties observed at lower extract levels (5–10 °B).

Physicochemical characteristics

In Fig. 1, the instant powders revealed a clear shift in colour intensity with increasing extract concentration. The powder at 10 °B exhibited a deep reddish-brown colour, indicating a rich phenolic profile and favourable consumer appeal. In contrast, powder from 5 °B was paler, reflecting its lower phenolic content, while powders from 15 and 20 °B appeared darker and clumpier, possibly due to higher moisture and stickiness during collection. These results allowed us to choose the appropriate extract concentration for spray -drying encapsulation. In the next experiments, the extract concentration was fixed at 10 °B, as this level is widely used in previous studies and demonstrated the most favourable performance (23–25).

Effect of maltodextrin concentration on the characteristics of spray-dried *Helicteres isora* powder

Process yield

The concentration of maltodextrin (5–20 % w/v) significantly influenced the PY, EE, TPC, moisture content and hygroscopicity of the spray-dried *H. isora* powder, as shown in Table 2. At the lowest maltodextrin concentration (5 %), the process yield was 51.83 ± 0.83 %, which gradually increased to 51.44 ± 0.69 % at 10 % maltodextrin. The highest yield (57.02 ± 0.79 %) was achieved at 15 % maltodextrin, but decreased at 20 % maltodextrin (34.69 ± 0.65 %). This increase in yield up to 15 % maltodextrin could be attributed to the improved powder consistency and better encapsulation efficiency as the maltodextrin concentration increased, enhancing the atomization process. However, beyond 15 %, further increase in maltodextrin concentration did not contribute significantly to higher yield, possibly due to over-thickening of the feed solution, which hindered efficient drying.

Encapsulation efficiency

Encapsulation efficiency also improved with increasing maltodextrin concentration. The highest efficiency (45.96 ± 0.37 %) was observed at 15 % maltodextrin, compared to 40.35 ± 0.48 % at 5 %. However, a further increase to 20 % maltodextrin resulted in decreased EE, which may be attributed to the combined effects of extract dilution, increased feed viscosity and reduced interaction between maltodextrin and phenolic compounds at higher carrier concentrations. These results suggest that 10–15 % maltodextrin was most effective for encapsulating phenolic compounds in the spray-dried powder.

Total phenolic content

The TPC was highest in powders produced with 5 % maltodextrin, reaching 103.40 ± 1.23 mg GAE/g, which was significantly greater than the value obtained at 10 % maltodextrin (88.62 ± 0.98 mg GAE/g). Increasing the maltodextrin concentration to 15 % and 20 % further reduced the total phenolic content. The reduction at higher maltodextrin levels could be attributed to a dilution effect, where the increased carrier material could weaken encapsulation efficiency, leading to a higher loss of phenolic compounds.

Moisture content

Moisture content and hygroscopicity are critical factors influencing the storage stability and handling properties of spray-dried powders. In this study, increasing the maltodextrin concentration from 5–20 % led to a clear reduction in both parameters. Moisture content was highest at 5 % maltodextrin (6.31 ± 0.37 %) and gradually declined to the lowest level at 20 % maltodextrin (4.15 ± 0.20 %), indicating that higher carrier content improved water removal during spray drying. This trend is consistent with previous reports showing that increasing the total solids in the feed, primarily due to higher maltodextrin levels, enhances the drying rate and reduces residual moisture in the final powder.

