

Encapsulation-based drying of sea buckthorn (*Hippophae rhamnoides* L.) juice

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ABSTRACT:

Sea buckthorn (*Hippophae rhamnoides* L.) is a rich source of phenolic compounds and flavonoids; however, its high sugar and organic acid content causes significant stickiness during drying, resulting in low powder recovery. This study focused to investigate the effect of maltodextrin (MD) concentration on spray-drying performance, physicochemical properties, microstructure, particle size, and bioactive compound retention of sea buckthorn juice powder. Fresh juice was mixed with MD at concentrations of 5, 10, 15, and 20% (w/w) and spray-dried under controlled conditions. Product yield, moisture content, bulk density, particle morphology, total phenolic content (TPC), and total flavonoid content (TFC) were evaluated. Increasing MD concentration significantly improved powder recovery, with the highest yield ($94.36 \pm 0.04\%$) obtained at 20% MD. All powders exhibited low moisture content (1.67–2.68%), indicating effective dehydration. Scanning electron microscopy revealed predominantly spherical particles with smooth surfaces, confirming successful encapsulation. Particle size analysis showed a mean diameter of $11.13 \pm 3.25 \mu\text{m}$, with sizes ranging from 4.24 to $43.56 \mu\text{m}$. The powder

containing 20% MD retained considerable amounts of bio-active compounds, with TPC and TFC values of $2.37 \pm 0.04\%$ and $0.367 \pm 0.004\%$, respectively. These results demonstrate that 20% MD is an effective carrier for encapsulation-based spray drying of sea buckthorn juice, producing a stable powder suitable for food and pharmaceutical applications.

INTRODUCTION

Sea buckthorn (*Hippophae rhamnoides* L.) is a medicinal and nutritional plant widely distributed in Europe and Asia and traditionally used in food, pharmaceutical, and cosmetic products. Its berries are rich in vitamins, particularly vitamin C, moreover, carotenoids, phenolic acids, flavonoids, and fatty acids, which contribute to antioxidant, anti-inflammatory, and cardioprotective activities.¹⁻³ Due to this unique phytochemical composition, sea buckthorn has attracted increasing interest as a functional ingredient in modern product development.

Despite its nutritional value, the processing of sea buckthorn juice into stable powder form remains challenging. The high content of low-molecular-weight sugars and organic acids results in a low

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glass transition temperature, causing stickiness, poor flowability, and adhesion to dryer walls during spray drying.^{4,5} Additionally, phenolic compounds and flavonoids are sensitive to heat, oxygen, and moisture, leading to degradation during thermal processing.⁶

Spray drying is one of the most widely applied techniques for converting liquid food and pharmaceutical materials into powders due to its scalability, economic efficiency, and ability to produce uniform particles.⁷ However, the addition of carrier agents is essential for the successful spray drying of fruit juices. MD is commonly used as an encapsulating agent because of its high glass transition temperature, low hygroscopicity, neutral flavor, and good film-forming properties.⁸ Previous studies on spraydried berry juices, such as blueberry, pomegranate, and acerola have demonstrated that MD improves powder yield, reduces moisture content, and enhances stability of phenolic compounds.^{9–11}

Although several studies have reported the drying of sea buckthorn products, systematic investigations focusing on the influence of MD concentration on spray-dried sea buckthorn juice powder, particularly in terms of microstructure and bioactive compound retention, remain limited. Therefore, the objective of this study was to evaluate the effect of different MD concentrations on the physical properties, microstructure, and preservation of phenolic and flavonoid compounds in spray-dried sea buckthorn juice powder.

MATERIALS AND METHODS

1.1. Raw materials and reagents

Ripe fruits of the Chuiskaya cultivar of sea buckthorn (*Hippophae rhamnoides* L.), cultivated in Sukhbaatar sum, Selenge aimag (latitude 50.2369° N, longitude 106.2114° E), were sourced from Monos Pharm LLC and utilized throughout the study.

Rutin and gallic acid standards (purity >98%) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Maltodextrin was purchased from New Francisco Biotechnology (Yunfu, China). All organic solvents and chemicals, including Folin–Ciocalteu reagent and sodium carbonate, were of analytical grade and obtained from Sigma-Aldrich (St. Louis, MO, USA).

