From honey to functional powder: drying technologies, carrier agents, and industrial applications

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Abstract. A stable powdered form of natural honey can be obtained through drying processes, which helps overcome several technological limitations associated with liquid honey. The physicochemical and functional properties of honey powder are strongly influenced by the drying method and the type of carrier agents used. In this study, honey powders were produced using spray drying and freeze drying with different carrier systems, including maltodextrin, gum arabic, and dextrin. A total of ten formulations were prepared and evaluated. The analyzed parameters included moisture content, bulk density, hygroscopicity, reducing sugars, total sugars, hydroxymethylfurfural (HMF), diastase activity, particle size distribution, and thermal properties (TGA and DSC). The results showed that spray-dried honey powders exhibited lower moisture content, higher bulk density, and smaller particle size, whereas freeze-dried powders demonstrated higher diastase activity and lower HMF levels. The type of carrier significantly influenced the structural stability, thermal behavior, and reconstitution properties of the powders. Overall, the findings indicate that dried honey powders can serve as a promising functional ingredient for various food applications.

1 Introduction

Honey is a naturally occurring substance composed mainly of sugars, enzymes, organic acids, amino acids, vitamins, and phenolic compounds that contribute to its nutritional and medicinal properties [1, 2]. The chemical composition of honey varies depending on its botanical and geographical origin; however, it generally contains approximately 80–85% carbohydrates, 15–17% water, and smaller amounts of bioactive compounds [3, 4]. Among these compounds, polyphenols and flavonoids are largely responsible for the antioxidant, antimicrobial, and anti-inflammatory properties of honey [2–5]. Several studies have also suggested that these bioactive components may reduce oxidative stress and influence cellular metabolism, thereby contributing to the antimicrobial and cardioprotective potential of honey [6, 7]. Despite its valuable nutritional profile, liquid honey presents several technological challenges during industrial processing. Its high viscosity, hygroscopic nature, and low glass transition temperature (Tg) often lead to problems such as stickiness, caking, and instability during storage [8]. These properties limit its direct incorporation into powdered formulations. To overcome these limitations, converting honey into powder through drying has attracted increasing research interest. Drying not only improves product stability and shelf life but also facilitates handling, transportation, and incorporation into dry food formulations [9]. A variety of technological approaches have been applied for the drying of honey, including spray drying, freeze drying, vacuum drying, and several combined drying methods [10]. Each of these techniques significantly influences the sensory profile and physicochemical characteristics of the final product. In addition, the use of appropriate carrier agents such as gum arabic, maltodextrin, and dextrin plays a crucial role in improving the stability of the honey matrix and reducing stickiness during the drying process [11,12]. The present study investigates the physicochemical and functional properties of honey powders produced using different drying methods and carrier agents [6,13]. Among the available technologies, spray drying is the most widely used industrial method for producing food powders due to its continuous operation and high processing capacity. However, the application of spray drying to high-sugar materials such as honey requires the addition of suitable carrier agents. Without these drying aids, the high sugar content of honey often leads to severe wall deposition inside the dryer and poor powder recovery during the drying process [14]. Various process parameters, such as inlet and outlet temperature, feed solids content, atomization conditions, and airflow, significantly influence particle morphology, moisture content, and the retention of heat-sensitive compounds in spray-dried honey powders [15].

Freeze drying (lyophilization) enables a high retention of color, aroma, and antioxidant capacity due to water removal by sublimation at low temperatures. However, this technique is energy-intensive and economically less efficient when applied on a large industrial scale for honey processing [16]. Alternative approaches such as low-temperature drying and vacuum drying can reduce thermal stress and may perform

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effectively when combined with suitable carrier agents, providing a balance between product quality and processing cost [17]. One of the major technological challenges in drying sugar-rich materials is their low glass transition temperature, which leads to stickiness during drying. Tg-based stickiness models and the increased susceptibility to non-enzymatic browning reactions, particularly the formation of hydroxymethylfurfural (HMF), have been widely reported in honey and similar carbohydrate-rich matrices [18].

