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Interplay between honey properties, carrier composition, and spray-drying performance of *Scaptotrigona mexicana* honey

Interacción entre las propiedades de la miel, la composición del acarreador y el rendimiento del secado por aspersión de la miel de *Scaptotrigona mexicana*

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Abstract

Scaptotrigona mexicana honeys typically exhibit moisture contents above 20%, which reduces their storage stability. In previous studies, spray-drying has been proposed as a strategy to stabilize stingless bee honeys by reducing water content; however, their high sugar content often decreases drying efficiency and powder recovery. In this study, the physicochemical and rheological properties of four *S. mexicana* honeys were characterized and their relationship with spray-drying yield and powder properties was evaluated. Two carrier systems were tested, combining maltodextrin (MD) and taro starch (TS) at different ratios (MD:TS = 1:0 and 1:1, w:w), using feed mixtures adjusted to 30% total solids. The resulting powders were evaluated in terms of color, moisture content, solubility, hygroscopicity, and process yield. Pearson correlation analysis revealed that the carrier composition had a significant influence on powder properties, with higher MD fractions enhancing both recovery (>50%) and solubility (>90%). These results highlight the importance of selecting the appropriate carrier for enhancing process efficiency and powder properties. The findings contribute to the technological valorization of stingless bee honeys by providing knowledge that may facilitate their stabilization and conversion into powdered form.

Keywords: stingless bee honey, spray-drying, taro starch, maltodextrin, powder recovery.

Resumen

Las mieles de *Scaptotrigona mexicana* suelen presentar una humedad superior al 20%, lo que reduce su estabilidad durante el almacenamiento. En estudios previos, el secado por aspersión se ha propuesto como una estrategia para estabilizar las mieles de abejas sin aguijón al reducir el contenido de agua; sin embargo, su alto contenido de azúcar reduce la eficiencia del proceso y la recuperación del polvo. En este estudio, se caracterizaron las propiedades fisicoquímicas y reológicas de cuatro mieles de *S. mexicana* y se evaluó su relación con el rendimiento del secado por aspersión y las propiedades del polvo. Se probaron dos sistemas de soporte, combinando maltodextrina (MD) y almidón de malanga (TS) en diferentes proporciones (MD:TS = 1:0 y 1:1, p/p), utilizando mezclas de alimentación ajustadas al 30% de sólidos totales. Los polvos resultantes se caracterizaron en términos de color, humedad, solubilidad, higroscopicidad y rendimiento del proceso. El análisis de correlación de Pearson mostró que la composición del material de soporte tuvo una fuerte influencia sobre las propiedades del polvo, donde fracciones de MD más altas mejoraron tanto el rendimiento (>50%) como la solubilidad (>90%). Estos resultados resaltan la importancia de la selección del material de soporte para mejorar la eficiencia del proceso y las propiedades del polvo. Los hallazgos contribuyen a la valorización tecnológica de las mieles de abejas sin aguijón al proporcionar conocimientos que pueden facilitar su estabilización y conversión en forma de polvo.

Palabras clave: miel de abeja sin aguijón, secado por aspersión, almidón de malanga, maltodextrina, recuperación de polvo.

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1 Introduction

Stinging bees and stingless bees share the same family, but taxonomically are different: *Apis* species belong to the Apinae subfamily, whereas stingless bees are classified under the Meliponinae. Although both groups produce honey, the global market is dominated by honey from *Apis mellifera* (Nordin *et al.*, 2018). In recent years, however, stingless bee honey has attracted increasing attention due to its phytochemical complexity, nutritional value, and traditional medicinal uses (Ávila *et al.*, 2018; Vit *et al.*, 2025), positioning meliponiculture as an emerging economic alternative in vulnerable regions (Gerginova *et al.*, 2023; Vit *et al.*, 2025).

Stingless bees are distributed throughout tropical regions and include more than 600 species with considerable potential for the development of nutraceutical products (Gerginova *et al.*, 2023; Nordin *et al.*, 2018; Vit *et al.*, 2025). Among them, the *Scaptotrigona mexicana* Guérin-Méneville species is conserved in various regions from Mexico from pre-Columbian times (Gerginova *et al.*, 2023; Lazcano-Hernández *et al.*, 2023). Honey from this species is characterized by higher moisture content, greater acidity, and a more complex profile of sugars and bioactive compounds compared to *Apis mellifera* honey. Although these features enhance its functional potential, stingless bee honeys typically exceeding 20% moisture, which makes them highly prone to fermentation, thereby reducing storage stability and limiting large-scale commercialization (Ávila *et al.*, 2018; Biluca *et al.*, 2020; Jimenez *et al.*, 2016; Lazcano-Hernández *et al.*, 2023; Nordin *et al.*, 2018; Vit *et al.*, 2025).