1.2. Spray Drying of the prepared juice

Freshly pressed sea buckthorn juice was mixed with MD at concentrations of 5, 10, 15, and 20% (w/w) and stirred manually until a homogeneous. The mixture was homogenized using a homogenizer (model YHAD500SH-18G, Shanghai Yuanhuai Industrial Co., Ltd.) at 6000 rpm for 15 min to ensure uniform dispersion.¹² Spray drying was carried out using a laboratory-scale spray dryer (model YC-015, Shanghai Pilotech Instrument & Equipment Co., Ltd.). The operating conditions were as follows: inlet temperature of 160–180 °C, outlet temperature of 70–85 °C, feed pump speed of 20 rpm, and air blower rate of 25. The encapsulation and drying process is illustrated in Figure 1.

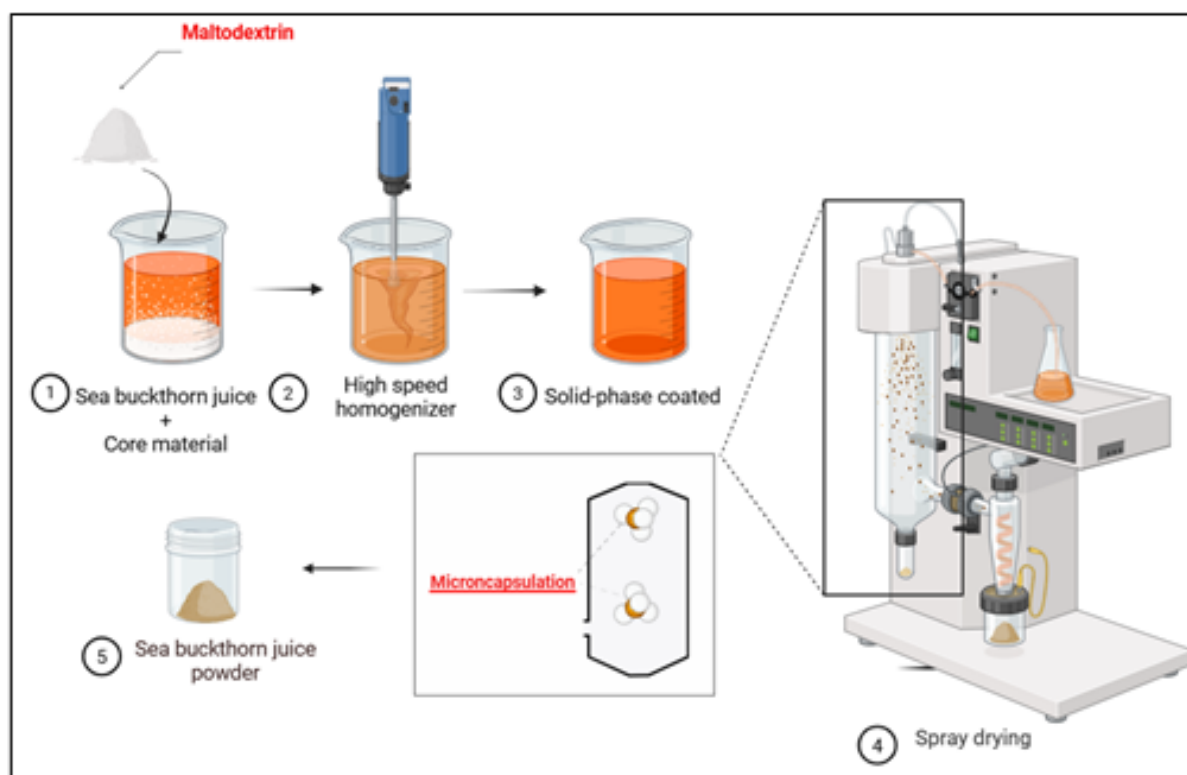


Figure 1. Process diagram of spray-drying¹³ (Illustration created with Biorender.com)

1.3. Product yield

Product yield (%) was calculated by comparing the mass of spray-dried powder to the total dry solids in the initial feed using the expression⁴:

$$\text{Yield (\%)} = \frac{m_p}{m_o + m_c}$$

where m_p denotes the mass (g) of the spray-dried sea buckthorn powder, while m_o and m_c indicate the masses (g) of the oil phase and carrier material present in the initial emulsion, respectively.