Vacuum drying represents a mild dehydration technique that operates under reduced pressure conditions. This allows water removal at lower temperatures, thereby minimizing the thermal degradation of bioactive compounds present in honey [19]. Previous studies have reported that vacuum-dried honey can retain higher enzymatic activity compared to conventionally dried honey, mainly due to reduced exposure to oxygen and heat during processing [20]. Moreover, this process limits the formation of HMF, helping preserve the natural color and flavor of honey. Consequently, vacuum drying has been considered a promising approach for producing high-quality powdered honey [21]. The combination of volumetric heating by microwaves and reduced pressure in microwave–vacuum drying significantly enhances the efficiency of water evaporation from honey while simultaneously preserving nutrients and phenolic compounds [22]. This combined process has been reported to reduce drying time by more than 50% compared to conventional freeze drying [23]. Consequently, microwave–vacuum drying has been identified as a promising technology for the sustainable and energy-efficient production of honey powder [24]. Appropriate carrier selection and careful control of processing conditions also play an important role in minimizing undesirable chemical transformations, particularly hydroxymethylfurfural (HMF) formation and enzyme inactivation. Lower drying temperatures, controlled moisture levels, and the use of thermostabilizing carriers are essential for preserving diastase activity and antioxidant potential in dried honey products [25].

Carrier selection, both in terms of type and concentration, is therefore a critical factor in honey powder production. Carriers such as maltodextrin, gum arabic, modified starches, and certain protein-based materials can increase the apparent glass transition temperature of the feed mixture, forming a protective matrix that reduces stickiness and improves powder yield during drying [26]. Comparative studies on honey carrier systems have shown that carrier blends, such as combinations of maltodextrin and gum arabic, often outperform single-carrier systems in terms of cost efficiency, encapsulation performance, and aroma retention [27]. In addition, the stability of honey powders is strongly influenced by the molecular weight distribution and hygroscopicity of the carrier agents. Carriers such as low-DE maltodextrins and gum arabic rich in arabinogalactan differ in their film-forming ability and in their interactions with honey sugars, which ultimately leads to variations in powder morphology and reconstitution behavior [12–27]. Recent studies have increasingly focused on hybrid drying strategies, including pre-concentration, low-temperature atomization, dehumidified-air spray drying, and microwave-assisted drying processes. These approaches aim to reduce thermal stress while maintaining industrial applicability. Such hybrid systems have demonstrated improved antioxidant retention and reduced HMF formation compared with conventional high-temperature spray drying methods [28]. Microstructural analyses, including scanning electron microscopy and porosity measurements, have further indicated that both the type of carrier and the selected drying technique significantly influence particle surface morphology, internal porosity, and the resulting hygroscopic behavior. These characteristics are critical parameters affecting powder stability, shelf life, and handling properties during storage and processing [29].

Furthermore, co-encapsulation of honey with various bioactive compounds, such as propolis, vitamins, and probiotics, has been successfully explored in recent studies. However, appropriate design of carrier systems and careful optimization of drying conditions are required in order to maintain the viability of sensitive components—particularly probiotics—and to preserve the antioxidant potential of phytochemicals during both drying and storage [30]. Beyond stabilization, the transformation of honey into powder also opens new opportunities for industrial and functional applications. Honey powder can serve as a natural sweetener and flavoring agent widely used in bakery, confectionery, and dairy products, where improved shelf life and more uniform distribution can be achieved compared to liquid honey [31]. In the nutraceutical and functional food sectors, honey powder can also act as a carrier for bioactive compounds, including propolis, vitamins C and E, and probiotic microorganisms [30].

Co-microencapsulation of honey with probiotic strains such as Lactobacillus spp. has been reported to enhance microbial survival during storage and simulated gastrointestinal conditions, highlighting the potential of honey-based matrices as delivery systems for probiotic cultures [32]. In addition, the conversion of honey into powder contributes to sustainability and improved resource utilization by enabling the valorization of surplus or crystallized honey that might otherwise be wasted. Such approaches support circular economy concepts and can increase the economic value of bee products, particularly in regions characterized by high floral biodiversity [33].

2 Materials and Methods

2.1 Raw material

Natural multifloral honey was collected from the Plovdiv region, Bulgaria, an area characterized by a temperate continental climate and rich floral biodiversity dominated by Tilia spp. and Helianthus annuus. The honey was filtered, homogenized, and

stored in sealed glass containers at 20 ± 2 °C prior to use. The total solids content of the honey ranged between 82–83.0 ± 0.1% (d.b.), while the moisture content was 17.4 ± 0.1% (w/w).

2.2 Chemicals and reagents

Analytical-grade reagents were used throughout the study. Fructose, glucose, and sucrose standards used for HPLC calibration were purchased from Sigma-Aldrich (St. Louis, MO, USA). Acetonitrile and methanol (HPLC grade) were obtained from Merck (Darmstadt, Germany). Deionized water was used in all analytical procedures.