Water solubility index and carr's index

Similarly, hygroscopicity decreased with increasing maltodextrin concentration, from 7.43 ± 0.40 g/100 g at 5 % to 4.41 ± 0.28 g/100 g at 20 %. This may be attributed to the formation of a more stable, glassy matrix by maltodextrin, which limits the exposure of hydrophilic functional groups and reduces moisture absorption during storage. Although maltodextrin is inherently hydrophilic, at sufficient concentrations it effectively encapsulates active compounds and masks their water-attracting sites, thereby reducing the overall hygroscopicity of the powder. These findings underscore the role of maltodextrin not only in improving EE and

Table 2. Effect of maltodextrin concentration (% w/v) on process yield, encapsulation efficiency, total phenolic content and physicochemical properties of spray-dried *H. isora* extract powder

Maltodextrin concentration (% w/v)	Process yield (%)	Encapsulation efficiency (%)	Total phenolic content (mg GAE/g)	Moisture content (%)	Hygroscopicity (g/100g)	WSI (%)	CI (%)
5	51.83 ± 0.83^{b}	40.35 ± 0.48^{b}	103.40 ± 1.23^{a}	6.31 ± 0.37^{a}	7.43 ± 0.40^{a}	84.67 ± 0.58^{c}	23.92 ± 1.23^{b}
10	51.44 ± 0.69^{b}	45.13 ± 0.50^{a}	88.62 ± 0.98^{b}	5.29 ± 0.25^{b}	6.13 ± 0.21^{b}	87.33 ± 0.58^{b}	24.40 ± 1.44^{b}
15	57.02 ± 0.79^{a}	45.96 ± 0.37^{a}	64.52 ± 0.51^{c}	4.84 ± 0.18^{b}	4.83 ± 0.22^{c}	88.00 ± 1.00^{ab}	25.31 ± 1.03^{ab}
20	34.69 ± 0.65^{c}	29.14 ± 1.29^{c}	55.38 ± 2.46^{d}	4.15 ± 0.20^{c}	4.41 ± 0.28^{c}	89.67 ± 1.53^{a}	26.99 ± 0.46^{a}
CD ($p < 0.05$)	1.47	1.42	2.79	0.49	0.54	1.88	2.08

Values are expressed as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences at $p < 0.05$ according to one-way ANOVA followed by Fishers' LSD test. CD: Critical Difference at $p < 0.05$.

yield, but also in enhancing the physical stability of bioactive-rich powders.

Maltodextrin levels increased from 5–20 % (w/v) and WSI gradually improved, indicating enhanced solubility of the spray-dried powders. The lowest WSI was recorded at 5 % maltodextrin (84.67±0.58 %), while the highest was observed at 20 % (89.67±1.53 %). This increase is likely due to the improved carrier matrix formed by higher maltodextrin content, which facilitates better solubilization upon reconstitution. In terms of powder flowability, the CI values also increased with maltodextrin concentration. The lowest CI was at 5 % (23.92 ± 1.23 %) and the highest was at 20 % (26.99 ± 0.46 %), suggesting that while solubility improved with more maltodextrin, the powders became slightly more cohesive and less free-flowing. These findings suggest that moderate maltodextrin levels (10–15 %) offer a balance between good solubility and acceptable flow properties for instant powder applications.

Physicochemical characteristics

Finally, the visual appearance of the powders, as depicted in Fig. 2, showed that increasing maltodextrin concentration resulted in a whiter and finer powder. The powder produced with 10 % maltodextrin exhibited a smooth and uniform texture, suggesting optimal drying conditions. In contrast, the powders at 5 % maltodextrin were slightly darker and coarser, while those at 15 % and 20 % maltodextrin were very uniform and smooth in texture. However, it is important to note that powder characteristics should be linked to phenolic retention and PY. Therefore, the results suggest that a maltodextrin concentration of 10 % is the most suitable level for producing water-soluble *H. isora* powder using the spray-drying method.

Effect of inlet temperature on the characteristics of spray-dried *Helicteres isora* powder

The effect of inlet temperature on the physicochemical properties of spray-dried *H. isora* powder is summarised in Table 3. As the inlet temperature increased from 160 to 190 °C, notable changes were observed across several parameters.

Process yield

The process yield ranged from 51.53 ± 0.52 to 53.49 ± 0.55 %. The highest yield was obtained at 180 °C, while the lowest was at 160 °C. A moderate yield was also recorded at 190 °C (51.91± 0.73 %). These results suggest that temperatures around 170-180 °C are optimal for maximising yield.