In this context, spray drying represents a promising strategy to improve the stability and handling of liquid foods by converting them into powders with extended shelf life and enhanced processability (Carpintero-Tepole *et al.*, 2024; Mutlu and Erbas, 2023; Samborska *et al.*, 2022; Torres-Aguilar *et al.*, 2024; Vázquez-León *et al.*, 2021). However, the spray drying of honey is particularly challenging due to its high viscosity and low glass transition temperature (Tg), which promote stickiness, wall deposition, and low powder recovery (Carpintero-Tepole *et al.*, 2024; Samborska, 2019; Suhag and Nanda, 2016; Suhag *et al.*, 2018; Toniazzo *et al.*, 2023b; Vázquez-León *et al.*, 2021). To mitigate these limitations, carrier agents such as maltodextrin are commonly used due to their high Tg, solubility, and protective properties (Samborska *et al.*, 2022; Sobulska and Zbicinski, 2021; Suhag *et al.*, 2018). Recently, interest has grown in alternative carriers derived from underutilized agro-resources, such as taro starch, which may offer additional technological and sustainability advantages (Hoyos-Leyva *et al.*, 2018a; Martínez-Cigarroa *et al.*, 2025).

Although the spray drying of *Apis mellifera* honeys has been widely studied (Jedlińska *et al.*, 2019; Osés *et al.*, 2021; Samborska, 2019; Suhag *et al.*, 2021; Toniazzo *et al.*, 2023b; Vosoghi *et al.*, 2025), research on stingless bee honeys remains limited. Cuevas-Glory *et al.* (2017) optimized the spray-drying process to obtain *Melipona beecheii* honey powder using response surface methodology, focusing on operational variables such as inlet air temperature and maltodextrin concentration, as well as their effects on powder yield and quality parameters, including hydroxymethylfurfural content, volatile retention, bulk density, moisture content, solubility time, hygroscopicity, and yield. Under those optimized conditions, Leyva-Moguel *et al.* (2022) processed honey from *Scaptotrigona pectoralis* and evaluated its physicochemical properties, including density, invertase activity, volatile compounds, hydroxymethylfurfural content, antioxidant activity, color, solubility, hygroscopicity, and moisture content. These studies provide valuable information on process optimization and the characterization of stingless bee honey powders. However, both approaches are primarily focused on processing conditions and final product properties, while limited information is available regarding the influence of the intrinsic physicochemical and rheological properties of stingless bee honeys on spray-drying performance. In addition, the use of alternative carrier systems beyond maltodextrin remains scarcely explored.

Therefore, the present study aims to evaluate the relationship between the physicochemical and rheological properties of *Scaptotrigona mexicana* honeys and their spray-drying performance, as well as the properties of the resulting powders, using different carrier formulations based on maltodextrin and taro starch. These findings contribute to the understanding of stingless bee honey processing and provide insights into their technological valorization as functional powdered ingredients.

2 Materials and methods

2.1 Materials

Four *Scaptotrigona mexicana* honey samples were obtained from different apiaries located in Cuetzalan, Puebla, Mexico. All samples were harvested in July 2024 and were provided by collaborating researchers from Instituto Tecnológico de Puebla (Mexico). Maltodextrin (DE-10) was obtained from FAPSA (Toluca, Mexico). Taro corms (*Colocasia esculenta*) were harvested in a commercial crop field in April 2023 in Santa Rosa, Veracruz, Mexico. All chemicals (reagent grade) were acquired from Golden Bell (Mexico City, Mexico).

2.2 *Taro starch isolation*

Taro starch was isolated following the methodology reported by Hoyos-Leyva *et al.* (2018b), with slight modifications. The main differences with respect to the original method include: (i) changes in drying conditions, (ii) the use of a sieving train (40 to 325 US mesh) prior to starch recovery, (iii) omission of the sodium bisulphite dispersion step and replacement with water suspension, and (iv) the use of different centrifugation parameters combined with repeated washing steps.