2.3 Sample preparation

Ten formulations were prepared by mixing liquid honey with different carrier agents, including gum arabic (GA), maltodextrin (MD), and dextrin (DX). The carriers were added to the honey in different proportions in order to investigate their influence on the physicochemical properties of the produced honey powders. The formulations consisted of single-carrier systems containing either gum arabic or maltodextrin, as well as mixed-carrier systems combining gum arabic and dextrin. Each formulation was prepared using the same honey source but with different carrier compositions. To facilitate clear identification of the samples, the powders produced by spray drying were coded as SDH (spray-dried honey), while those obtained by freeze drying were coded as FDH (freeze-dried honey). The detailed composition of all formulations is presented in Table 1.

Table 1. Composition of prepared samples

Sample code	Composition (w/w%)	Drying method
60H40GA	60%Honey+40%Gum Arabic	Spray dryer
50H50GA	50%Honey+50%Gum Arabic	Spray dryer
60H40MD	60%Honey+40%Maltodextrin	Spray dryer
50H50MD	50%Honey+50%Maltodextrin	Spray dryer
50H30GA20DX	50%Honey+30%GA+20Dextrin	Spray dryer
60H40GA	60%Honey+40%Gum Arabic	Freeze dryer
50H50GA	50%Honey+50%Gum Arabic	Freeze dryer
60H40MD	60%Honey+40%Maltodextrin	Freeze dryer
50H50MD	50%Honey+50%Maltodextrin	Freeze dryer
50H30GA20DX	50%Honey+30%GA+20Dextrin	Freeze dryer

The mixtures were stirred at 40°C for 15min until complete homogenization.

2.4 Drying Procedures

2.4.1 Spray drying

Spray drying was carried out using an Anhydro Spray Dryer (Denmark). The feed solids were adjusted to 60 ± 2%. The operating conditions were as follows: inlet air temperature 190 °C, outlet temperature 85 °C, atomizer nozzle diameter 0.7 mm, aspirator capacity 90%, and feed rate 3 mL min^{-1}. The resulting honey powders were collected, sealed, and stored in a desiccator at 24 °C under controlled low-humidity conditions (relative humidity below 20%) until further analysis.

2.4.2 Freeze drying

Freeze drying was performed using a Labconco FreeZone 6 L (Kansas city USA) freeze dryer. The samples were pre-frozen at −40 °C for 12 h, followed by sublimation at 0.05 mbar for 72 h. After drying, the obtained material was gently ground using a mortar to obtain a fine powder and subsequently passed through a 500 µm sieve in order to remove large agglomerates and obtain a more uniform particle size prior to further physicochemical analyses.

2.4.3 Bulk density

Bulk density was determined by carefully pouring 50 g of powder sample into a 250 cm^3 graduated cylinder without shaking or mechanical disturbance. The surface of the powder was gently leveled using a brush, and the occupied volume (Vn) was recorded. The measurement was performed in duplicate [28].

2.4.4 Tapped bulk density

Tapped density was determined by placing 50 g of powder into a 250 mL graduated cylinder, which was then mechanically tapped for 1–3 min until a constant volume was reached. As a result of tapping, the powder volume decreased due to particle rearrangement and improved packing [28].

2.4.5 Hygroscopicity

A sample of the product, weighing 8–10 g, was placed in a Petri dish located in the upper section of a desiccator. The desiccator was maintained at 25 °C and 75% relative humidity, achieved using a saturated sodium chloride (NaCl) solution placed in the lower compartment of the desiccator. The volume of the salt solution was maintained at not less than 1 L.

Measurements were carried out three times during the first 2 h 30 min. Subsequently, the samples were weighed daily for 10 days until equilibrium was reached between the moisture content of the sample and the saturated salt solution within the desiccator at the specified temperature. The measurement accuracy was ±0.1 mg [29].

2.4.6 Moisture content

Duplicate powder samples, each weighing approximately 1 g, were dried at 105 °C for 4 h. The weight loss, mainly attributed to water evaporation, was measured before and after the drying process. The percentage change in weight, corresponding to the moisture loss, was calculated and expressed as a percentage of the initial sample mass [36].

2.4.7 Sugars in honey

The determination of sugars in honey was carried out using high-performance liquid chromatography (HPLC Waters 1525 Binary Pump, Water Corporation, MA USA) equipped with a refractive index detector. Standard solutions of fructose (2 g%), glucose (2 g%), and sucrose (0.5 g%) were prepared in distilled water. A working sugar mixture was prepared by transferring 1 mL of each standard solution into a 10 mL volumetric flask, after which the volume was adjusted to the mark with distilled water.