Encapsulation efficiency

Encapsulation efficiency improved significantly with increasing temperature, rising from 43.07 ± 0.44 % at 160 °C to 45.96 ± 0.57 % at 190 °C. At temperatures of 170 °C and above, statistically similar and higher EE (p<0.05) were obtained, indicating more effective retention of phenolic compounds within the carrier matrix at higher temperatures.

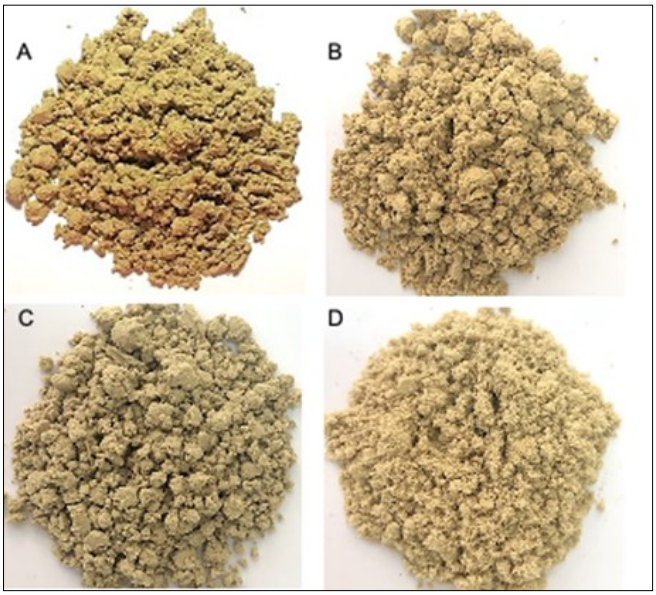

Fig. 2. The instant powder was formed with different maltodextrin concentrations (with extract concentration of 10 %, inlet temperature of 180 °C, a feed flow rate of 555 mL/h): (A) 5 %, (B) 10 %, (C) 15 %, (D) 20 %.

Total phenolic content

A progressive increase was also seen in the TPC, which rose from 84.84 ± 0.87 mg GAE/g at 160°C to a peak of 88.52 ± 1.09 mg GAE/g at 190 °C. This enhancement may be attributed to improved encapsulation and reduced degradation of phenolic compounds at more efficient drying conditions.

Moisture content

Conversely, the moisture content decreased significantly as the inlet temperature increased. The highest moisture content was observed at 160 °C (5.50 ± 0.17 %), which gradually declined to 4.42 ± 0.64 % at 190 °C. This trend confirms that higher temperatures accelerate water evaporation, resulting in a drier final product. Hygroscopicity exhibited an inconsistent pattern. The lowest hygroscopicity was observed at 160 °C (5.84 ± 0.17 g/100 g), whereas higher values were recorded at 170 °C (6.81 ± 0.37 g/100 g) and 190 °C (6.79 ± 0.28 g/100 g). This may reflect the influence of drying temperature on powder matrix structure and exposure of hydrophilic groups.

Water solubility index and carr's index

In terms of WSI, values remained high across all temperatures, ranging from 85.33 ± 0.58 to 87.00 ± 1.00 %, with no significant differences observed (p>0.05), indicating that inlet temperature had

Table 3. Effect of inlet temperature on process yield, encapsulation efficiency, total phenolic content and physicochemical properties of spray-dried *H. isora* extract powder