1.4. Moisture content

Approximately 2 g of dried powder was weighed on an analytical balance, and the moisture content was determined using a moisture analyzer (model PMB 53, Adam Equipment Co. Ltd.) at 105 °C until a constant weight.¹⁴ Results are expressed as a percentage (%).

1.5. Bulk density

Five g of the powder sample was gently transferred into a clean 10 mL graduated cylinder and vortexed for 1 min (vortex mixer, model DY-100B, Guangdong, China) to ensure uniform particle distribution. The occupied volume was recorded, and bulk density was calculated as mass divided by occupied volume and expressed in g/mL¹⁵:

$$\text{Bulk density (g/mL)} = \frac{\text{Mass of power(g)}}{\text{Volume occupied(mL)}}$$

1.6. Microstructure

The morphology of sea buckthorn powder prepared by encapsulation was analyzed using a scanning electron microscope (model TM-1000, Hitachi Co. Ltd., Japan). For morphological observation, samples were mounted on double-sided conductive carbon tape, placed under vacuum, and examined at an accelerating voltage of 5 kV with a magnification range of 800, 1500 and 2000 ×. The surface uniformity, aggregation, pore structure, and fracture characteristics of the spray-dried powder were observed and imaged.¹⁶

1.7. Total Flavonoid Content (TFC)

The TFC of the sea buckthorn juice powder was determined following the method described by Zhang et al.¹⁷ Sea buckthorn juice powder (1.0 g) was extracted with 20 mL of 95% ethanol (1:20, w/v) using sonication at 50 °C and 150 W for 40 min. The extract was filtered through a 0.45 µm membrane filter. An aliquot of 1 mL of the filtrate was mixed with 0.3 mL of 5% NaNO₂ solution. After 5 min, 0.3 mL of 10% AlCl₃ solution was added. Then, after 6 min, 2 mL of 1 M NaOH was added, and the total volume was adjusted with distilled water. The mixture was thoroughly mixed, and the absorbance was measured at 510 nm using a UV

spectrophotometer (UVmini-1240, Shimadzu, Japan). TFC of the samples was expressed as a percentage (%) on a dry weight basis and calculated using the following equation:

$$\text{Total flavonoid content} = \frac{x \cdot V \cdot n}{m} \cdot 100$$

where x is the experimentally determined total flavonoid concentration, V is the extraction volume (mL), n is the dilution factor, and m is the dry weight of the sample (g). Total flavonoid content was expressed as a percentage (%) on a dry weight basis by multiplying the calculated value by 100.

1.8. Total phenol content (TPC)

Total phenolic content (TPC) was determined using the Folin–Ciocalteu method with minor modifications. Sea buckthorn powder (100 mg/mL) was prepared in 20 mM PBS (pH 7.4), ultrasonicated for 10 min, and centrifuged at 10,000 rpm for 10 min. The supernatant was used for analysis. An aliquot (0.33 mL) was mixed with 2.5 mL distilled water and 0.16 mL Folin–Ciocalteu reagent, reacted for 5 min, followed by addition of 0.3 mL 10% sodium bicarbonate. The mixture was incubated for 30 min at room temperature in the dark. The absorbance was measured at 760 nm using a UV–Vis spectrophotometer (model UVmini-1240, Shimadzu, Japan). TPC was expressed as a percentage of gallic acid equivalents relative to dry weight (% GAE, DW basis)¹⁸.

$$\text{Total phenol content} = \frac{x \cdot V \cdot n}{m} \cdot 100$$

where x is the experimentally determined total phenolic concentration, V is the extraction solution volume (mL), n is the dilution factor, and m is the dry weight of the sample (g). The final result is expressed as a percentage (%) on a dry weight basis after multiplication by 100.

1.9. Statistical analysis

Results are presented as mean ± standard deviation (mean ± SD) with the number of replicates (n) indicated. Statistical analysis was performed using Microsoft Excel. Image analyses were conducted with ImageJ software, and graphs were prepared using OriginPro 2026 software.