Briefly, the corms were reduced to 1-2 cm cubes and dried in a convection oven (Lobo Hornos Industriales S.A. de C.V., Mod. 12CH-160; CDMX, Mexico) at 55 °C until constant weight was reached. The dried material was milled and sieved through 40, 100, 200 and 325 US mesh. The powder was then suspended in water and centrifuged at 4000 $\times g$ for 10 min was carried out (Thermo Fisher Scientific Inc., Heraeus Megafuge 16R; MA, USA), this washing step was repeated twice. The final sediment was recovered, dried at 55 °C, milled, and sieved (100 US mesh). The resulting taro starch powder was stored in airtight containers. Moisture content (7.98 ± 0.23 g 100 g^{-1} d.b.) and protein content (4.63 ± 0.38g 100 g^{-1} d.b.) were determined according to AACCI methods 44-19 and 46-30 (AACCI, 2000), respectively.

2.3 *Physicochemical characterization of Scaptotrigona mexicana honey*

2.3.1 *Color parameters*

Color parameters were measured using a portable digital colorimeter (3nh Technology Co., TD, NR-145; Guangzhou, P.R. China) in the LCH color space.

2.3.2 *Moisture content*

Moisture content in the honey samples was analyzed according to the 969.38 AOAC official method (AOAC, 2006). Briefly, 1.0 g of honey was placed in a pre-dried aluminum tray and oven-dried at 110 °C to constant weight. Moisture content was determined gravimetrically from the difference between the initial sample mass and the final mass after drying.

2.3.3 *Soluble solids content*

Total soluble solids in the honey samples were determined with a portable optical refractometer. Following Toniazzo *et al.* (2023a), honey samples were homogenized at 50 ºC under magnetic stirring to prevent sugar crystallization. After cooling to room temperature (22 ± 1 ºC), readings were taken, and results were expressed in °Brix.

2.3.4 *pH and free acidity*

The free acidity and pH were analyzed in the honey samples according to the 962.19 AOAC official method (AOAC, 2006). First, the honey (10 g) was dispersed in distilled water (50 mL). Then, the pH was measured with a previously calibrated potentiometer (Shanghai Yueping Scientific Instrument Co. LTD, PHS-3CU; Shanghai, P.R. China.). Titration was then carried out with 0.05 N NaOH under magnetic stirring until reaching pH 8.5. The free acidity was expressed in milliequivalents per kilogram of honey.

2.4 *Rheological characterization of Scaptotrigona mexicana honey*

Honey flow behavior and viscoelastic properties (oscillatory tests) were analyzed using a parallel plate geometry (diameter: 40 mm) installed in a rheometer (TA Instruments, Discovery HR-2 Hybrid; DE, USA). All measurements were performed at 25 °C, with a 500 μm gap, and data were acquired using Trios software version 5 (TA Instruments; DE, USA).

2.4.1 *Flow behavior*

A shear rate intervale of 0.001 to 100 s^{-1} was used to obtain the flow curves. The data were fitted to the Ostwald–de Waele model (Suarez-Ramos *et al.*, 2023):

$$\tau = k\dot{\gamma}^n \tag{1}$$

where the shear stress (τ, Pa) is a function of the consistency index (k, Pa s^n), the shear rate ($\dot{\gamma}$, s^{-1}), and the flow behavior index (n, dimensionless) (Suarez-Ramos *et al.*, 2023). Apparent viscosity at 50 s^{-1} (η50) was used for comparison of the honey samples.

2.4.2 *Oscillatory rheological measurements*

Amplitude sweep tests (1 Hz) were carried out to identify the linear viscoelasticity range (LVR). Then, the frequency sweeps were carried out at a constant stress to determine the storage modulus (G’) and the loss modulus (G’ ’) as functions of the angular frequency (ω, rad s^{-1}) (Suarez-Ramos *et al.*, 2023; Sun *et al.*, 2020). G’ (Pa) and G’ ’ (Pa) data were fitted to model described by Sun *et al.* (2020):

$$G^{'}(Pa) = \Gamma(1-n')\cos\left(\frac{n'\pi}{2}\right)S'\omega^{n''} \tag{2}$$

$$G^{''}(Pa) = \Gamma(1-n'')\sin\left(\frac{n''\pi}{2}\right)S''\omega^{n''} \tag{3}$$

where $\Gamma(1-n)$ is the gamma function for $1-n$. According to Sun *et al.* (2020), for samples with wide range of physicochemical properties, separate gel strength (S) and gel index (n) parameters are required to attain good fits to the experimental data for the LVR region. Therefore, S' and n' were used for modeling of G', and S'' and n'' were the counterparts for modeling of G'' (Sun *et al.*, 2020).