Inlet temperature (°C)	Process yield (%)	Encapsulation efficiency (%)	Total phenolic content (mg GAE/g)	Moisture content (%)	Hygroscopicity (g/100g)	WSI (%)	CI (%)
160	51.53 ± 0.52^{c}	43.07 ± 0.44^{b}	84.84 ± 0.87^{c}	5.50 ± 0.17^{a}	5.84 ± 0.17^{b}	85.33 ± 0.58^{a}	27.52 ± 1.22^{a}
170	52.91 ± 0.98^{ab}	45.38 ± 0.12^{a}	85.71 ± 0.23^{bc}	4.74 ± 0.36^{b}	6.81 ± 0.37^{a}	87.00 ± 1.00^{a}	23.81 ± 1.19^{b}
180	53.49 ± 0.55^{a}	45.75 ± 0.53^{a}	86.75 ± 0.99^{b}	4.67 ± 0.39^{b}	6.34 ± 0.20^{a}	86.67 ± 0.58^{a}	24.43 ± 1.16^{b}
190	51.91 ± 0.73^{bc}	45.96 ± 0.57^{a}	88.52 ± 1.09^{a}	4.42 ± 0.64^{b}	6.79 ± 0.28^{a}	87.00 ± 1.00^{a}	22.51 ± 1.80^{b}
CD (p < 0.05)	1.35	0.84	1.62	0.80	0.50	1.54	2.58

Values are expressed as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences at p < 0.05 according to one-way ANOVA followed by Fishers' LSD test. CD: Critical Difference at p < 0.05

minimal impact on solubility. Finally, the CI, a measure of powder flowability, was highest at 160 °C (27.52 ± 1.22 %), suggesting poor flowability. CI values improved significantly at higher temperatures, reaching the lowest value at 190 °C (22.51 ± 1.80 %), indicating better flow properties.

Physicochemical characteristics

The morphological characteristics of *H. isora* powders produced at varying inlet temperatures (Fig. 3) reveal distinct differences in texture, colour and granule size. At 160 °C, the powder appeared coarse, darker and aggregated, indicating incomplete drying and higher moisture retention. As the temperature increased to 170 °C and 180 °C, the powders became finer, whiter and more uniform in texture, reflecting improved drying efficiency and better powder structure. At 190 °C, the powder maintained a smooth texture but appeared slightly more clumped, possibly due to rapid surface drying and partial thermal degradation. Overall, powders dried at 170–180 °C exhibited the most desirable morphology-smooth, non-sticky and visually consistent-suggesting optimal spray-drying performance at these temperatures.

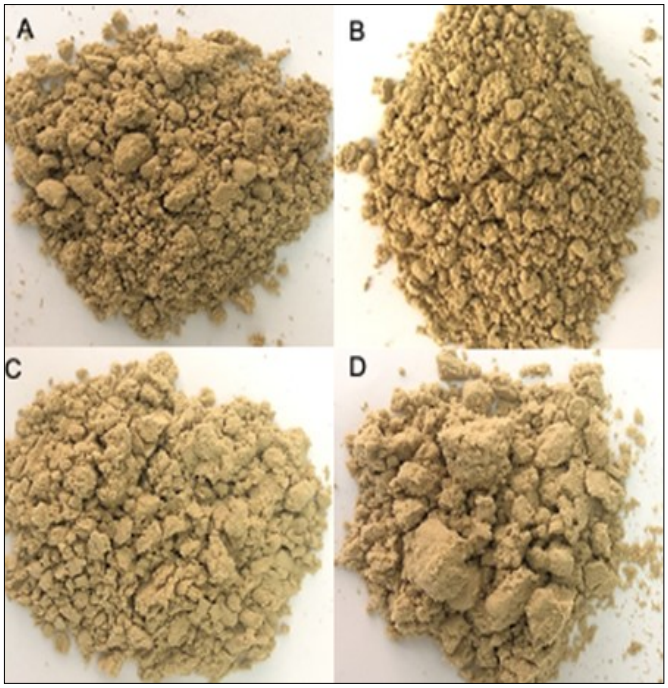

Fig. 3. The instant powder formed with different inlet temperatures (with extract concentration of 10 %, maltodextrin concentration 10 %, a feed flow rate of 555 mL/h): (A) 160 °C, (B) 170 °C, (C) 180 °C, (D) 190 °C.