RESULTS

1.10. Yield, moisture content and bulk density

The effect of MD concentration on juice yield, dry powder yield, moisture content, and bulk density of spray-dried sea buckthorn juice powder is presented in Table 1. Juice yield increased progressively with increasing MD concentration, rising from 15.21 ±

0.14% at 5% MD to $17.85 \pm 0.30\%$, $20.90 \pm 0.19\%$, and $25.50 \pm 0.04\%$ at 10%, 15%, and 20% MD, respectively. This trend suggests that increasing MD concentration enhances drying performance by increasing the total solid content of the feed solution and reducing stickiness associated with the high sugar and organic acid content of sea buckthorn juice.

Dry powder yield could not be obtained at 5% MD, likely due to insufficient carrier material resulting in severe adhesion of the product to the drying-chamber walls. However, powder recovery improved markedly at higher MD concentrations: $50.19 \pm 0.81\%$ at 10% MD, $73.59 \pm 0.55\%$ at 15% MD, and $94.36 \pm 0.04\%$ at 20% MD. The improvement in powder yield can be attributed to the higher glass transition temperature of the feed solution with increasing MD concentration, which reduces stickiness during spray drying.

Moisture content of the obtained powders remained relatively low, ranging from $1.67 \pm 1.01\%$ to 2.68

$\pm 0.41\%$. Slight variations were observed among samples; however, all values are within an acceptable range for spray-dried powders. Low moisture content is important for improving microbial stability and extending shelf life.

Bulk density showed a gradual decrease with increasing MD concentration, from $2.01 \pm 0.41 \text{ g/cm}^3$ at 10% MD to $1.89 \pm 0.26 \text{ g/cm}^3$ at 15% MD, and $1.78 \pm 0.99 \text{ g/cm}^3$ at 20% MD. This reduction may be associated with changes in particle structure and the formation of larger, less compact particles at higher carrier concentrations.

Overall, the 20% MD formulation demonstrated the most favorable characteristics, including the highest powder yield, acceptable moisture content, and suitable bulk density, and was therefore selected for further analysis in this study.

Table 1. Results of the physical parameters of sea buckthorn juice powder

Parameter	5% MD	10% MD	15% MD	20% MD
Appearance	-			
Juice yield (%)	15.21 ± 0.14	17.85 ± 0.30	20.9 ± 0.19	25.5 ± 0.04
Dry powder yield (%)	-	50.19 ± 0.81	73.59 ± 0.55	94.36 ± 0.04
Moisture content (%)	-	1.67 ± 1.01	2.68 ± 0.41	2.33 ± 0.78
Bulk density (g/cm^3)	-	2.01 ± 0.41	1.89 ± 0.26	1.78 ± 0.99

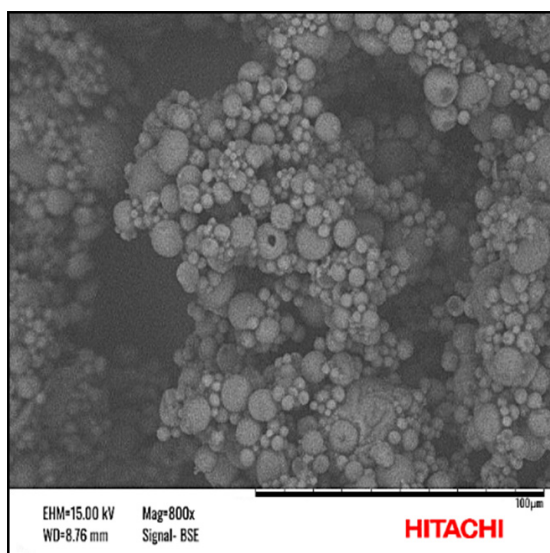
Note: Data are expressed as mean $\pm$ standard error ($n = 3$); MD-MD, ND = not determined.