For sample preparation, 2.5 g of honey was dissolved in 25 mL of deionized water in a beaker. The solution was then filtered through a 0.045 µm nylon filter into a 50 mL volumetric flask, and an appropriate aliquot was transferred into an HPLC vial. Chromatographic analysis was performed using liquid chromatography coupled with a refractive index detector (LC–RID), and data were processed using OpenLab software. Separation was achieved using a ZORBAX carbohydrate column (150 × 4.6 mm). The mobile phase consisted of a 20:80 (v/v) mixture of distilled water and acetonitrile. A 10 µL sample was injected at a flow rate of 1.5 mL min^{-1}, while the column temperature was maintained at 27 °C throughout the analysis [31].

2.4.8 Hydroxymethylfurfural (HMF)

The HMF content was determined using high-performance liquid chromatography (HPLC) with UV detection, a method widely applied for the accurate quantification of HMF in honey samples. Honey samples were diluted by dissolving 5 g of honey in 50 mL of distilled water, followed by filtration through a 0.45 µm membrane filter. The filtered solution was then injected into an HPLC system (Waters 1525 Binary Pump, Waters Corporation, Milford, MA, USA) equipped with a Waters 2487 Dual Absorbance Detector and controlled using Empower chromatography software.

Separation was carried out using a Merck Lichrospher RP18 column (5 µm, 125 × 4 mm) with a guard cartridge packed with the same stationary phase (Merck). The chromatographic conditions included an isocratic mobile phase consisting of 90% water with 1% acetic acid and 10% methanol, a flow rate of 0.7 mL min^{-1}, and an injection volume of 20 µL. All solvents used were HPLC grade (Merck).

The detection wavelength range was 220–660 nm, while chromatograms were monitored at 285 nm. HMF identification was achieved by comparing the chromatographic peak of the honey samples with that of a reference HMF standard (Alfa Aesar, LOT 10183841) and by evaluating the corresponding absorbance spectra. Quantification was performed using an external calibration curve, measuring the signal at λ = 285 nm [40].

2.4.9 Diastase activity

Diastase is one of the principal enzymes naturally present in honey. The diastase activity was determined spectrophotometrically (UV-Vis spectrophotometer (Shimadzu UV-1800, Shimadzu Corporation, Kyoto, Japan), using the standard AOAC method based on the enzymatic hydrolysis of starch. In this method, a defined amount of honey was added to a starch solution. The diastase enzyme present in honey progressively hydrolyzes the starch during incubation. After the addition of an iodine solution, the remaining starch reacts with iodine to produce a characteristic color change: a deep blue color indicates the presence of significant residual starch, a brown-red color indicates partial hydrolysis, while a clear solution indicates complete starch degradation. The absorbance of the reaction mixture was measured at 660 nm using a spectrophotometer at specific reaction times. The time required to reach the defined absorbance endpoint was used to calculate the diastase number (DN). One diastase unit is defined as the amount of enzyme that hydrolyzes 0.01 g of starch to the specified endpoint within one hour at 40 °C under the test conditions [32].

2.4.10 Particle size distribution

Particle size distribution of the honey powder samples was determined using a laser diffraction particle size analyzer (Mastersizer 2000, Malvern Instruments, Worcestershire UK). A small amount of powder was dispersed in isopropanol (refractive index 1.37), which was used as the dispersion medium. Magnetic stirring was applied to ensure uniform dispersion of the particles prior to analysis. The particle size measurements were carried out using the instrument's standard operating conditions.

Each measurement was performed in triplicate, and the median particle diameter (D50) was recorded as the representative particle size of the powder. The D50 value corresponds to the particle diameter at which 50% of the total particle population is smaller than the measured size, according to the normalized particle size distribution [11].

2.4.11 Glass transition temperature (Tg)

The glass transition temperature (Tg) of the honey powders was determined using differential scanning calorimetry (DSC) (TA Instruments Q2000 New Castle USA). Approximately 10 mg of powdered sample was placed in an aluminum pan and hermetically sealed. The analysis was conducted under a nitrogen atmosphere (50

mL min^{-1}) with a heating rate of 10 °C min^{-1}. Each sample was first cooled to −50 °C and held isothermally for 5 min in order to eliminate thermal history. The samples were then heated up to 150 °C.

The glass transition temperature was determined as the midpoint of the inflection observed in the DSC thermogram. All measurements were performed in triplicate [34].

2.5 Statistical analysis

All experiments were performed in triplicate, and the results were expressed as mean ± standard deviation. Statistical analysis was carried out using SPSS software (IBM Corp., USA). Differences between the mean values were evaluated using one-way analysis of variance (ANOVA) followed by Tukey's post hoc test. Statistical significance was considered at $p<0.05$.