2.5 *Spray drying of Scaptotrigona mexicana honey*

2.5.1 *Preparation of feed mixtures*

Feed mixtures were prepared following Tomczyk *et al.* (2020). Dispersions were formulated to contain 30% total solids (w/v), maintaining a honey solids to carrier ratio of 1:1 (w:w) on a dry basis. The amount of liquid honey incorporated was calculated according to its initial moisture content to ensure the desired proportion of honey solids in the final mixture. Briefly, honey and carrier material were dispersed in distilled water and homogenized using an immersion homogenizer for 10 min to obtain uniform suspensions prior to spray drying.

2.5.2 *Spray drying conditions*

A 4 × 2 factorial experimental design was used, with four honey types and two carrier material formulations (maltodextrin:taro starch, MD:TS, 1:0 and 1:1 w/w). The spray drying conditions were adjusted according to the work of Toniazzo *et al.* (2023b): drying air flow rate of 35 m^3 h^{-1}, inlet temperature of 120 °C, using a spray dryier Büchi, model B-290 (Lawil, Switzerland). While the feed flow rate was maintained at 15% of the dryer pump capacity (0.33 ± 0.01 kg of feed h^{-1}) resulting in an outlet temperature of 63.6 ± 1.1 °C. According to the glass transition temperature (Tg) results reported by Suhag *et al.* (2018), this value would be below the Tg of dry honey particles (aw < 0.3) obtained with maltodextrin. The spray drying yield was calculated using Equation (4) (Torres-Aguilar *et al.*, 2024). Powders were stored in tightly sealed containers until further analysis. All spray drying experiments were conducted in duplicate.

$$Yield\ (\%) = \left\{ \frac{[dry\ product\ (g)]}{[dry\ solids\ in\ the\ feed\ mixture\ (g)]} \right\} 100 \qquad (4)$$

2.6 *Physicochemical characterization of spray-dried powders*

Powders were evaluated for color and moisture content as previously described (Sections 2.3.1 and 2.3.2). Solubility and hygroscopicity were also assessed.

2.6.1 *Solubility of powders*

Solubility test was carried out following to Toniazzo *et al.* (2023b). First, the honey powder (0.5 g) was dispersed in distilled water (50 mL) during 30 min at 25 °C and 100 rpm. After centrifugation (100 ×g, 5 min), the supernatant was recovered and dried at 110 °C. Solubility was calculated based on the dried solids mass in the aliquot relative to the initial sample mass.

2.6.2 *Hygroscopicity of powders*

Hygroscopicity was assessed according to Toniazzo *et al.* (2023b). The honey powder (1.0 g) was placed in a pre-dried aluminum tray and stored for seven days in a desiccator with NaCl saturated solution (25 ºC; ~75% RH). The mass gain was used to calculate water adsorption (g H_2O 100 g d.m.$^{-1}$).

2.7 *Statistical analysis*

Physicochemical and rheological analyses of liquid honey samples, as well as spray-drying experiments, were conducted twice. The characterization of the resulting powders was performed on each powder batch obtained from independent spray-drying runs. Results are expressed as mean ± standard deviation. One-way analysis of variance (ANOVA) was applied to evaluate differences among samples, followed by Tukey's multiple comparison test, as described in standard statistical procedures (Mason *et al.*, 2003). Differences were considered statistically significant at $p < 0.05$.

Pearson's correlation analysis (Mason *et al.*, 2003) was performed to assess relationships between the physicochemical and rheological properties of *S. mexicana* honeys, carrier composition (MD:TS ratio), spray-drying yield, and powder properties. Correlations were considered significant at $p < 0.05$.

3 Results and discussion

Four *Scaptotrigona mexicana* honey samples were obtained from different apiaries located in Cuetzalan, Puebla, Mexico, and were coded as H1, H2, H3, and H4. The use of samples from different apiaries allowed the assessment of natural variability in physicochemical and rheological properties of honeys. This variability was considered to explore potential correlations between the intrinsic properties of honey, carrier composition, and the properties of the resulting powders.