1.11. Microstructure

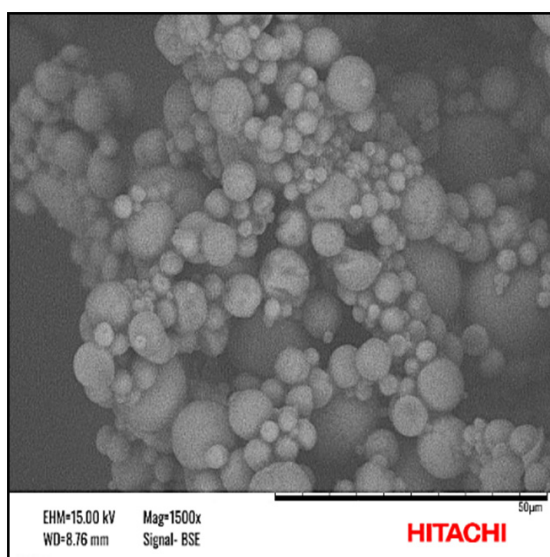
The surface morphology of dried sea buckthorn juice powder containing 20% MD was investigated by scanning electron microscopy (SEM) operated in backscattered electron (BSE) mode at magnifications of $800\times$, $1500\times$, and $2000\times$. As shown in Figure 2, the powder particles predominantly exhibited a spherical to near-spherical morphology. At lower magnification ($800\times$), the powder appeared as agglomerates composed of individual particles of various sizes. Higher magnifications ($1500\times$ and $2000\times$) revealed smooth particle surfaces and well-formed spherical

structures, indicating effective encapsulation and film-forming behavior of MD.

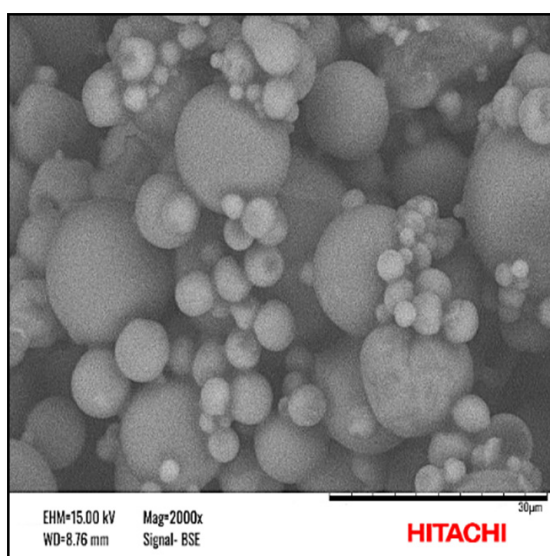
The absence of cracks or collapsed structures suggests that MD provided sufficient mechanical strength during drying, contributing to the structural integrity of the particles. Smaller particles adhered to larger ones were also observed, which may be attributed to particle coalescence or partial agglomeration during drying. Such morphology is commonly reported for spray- or hot-air-dried fruit juice powders containing MD and is beneficial for improving powder stability and reducing stickiness.



(A). 800× magnification



(B). 1500× magnification



(C). 2000× magnification

Figure 2. Microstructure of 20% MD sea buckthorn juice powder

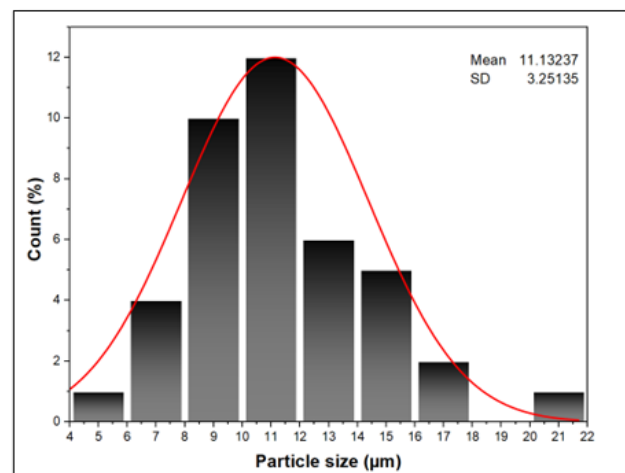


Figure 3. Histogram of the particle size distribution of sea buckthorn juice powder

A histogram of particle size distribution was constructed in Figure 3 using OriginLab 2026 software. The particle size distribution was determined from SEM micrographs using ImageJ software, and the results are summarized in Table 2. The mean particle diameter was $11.13 \pm 3.25 \mu\text{m}$, with sizes ranging from 4.24 to 43.56 μm . The relatively broad size distribution indicates the coexistence of fine and coarse particles, which is consistent with the observed SEM images.