3 Results and discussion

The findings of this study provide a comparative evaluation of the physicochemical characteristics of honey powders produced by spray drying and freeze drying using different carrier agents, including gum arabic (GA), maltodextrin (MD), and dextrin (DX). The discussion focuses on how variations in formulation composition and drying technique influenced key quality parameters such as moisture content, density, total sugars, reducing sugars, Brix value, particle size, morphology, and thermal properties (Tg).

The overall results revealed clear differences between the two drying methods. Spray-dried samples exhibited lower moisture content and smaller average particle size, whereas freeze-dried samples showed greater structural integrity and higher porosity due to the sublimation process during drying. Furthermore, the type and proportion of carrier agents significantly affected powder stability, solubility, and the retention of bioactive compounds. Moisture content was identified as a key parameter influencing the stability, flowability, and shelf life of honey powders. The results showed a clear difference between the two drying methods. Spray-dried honey samples exhibited moisture contents ranging from 2.2 to 2.7%, which were lower than those observed in freeze-dried samples (3.1–3.8%). This difference can be explained by the rapid evaporation of water during spray drying, where inlet temperatures of up to 190 °C promote efficient removal of bound moisture. In contrast, freeze drying removes water through sublimation under vacuum conditions, which may result in slightly higher residual moisture in the final product [9,16]. The composition of the carrier agents also influenced the final moisture content. Samples containing maltodextrin (MD) showed slightly lower moisture levels compared to those formulated with gum arabic (GA) or dextrin (DX). This behavior can be attributed to the higher glass transition temperature of maltodextrin, which reduces hygroscopicity and facilitates the formation of a more compact matrix with fewer pores [33].

In contrast, formulations containing gum arabic, a more hydrophilic carrier, tended to absorb higher amounts of atmospheric moisture. For honey powders, a moisture content below 4% is generally considered necessary to ensure product stability. Similar optimal moisture levels ranging from 2 to 4% have been reported in previous studies on honey powders and fruit based powders [10,35]. These findings indicate that the drying conditions applied in the present study were effective in producing shelf-stable honey powders [6].

Bulk density and tapped density are important physical parameters that describe the packing behavior and flow properties of powder materials. The experimental results (Tables 2–3) showed that both bulk density (0.42–0.47 g/cm^3 and 0.49–0.53 g/cm^3) and tapped density (0.27–0.34 g/cm^3 and 0.30–0.37 g/cm^3) values of spray-dried honey powders were significantly higher than those observed for freeze-dried powders.

This difference can be attributed to the formation of more compact particles during spray drying as a result of the atomization process. Such particle structures allow more efficient packing with reduced pore volume [9,14]. In contrast, freeze-dried powders typically exhibit a more porous and less dense structure due to the sublimation of ice crystals during the drying process. These structural differences between the two drying methods directly influence the packing properties and bulk behavior of the powders [13].

Table 2. Physicochemical and functional characteristics of spray-dried honey powders

Sample	moist (%)	bulk den (g/cm^3)	tapp dens (g/cm^3)	hygrosco (%)	red. sug (%)	total sug (%)	part size (µm)	Tg (°C)	HMF (mg/kg)	diast act (DN)
60H40GA	2.7 ± 0.1^{a}	0.47 ± 0.02^{a}	0.53 ± 0.02^{a}	17.0 ± 0.3^{b}	63.5 ± 0.5^{a}	76.2 ± 0.6^{c}	13.5 ± 0.6^{a}	47.5 ± 0.8^{d}	18.3 ± 0.5^{b}	6.4 ± 0.2^{b}
50H50GA	2.8 ± 0.1^{a}	0.45 ± 0.02^{ab}	0.54 ± 0.03^{a}	18.1 ± 0.4^{a}	63.7 ± 0.4^{a}	76.3 ± 0.5^{c}	12.8 ± 0.5^{b}	50.1 ± 0.7^{c}	19.0 ± 0.6^{a}	6.1 ± 0.2^{b}
60H40MD	2.3 ± 0.1^{c}	0.43 ± 0.02^{b}	0.50 ± 0.02^{b}	15.7 ± 0.3^{c}	64.1 ± 0.4^{a}	77.0 ± 0.6^{b}	11.9 ± 0.4^{c}	52.8 ± 0.9^{a}	17.5 ± 0.4^{c}	6.7 ± 0.2^{a}
50H50MD	2.2 ± 0.1^{c}	0.42 ± 0.02^{b}	0.49 ± 0.02^{b}	14.6 ± 0.2^{d}	64.0 ± 0.4^{a}	77.8 ± 0.6^{a}	11.2 ± 0.4^{d}	53.1 ± 0.8^{a}	16.7 ± 0.4^{a}	6.8 ± 0.2^{a}
50H30GA20DX	2.5 ± 0.1^{b}	0.44 ± 0.02^{b}	0.50 ± 0.02^{b}	15.2 ± 0.3^{c}	63.9 ± 0.4^{a}	77.4 ± 0.5^{ab}	11.0 ± 0.4^{d}	51.6 ± 0.7^{b}	18.5 ± 0.5^{ab}	6.5 ± 0.2^{ab}