3.1 *Physicochemical properties of Scaptotrigona mexicana honey*

3.1.1 *Color parameters*

Color parameters are showed on the LCH scale in Table 1, where L* represents lightness, C* indicates chroma (saturation or vividness), and h* corresponds to the hue angle (Carpintero-Tepole *et al.*, 2024). The results show that H4 had a significantly higher L* value (57.78 ± 1.38) than the other samples ($p < 0.05$, indicating statistically significant differences), indicating that it was the lightest honey, whereas H2 was the darkest sample (39.86 ± 0.57). In contrast, H1 and H2 exhibited the highest chroma values (C*), reflecting more saturated coloration. While hue angle values located all samples within the transition range between orange and yellow tones.

These trends are consistent with previous reports using the CIE-LAB color space, where the parameters L*, a*, and b* correspond to lightness and the red–green and yellow–blue coordinates, respectively (Ávila *et al.*, 2018). In this context, the relatively low L* values observed for H1–H3 support their classification as darker honeys. Such darkening is commonly associated with non-enzymatic browning reactions, including Maillard-type processes (Ávila *et al.*, 2018). Overall, the observed color variability among samples suggests differences in floral origin and compositional factors, which may also influence other physicochemical and functional properties of the honeys.

3.1.2 *Moisture content and soluble solids*

Moisture and soluble solids contents are summarized in Table 1. Based on the *Codex Alimentarius* international standard (CXS-12-1981) and the NOM-004-SAG/GAN-2018 (2018) mexican standard for *Apis mellifera* honey, all samples except H3 exceed the recommended maximum moisture of 20%. However, there are no significant differences ($p > 0.05$) were observed among H1, H3, and H4, indicating comparable moisture levels within this group. The samples in this study fall within the interval reported for stingless bee honeys (Nordin *et al.*, 2018; Vit *et al.*, 2025), which typically exhibit higher moisture content due to their storage in cerumen pots and distinct maturation processes (Lazcano-Hernández *et al.*, 2023; Vit *et al.*, 2004).

Soluble solids ranged from 74.0 ± 0.00 to 77.0 ± 0.00 °Brix, lower than the 78–88 °Brix reported for *S. mexicana* by Lazcano-Hernández *et al.* (2023). In *Apis mellifera* honey, soluble solids are typically higher than in stingless bee honey, reflecting the latter's elevated water content and thus relatively lower sugar concentration (Ávila *et al.*, 2018). Altogether, these results reinforce that moisture is a defining parameter of *S. mexicana* honey, with direct implications for its physicochemical behavior and subsequent processing performance.

3.1.3 *Free acidity and pH*

The pH values obtained (Table 1) are higher than the mean value of 2.74 reported by Lazcano-Hernández *et al.* (2023) for *S. mexicana* honeys, although these authors indicate that pH may vary widely (up to 6.9) depending on floral source and fermentation state. In this context, the values observed in the present study fall within the variability reported for stingless bee honeys (Ávila *et al.*, 2018).

Table 1. Physicochemical parameters evaluated in the *Scaptotrigona mexicana* honeys studied.

Variable		Honey			
		H1	H2	H3	H4
Color parameters	L*	44.13 ± 0.25[c]	39.86 ± 0.57[d]	50.86 ± 0.21[b]	57.78 ± 1.38[a]
	C*	44.49 ± 0.29[a]	43.82 ± 0.50[a]	33.06 ± 0.07[b]	31.76 ± 0.56[b]
	h* (°)	71.33 ± 0.04[c]	69.32 ± 0.11[d]	76.14 ± 0.01[b]	77.56 ± 0.11[a]
Color sample					
pH		4.12 ± 0.03[bc]	4.07 ± 0.06[c]	4.34 ± 0.03[a]	4.28 ± 0.04[ab]
Free acidity (meq/kg)		117.75 ± 0.71[c]	167.75 ± 0.71[a]	140.25 ± 0.71[b]	94.25 ± 0.71[d]
Moisture (% w.b.)		21.12 ± 0.43[ab]	22.41 ± 0.53[a]	19.59 ± 0.39[b]	20.71 ± 0.09[b]
Soluble solids (°Brix)*		75.0 ± 0.0[c]	74.0 ± 0.0[d]	77.0 ± 0.0[a]	76.5 ± 0.0[b]

Reported values are the mean ± standard deviation ($n = 3$). In the same row, means that do not share a superscript letter are significantly different according to Tukey's test ($p < 0.05$).

*Soluble solids content (°Brix) was measured using a manual refractometer. The reported zero standard deviation reflects identical readings within the resolution of the instrument.