Table 2. Particle size parameters of dried sea buckthorn juice powder

Parameter	Particle size (μm)
Mean	11.13
SD	3.25
Min	4.243
Max	43.566

Note: Mean represents the average particle diameter calculated from SEM images using ImageJ software; SD indicates the standard deviation; Min and Max denote the minimum and maximum particle sizes observed.

1.12. Total Phenolic Content and Total Flavonoid Content

TP and TF contents of the dried sea buckthorn juice powder containing 20% MD were determined, and the results are presented in Table 3. The TPC of the powder was $2.370 \pm 0.040\%$ and the TFC was $0.367 \pm 0.004\%$. The relatively high TPC indicates that a considerable proportion of phenolic compounds was retained after the drying process. Phenolic compounds are known for their strong antioxidant activity and play an important role in the health-promoting properties of sea buckthorn. MD likely helped protect these compounds during drying by forming a physical barrier against heat and oxygen. Similarly, the detectable level of total flavonoids suggests that flavonoid compounds were

partially preserved despite their known sensitivity to thermal processing. The lower content of flavonoids compared to total phenolics is consistent with previous reports, as flavonoids represent a specific subgroup of phenolic compounds and are more susceptible to degradation during drying.¹⁷

Table 3. Comparison of TPC and TFC in sea buckthorn juice and spray-dried juice powder containing 20% MD

Bioactive	Juice (%)	Juice powder (%)
TP	0.803 ± 0.006	2.370 ± 0.040
TF	0.132 ± 0.001	0.367 ± 0.004

Note: Data are expressed as mean ± standard error (n = 3). Mean values are given in percent (%) of sample weight.

2. DISCUSSION

MD concentration significantly affected spray-drying performance. Powder yield increased markedly with increasing MD content, reaching 94.36% at 20% MD. At lower concentrations (5–10% MD), powder recovery was poor due to severe adhesion of the feed material to the drying-chamber walls. This phenomenon is commonly reported in spray drying of fruit juices rich in sugars and organic acids and is attributed to their low glass transition temperatures.^{4,7}

The improved powder yield at higher MD levels can be explained by increased total solids in the feed and elevation of the feed's glass transition temperature, both reducing stickiness during drying. Similar trends have been reported for spray-dried pomegranate and acerola juices, where 15–25% MD was required to achieve acceptable recovery.^{9,10} All powders exhibited low moisture content (1.67–2.68%), consistent with typical fruit juice powders and favorable for storage stability, since low moisture content reduces microbial growth, caking, and bioactive degradation.¹¹

Bulk density decreased with increasing MD concentration, indicating the formation of larger, less compact particles with higher apparent porosity. This trend may affect packing and flow properties and should be considered for packaging design. Comparable reductions in bulk density with higher carrier content have been observed in other MD-based spray-dried fruit powders.^{8,12}

SEM revealed predominantly spherical particles with smooth surfaces, characteristic of carbohydrate-based encapsulation matrices produced by spray drying. The absence of extensive surface cracks or collapsed structures suggests that MD provided sufficient mechanical strength to the particle shell during drying. Partial agglomeration of fine particles onto larger ones was observed, commonly attributed to

particle collisions during drying and collection.⁷ The mean particle diameter ($11.13 \pm 3.25 \mu\text{m}$) is within the micrometer range reported for spray-dried fruit juice powders and is considered suitable for applications requiring good flowability and rapid reconstitution.¹²

The 20% MD spray-dried sea buckthorn juice powder retained substantial amounts of phenolic and flavonoid compounds. The relatively high TPC value ($2.370 \pm 0.040\%$) indicates effective protection of phenolics during spray drying, likely because MD forms a protective matrix limiting heat, oxygen, and light.⁶ Flavonoids, more susceptible to thermal degradation than total phenolics, were at lower levels ($0.367\% \pm 0.004\%$), a pattern consistent with previous spray-dried fruit juices.¹⁰ Nevertheless, the observed flavonoid retention shows that encapsulation-based spray-drying can preserve a significant fraction of these bioactive compounds.

Overall, these results agree with international studies and confirm that MD is an effective carrier for improving spray-drying efficiency and preserving bioactive compounds in sea buckthorn juice powder.

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