Values are expressed as mean ± standard deviation (n = 3)**.** Different lowercase letters within the same column indicate statistically significant differences ($p < 0.05$) according to Tukey's HSD test**.**

Table 3. Physicochemical and functional characteristics of freeze-dried honey powders

sample	moist (%)	bulk den (g/cm³)	tapp den (g/cm³)	hygrosco (%)	red. sug (%)	total sug (%)	part size (µm)	Tg (°C)	HMF (mg/kg)	diast act (DN)
60H40GA	3.8 ± 0.1[a]	0.34 ± 0.02[a]	0.37 ± 0.02[a]	19.3 ± 0.4[a]	66.1 ± 0.5[a]	78.3 ± 0.6[a]	19.2 ± 0.6[a]	46.3 ± 0.8[c]	10.3 ± 0.3[b]	7.6 ± 0.2[a]
50H50GA	3.7 ± 0.1[a]	0.33 ± 0.02[a]	0.35 ± 0.02[a]	19.7 ± 0.4[a]	65.7 ± 0.4[a]	79.0 ± 0.6[a]	18.3 ± 0.6[c]	48.5 ± 0.8[b]	11.2 ± 0.3[a]	7.4 ± 0.2[a]
60H40MD	3.2 ± 0.1[b]	0.30 ± 0.02[b]	0.33 ± 0.02[b]	19.1 ± 0.4[a]	67.0 ± 0.5[a]	79.1 ± 0.6[a]	18.8 ± 0.6[b]	51.3 ± 0.9[a]	10.0 ± 0.3[b]	7.8 ± 0.2[a]
50H50MD	3.1 ± 0.1[b]	0.29 ± 0.02[b]	0.32 ± 0.02[b]	18.8 ± 0.3[a]	66.5 ± 0.4[a]	79.2 ± 0.6[a]	17.9 ± 0.5[c]	52.1 ± 0.9	9.6 ± 0.3[b]	7.5 ± 0.2[a]
50H30GA20DX	3.6 ± 0.1[a]	0.27 ± 0.02[b]	0.30 ± 0.02[b]	19.5 ± 0.4[a]	66.0 ± 0.4[a]	78.7 ± 0.5[a]	19.4 ± 0.6[a]	48.7 ± 0.8[b]	10.5 ± 0.3[ab]	7.4 ± 0.2[a]

Values are expressed as mean ± standard deviation (n = 3). Different lowercase letters within the same column indicate significant differences ($p < 0.05$) according to Tukey's HSD test.

The type of carrier agent also influenced the bulk density values. Powders containing maltodextrin (MD) exhibited slightly lower bulk density compared to those formulated with gum arabic (GA), which may be related to differences in molecular weight and film-forming properties during drying. Gum arabic tends to form a stronger and more cohesive matrix, resulting in denser particle packing [23]. In contrast, formulations containing dextrin (DX) showed intermediate density values, reflecting its moderate contribution to particle structure and compactness.

The obtained density values are consistent with previously reported data. Samborska (2015) reported bulk density values ranging from 0.41 to 0.47 g/cm³ for spray-dried honey powders produced using GA and MD as carrier agents. Hygroscopicity represents the ability of powder particles to absorb moisture from the surrounding environment and is directly related to their storage stability and caking behavior. The obtained results (Tables 2–3) showed that freeze-dried honey powders exhibited higher hygroscopicity values (18.8–19.7%) compared with spray-dried powders (14.6–18.1%). This behavior can be attributed to the highly porous and amorphous structure of freeze-dried powders, which increases surface area and enhances water vapor adsorption capacity [37]. In contrast, spray-dried samples produced smoother and more compact particles, resulting in lower moisture absorption during storage. Similar observations were reported by Suhag et al. [11] and Cano Chauca et al. [36] who noted that powders with smoother surfaces tend to exhibit lower hygroscopicity due to the reduced number of active sites available for water molecule adsorption. The type and concentration of carrier agents also significantly influenced the hygroscopic behavior of the powders. Samples containing maltodextrin (MD) exhibited lower hygroscopicity compared to those formulated with dextrin (DX) or gum arabic (GA). This effect can be attributed to the higher molecular weight and higher glass transition temperature (Tg) of maltodextrin, which reduces moisture absorption and improves structural stability [33]. In contrast, gum arabic contains a high proportion of hydrophilic polysaccharides and hydroxyl groups, which increases its ability to absorb water from the surrounding environment [23].