Effect of feed flow rate on the characteristics of spray-dried *Helicteres isora* powder

An increase in feed flow rate typically leads to larger droplet size and shorter residence times, which can reduce the exposure of the product to high air temperatures and help preserve bioactive compounds. However, a higher feed flow rate can also lead to higher moisture content in the powder, as the material may not have sufficient contact with hot air for efficient drying (26). Table 4 presents the effects of varying feed flow rates on the characteristics of *H. isora* spray-dried powder. The data show that as the feed flow rate increased from 750 to 1200 mL/h, both process yield and encapsulation efficiency declined, while the moisture content of the powder increased. This can be explained by the fact that higher pump speeds reduce the residence time of the material in the drying chamber, leading to less efficient drying. As a result, the moisture content increases and more wet particles adhere to the chamber walls, reducing the recovery efficiency after the drying process. Moisture content is a critical factor for powder quality, as it affects properties such as flowability, stability and stickiness (27).

A similar trend was observed in a study on the encapsulation of *Phaleria macrocarpa* extracts using maltodextrin in a laboratory spray dryer (Lab Plant SD06A, UK), where the moisture content of the spray-dried powder increased from 4.88 to 6.83 % as the feed flow rate rose from 485 to 2115 mL/h (28). Additionally, a study on the encapsulation of anthocyanins extracted from *Hibiscus sabdariffa* L. flowers indicated that increasing the flow rate from 300 to 420 mL/h improved encapsulation efficiency from 87.89 % to 94.11 %, but further increasing the rate to 660 mL/h resulted in a decline to 85.15 % (29).

A comparison of two feed flow rates used in this experiment, 555 and 750 mL/h, showed that most properties of the *H. isora* spray-dried powder were similar, with the exception of hygroscopicity. The powder from the 750 mL/h treatment had lower hygroscopicity than the powder from the 555 mL/h treatment, despite their similar moisture contents (Table 4). Therefore, to achieve a higher-quality powder and reduce spray drying time for better economic efficiency, a feed flow rate of 750 mL/h was selected.

Fig. 4 displays the morphological characteristics of *H. isora* powders spray-dried at different feed flow rates ranging from 555 to 1200 mL/h. Visually, powders produced at lower flow rates (555-750 mL/h) appear finer, more uniform and less aggregated, indicating better atomization and drying. In contrast, flow rates 555-750 mL/h exhibit coarser and more irregular particle structures, possibly due to shorter residence times and incomplete drying at higher flow rates.

Table 4. Effect of feed flow rate on process yield, encapsulation efficiency, total phenolic content and physicochemical properties of spray-dried *H. isora* extract powder

Feed flow rate (mL/h)	Process yield (%)	Encapsulation efficiency (%)	Total phenolic content (mg GAE/g)	Moisture content (%)	Hygroscopicity (g/100g)	WSI (%)	CI (%)
555	51.58 ± 1.48^{ab}	44.91 ± 0.56^{ab}	85.67 ± 1.06^{a}	4.46 ± 0.15^{b}	7.26 ± 0.30^{a}	86.67 ± 1.53^{a}	23.90 ± 1.04^{a}
750	52.42 ± 0.88^{a}	45.53 ± 0.41^{a}	86.18 ± 0.77^{a}	4.61 ± 0.20^{ab}	6.51 ± 0.24^{b}	87.33 ± 1.15^{a}	23.49 ± 1.50^{a}
990	49.81 ± 0.75^{bc}	44.09 ± 0.37^{b}	86.20 ± 0.72^{a}	4.81 ± 0.17^{a}	6.42 ± 0.29^{b}	86.33 ± 1.53^{a}	23.28 ± 0.84^{a}
1200	49.00 ± 0.77^{c}	41.06 ± 0.39^{c}	85.45 ± 0.80^{a}	4.90 ± 0.16^{a}	6.67 ± 0.19^{b}	87.00 ± 1.00^{a}	23.59 ± 1.16^{a}
CD ($p < 0.05$)	1.63	1.86	1.60	0.51	0.52	1.53	2.82

Values are expressed as mean ± SD (n = 3). Different superscript letters within the same column indicate significant differences at $p < 0.05$ according to one-way ANOVA followed by Fishers' LSD test. CD: Critical Difference at $p < 0.05$.