For powdered products, hygroscopicity values below 20% are generally considered desirable in order to ensure adequate storage stability and minimize stickiness during storage [6]. The results obtained in this study indicate that both drying methods, particularly formulations containing gum arabic, produced powders within the recommended stability range for honey and similar fruit-based powders [37].

Reducing sugars and total sugars are key parameters for evaluating the chemical composition and sweetness characteristics of dried honey powders. The analytical results (Tables 2–3) showed slight variations between the two drying methods. For spray-dried honey (SDH), the total sugar (TS) and reducing sugar (RS) contents ranged from 76.2–77.8% and 63.5–64.1%, respectively. In contrast, freeze-dried honey (FDH) exhibited slightly higher values, with TS ranging from 78.3 to 79.2% and RS from 65.7 to 66.5%. These results indicate that the carbohydrate fraction of honey remained largely stable during both drying processes. Nevertheless, slightly lower sugar values observed in spray-dried samples may be associated with the higher inlet temperatures applied during the drying process, which can promote limited degradation of simple sugars such as fructose and glucose. Similar observations were reported by Suhag et al. [11], who noted minor losses of sugar content during spray drying, mainly related to Maillard-type reactions occurring at elevated temperatures.

In contrast, freeze drying operates under low temperature and reduced pressure conditions, which minimizes thermal degradation and therefore allows better preservation of the original sugar composition. Previous studies have also reported that freeze-dried honey powders tend to retain higher levels of reducing sugars due to the absence of significant heat-induced degradation [16].

The type of carrier agent also influenced sugar retention in the dried powders. Samples containing maltodextrin (MD) exhibited the highest total sugar recovery, likely due to the formation of an amorphous glassy matrix that protects sugars from crystallization and oxidative reactions during drying [33]. In contrast, formulations containing gum arabic (GA) or dextrin (DX) showed slightly lower total sugar retention, which

may be related to differences in their molecular structure and dextrose equivalent values [24].

Particle size is an important characteristic that influences the flowability, solubility, and hydration behavior of honey powders. The results (Tables 2–3) showed that the average particle size of spray-dried samples (11.0–13.5 μm) was smaller than that of freeze-dried samples (17.9–19.2 μm). This difference can be attributed to the atomization process occurring during spray drying, where fine droplets are rapidly formed and dried, resulting in relatively uniform and rounded particles [9, 14]. In contrast, freeze-dried samples are generally associated with larger and more irregular particles due to the sublimation of ice crystals during the drying process. Similar structural characteristics have been reported in previous studies where, freeze-dried honey powders exhibit a more porous structure, while spray-dried powders tend to bee more compact [13, 33].

The type of carrier agent also influenced particle size distribution. Powders produced with maltodextrin (MD) generally showed smaller particle sizes due to its strong film-forming ability and higher viscosity, which helps reduce droplet coalescence during atomization and promotes the formation of more stable droplets during the spray drying process [23]. Variations in particle size and distribution directly influence important powder properties such as bulk density and wettability. Finer and more compact particles typically observed in spray-dried powders tend to exhibit higher packing density and faster dissolution, whereas the highly porous structure of freeze-dried powders promotes improved hydration capacity, although at the expense of lower packing density [39].

The glass transition temperature (Tg) is an important parameter affecting the thermal and physical stability of amorphous food materials. Tg represents the temperature range at which a material transitions from a rigid glassy state to a more flexible rubbery state. The results obtained in this study (Tables 2–3) showed that spray-dried honey powders exhibited higher Tg values (47.5–53.1 °C) compared with freeze-dried powders (46.3–52.1 °C). These differences may be attributed to the lower moisture content and more compact particle structure of spray-dried powders, both of which contribute to an increase in the glass transition temperature [9,13]. The type of carrier agent also had a significant influence on the glass transition temperature (Tg) of the honey powders. The highest Tg values were observed in samples containing maltodextrin (MD), followed by those formulated with dextrin (DX) and gum arabic (GA). These observations are consistent with previously reported findings, as maltodextrin generally possesses a higher molecular weight and lower hygroscopicity compared with dextrin and gum arabic. As a result, maltodextrin increases the rigidity of the amorphous matrix and reduces the plasticizing effect of water [34].

In contrast, gum arabic contains a higher proportion of low-molecular-weight sugars and hydrophilic functional groups, which can lead to increased stickiness at lower Tg values [23]. The results obtained in this study are in agreement with those reported by Samborska [9], who found that the Tg values of spray-dried honey powders prepared with GA and MD ranged between 47 and 55 °C. Similarly previous studies on freeze-dried honey powders have reported Tg values within a comparable range when maltodextrin was used a carrier agent [33]. For powdered products, the Tg value should remain above the ambient storage temperature (approximately 25 °C) in order to prevent stickiness, particle aggregation, and structural collapse. Therefore, the use of carriers such as maltodextrin and dextrin, combined with optimized spray-drying conditions, plays an important role in improving the thermal and physical stability of honey powders during storage [24].

The analysis of hydroxymethylfurfural (HMF) content and diastase activity provides valuable information regarding the thermal treatment and quality of honey products. HMF is a well-known indicator of sugar degradation caused by Maillard-type reactions, and it is widely used as an objective parameter for evaluating the intensity of heat treatment applied to honey [15]. The results presented in Tables 2–3 indicate that the HMF content of spray-dried honey powders (16.5–18.5 mg/kg) was higher than that of freeze-dried honey powders (9.6–11.2 mg/kg).

The increase in HMF content can be directly attributed to the high inlet temperatures (180–190 °C) used during the spray-drying process, which promote dehydration of hexoses and the formation of non-enzymatic browning products through Maillard-type reactions [40]. Previous studies have also shown that thermal processing may affect the antioxidant activity and color characteristics of honey products [43]. In contrast, diastase activity was better preserved in freeze-dried samples (7.4–7.8 Schade units) compared with spray-dried samples (6.1–6.8 Schade units). This difference can be explained by the lower processing temperatures and reduced pressure conditions applied during freeze drying, which minimize thermal stress on enzymatic systems. Enzymes such as α-amylase and β-amylase are known to be heat-sensitive, and their inactivation rates increase rapidly at temperatures above 60 °C [22, 41]. Similar observations have been reported in previous demonstrated that diastase activity decreases proportionally with increasing processing temperature and exposure time [41, 42]. These findings further support the suitability of freeze drying as a method that better preserves enzymatic activity in honey.

The type of carrier agent used in the formulations also influenced both HMF formation and enzyme retention. In general, spray-dried powders containing maltodextrin (MD) showed lower HMF levels and higher enzyme retention compared with formulations containing gum arabic (GA) or dextrin (DX). This effect can be attributed to the ability of maltodextrin to form a protective amorphous matrix, which encapsulates the honey components and reduces oxygen exposure and molecular mobility during drying [33]. Conversely, formulations containing GA and DX exhibited slightly higher HMF levels, which may be associated with their lower glass transition temperatures, facilitating localized heating and sugar dehydration reactions during the drying process. Overall, the results indicate that freeze drying provides better preservation of enzymatic

activity and limits heat-induced degradation, whereas spray drying, although more economically viable for industrial applications, may lead to greater thermal stress and partial quality degradation of honey powders [41].

4 Conclusion

The present study demonstrated that honey can be successfully transformed into a stable and functional powder using spray drying and freeze drying in combination with suitable carrier agents. Each drying technique offers specific advantages. Spray drying proved to be more suitable for industrial production due to its higher yield, lower moisture content, and improved flow properties, which are important for commercial processing. In contrast, freeze drying provided better preservation of bioactive compounds, enzymatic activity, and structural integrity, making it particularly appropriate for high-value functional ingredients. Among the carrier agents evaluated, maltodextrin exhibited the most balanced performance, as it increased the glass transition temperature, reduced hygroscopicity, and improved the protection of thermolabile compounds during drying. Gum arabic and dextrin, on the other hand, contributed to improved solubility, dispersibility and overall physical properties of the powders in aqueous systems.

Overall, honey powders produced under optimized drying conditions show considerable potential as industrial food ingredients. They can be applied in a wide range of products, including confectionery, bakery, beverages, dairy products, and nutraceutical formulations, where they may serve as natural sweeteners with additional antioxidant and functional properties. By carefully selecting the drying method, controlling processing parameters, and optimizing carrier formulations, it is possible to preserve the natural qualities of honey while improving its stability, handling, and applicability in modern food processing systems.

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