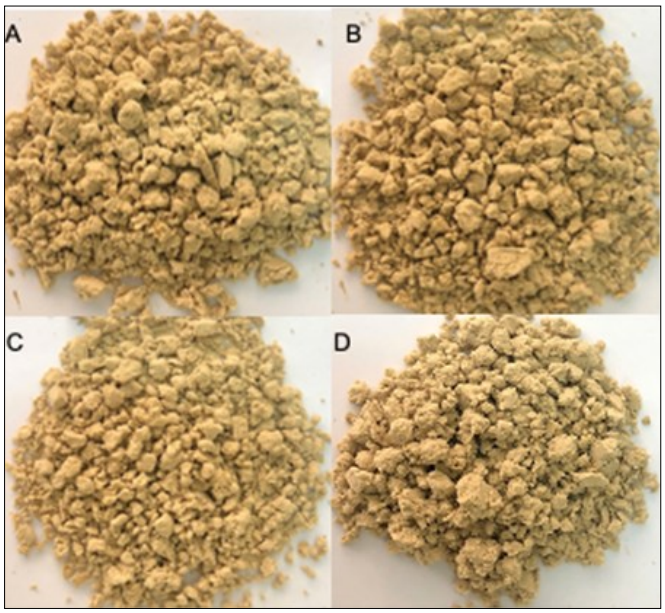

Fig. 4. The instant powder formed with different feed flow rate (with extract concentration of 10 %, maltodextrin concentration 10 %, inlet temperature of 170 °C: (A) 555 mL/h, (B) 750 mL/h, (C) 990 mL/h, (D) 1200 mL/h.

Discussion

This study investigated the effects of different extract concentrations, maltodextrin concentration, inlet temperature and feed flow rate on the spray-drying encapsulation of *H. isora* extract. The primary aim was to identify optimal conditions for producing instant powder with high phenolic retention, EE and desirable physicochemical properties. Extract concentration had a substantial impact on both encapsulation efficiency and powder quality. While the highest phenolic content (96.97 ± 1.16 mg GAE/g) was achieved at 20 °B extract concentration, this was accompanied by poor process yield and high moisture content. These issues likely stem from the increased viscosity of the feed solution, which reduces atomization efficiency and promotes wall deposition during drying. Previous studies have also reported that overly concentrated feed solutions can compromise drying efficiency and powder recovery due to increased resistance to atomization and heat transfer (23, 27). On the other hand, 10 °B extract concentration offered a balance between high encapsulation efficiency (41.12 ± 0.27 %), acceptable phenolic retention and stable moisture and flow properties, making it the most suitable core concentration.

Maltodextrin concentration significantly influenced PY, EE and powder stability. As a carrier, maltodextrin facilitated drying by increasing total solids, which improved atomization and reduced stickiness at concentrations up to 15 %. The highest yield (57.02 ± 0.79 %) and EE (45.96 ± 0.37 %) were observed at 15 % maltodextrin. However, phenolic retention decreased as maltodextrin concentration increased, likely due to the dilution effect and reduced loading of bioactives per unit mass of powder. Research has demonstrated that decreased phenolic concentration at high maltodextrin levels occurs despite improved encapsulation efficiency (16). Furthermore, moisture content and hygroscopicity decreased as maltodextrin concentration increased, supporting its role in forming a stable matrix that protects encapsulated compounds while limiting water absorption (21).

Water solubility index and carr's index further affirmed the influence of maltodextrin. Water solubility index improved from 84.67 % at 5 % maltodextrin to 89.67 % at 20 %, while CI values increased slightly, indicating reduced flowability at higher maltodextrin concentrations. Similarly, for spray-dried 'cempedak' fruit juice, response-surface optimisation identified 15 % maltodextrin (DE10) at 160 °C as the optimum condition, providing a high WSI together with acceptable bulk density and caking characteristics (30). In plant-based 'milk' powders, the addition of 5–10 % maltodextrin has also been shown to enhance solubility while maintaining CI values in the fair-flowability region (31). These results suggest that a moderate concentration of 10–15 % maltodextrin is ideal for achieving a balance between solubility and handling characteristics. Inlet temperature also played a pivotal role in powder quality. As the temperature increased from 160 to 190 °C, PY, EE and phenolic retention improved, while moisture content decreased. The enhanced drying performance at higher temperatures is attributed to the greater thermal energy available for rapid water evaporation and solid matrix formation (27). Although the highest TPC (88.52± 1.09 mg GAE/g) was observed at 190 °C, the best overall balance between drying efficiency and powder stability was noted at 170–180 °C. At 190 °C, minor signs of thermal degradation and increased powder clumping were observed, potentially compromising sensory quality.

Feed flow rate influenced both drying efficiency and powder characteristics. Increasing flow rates from 555 to 1200 mL/h resulted in reduced EE and higher moisture content, consistent with the shortened residence time in the drying chamber. This limits water removal and encourages wall deposition, as noted in other plant extract encapsulation studies (28, 30). High feed flow rates decreased the contact time of drying air with the feed, thus reducing heat transfer efficiency and powder moisture content (32). Extraction using ciriguela peel was also found to behave similarly with influence of feed flow rate over either wet basis or encapsulation efficiency and interactions between feed flow rate–temperature affecting powder quality (36). Among the flow rates tested in the present study, 750 mL/h produced powders with the best EE, least hygroscopicity and a satisfactory water content, which confirmed that moderate flow rates are capable of achieving full-fledged microcapsule formation and powder stability. This finding is consistent with a study on ciriguela peel extract, which also reported optimal results at a feed flow rate of 800 mL/h (33). Collectively, the identified optimal conditions: 10 °B extract concentration, 10–15 % maltodextrin, an inlet temperature of 170–180 °C and a feed flow rate of 750 mL/h produce a powder with high solubility, low moisture content, acceptable flowability and good retention of phenolic compounds. These properties are particularly advantageous for the formulation of instant *H. isora* tea, as they promote rapid reconstitution, stable storage, favourable sensory attributes and consistent dosage of bioactives.

Conclusion

In this study, the selection of spray-drying conditions for *H. isora* extract was carried out using the One-Factor-At-A-Time. According to the results, the spray drying conditions for producing *H. isora* instant powder were successfully determined, which were extract concentration of 10 °B, maltodextrin concentration of 10 % w/v, inlet air temperature of 170 °C and feed flow rate of 750 mL/h. The best process yield, encapsulation efficiency, total phenolic content, moisture content, hygroscopicity, water solubility index and Carrs' index achieved on these selected conditions were 52.42 %, 45.53 %, 86.18 mgGAE/g, 4.61 %, 6.51 %, 87.33 % and 23.49 %. Furthermore,

the obtained powder has a pale-yellow colour and the characteristic aroma of the original medicinal plant, which are favourable conditions for instant tea production. Beyond identifying optimal conditions, this study provides a solid foundation for utilising *H. isora* powder as a functional ingredient. The spray-dried powder demonstrated high solubility, good flowability and stable moisture content, indicating its suitability for instant tea and other nutraceutical beverages. Future work should focus on evaluating storage stability, optimising reconstitution and sensory properties and assessing the bioavailability of encapsulated phenolics. Scaling up the process and exploring alternative encapsulating materials may further improve product performance and support the development of a commercially viable *H. isora* instant tea.

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Authors' contributions

DTB conceptualised and executed the study and authored the manuscript. TLGT, THHL, TBT, QDV and NTLL served as investigators in the study. THH served as an investigator, finalised the manuscript and coordinated its submission to the journal. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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