Free acidity values of the studied samples (Table 1) exceeded the 50.00 meq/kg established as the maximum limit for *Apis mellifera* honey in the *Codex Alimentarius* international standard (CXS-12-1981) and the NOM-004-SAG/GAN-2018 (2018) mexican standard. However, this comparison should be interpreted with caution, as stingless bee honeys are known to exhibit higher and more variable acidity levels associated to its organic acid profile. Indeed, no specific international standard currently exists for *S. mexicana* honey (Ávila *et al.*, 2018; Nordin *et al.*, 2018; Vit *et al.*, 2025).

The elevated free acidity observed in this study is consistent with previous reports for stingless bee honeys, which may range widely depending on species and processing conditions (Nordin *et al.*, 2018). This behavior is commonly associated with their high moisture content, which promotes fermentation processes during maturation (Lazcano-Hernández *et al.*, 2023; Vit *et al.*, 2025). In particular, the values obtained here suggest that the analyzed samples may have undergone partial fermentation, a characteristic frequently reported for *S. mexicana* honeys (Vit *et al.*, 2004).

From a technological perspective, the combination of high moisture content and elevated acidity constitutes a distinctive feature of stingless bee honeys, with direct implications for their stability. These properties reinforce the need for alternative stabilization strategies, such as spray drying, to improve their handling and potential applications.

3.2 *Rheological properties of Scaptotrigona mexicana honey*

To the best of our knowledge, rheological data for *S. mexicana* honey have not been previously reported; therefore, the results presented here contribute to the fundamental understanding of its flow and dynamic behavior.

3.2.1 Flow behavior

Flow curves (Figure 1) showed that all samples behaved as Newtonian fluids within the evaluated shear rate range (1-100 s^{-1}). Apparent viscosity remained constant (Figure 1a), while shear stress increased linearly with shear rate (Figure 1b). This behavior was confirmed by flow behavior index (n) values close to 1, with no significant differences among samples ($p > 0.05$) (Table 2). These results are consistent with previous studies reporting Newtonian flow in different honey types, typically attributed to concentrated solutions of low-molecular-weight constituents (Price *et al.*, 2019; Salamanca Grossoa *et al.*, 2017; Suarez-Ramos *et al.*, 2023; Yanniotis *et al.*, 2006).

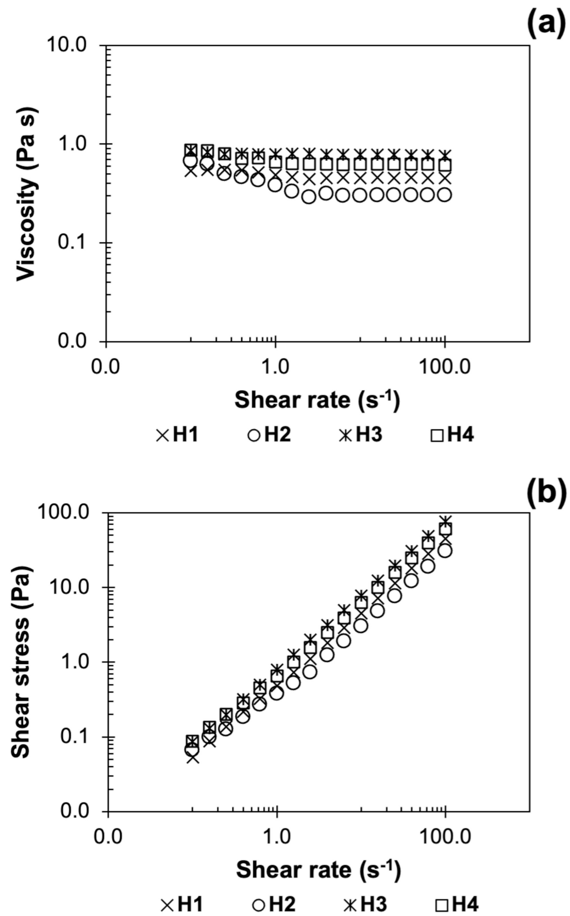

Figure 1. Apparent viscosity (a) and shear stress (b) as a function of shear rate, for different *Scaptotrigona mexicana* honeys studied: H1, H2, H3 and H4. Temperature: 25 °C. Reported values are the mean ($n = 2$).

Despite the uniform Newtonian behavior, quantitative differences in viscosity were observed among samples. Apparent viscosity at 50 s^{-1} ($\eta 50$) is reported in Table 2. H3 showed the highest $\eta 50$ value (0.70 ± 0.09 Pa s), statistically similar to H4 (0.60 ± 0.05 Pa·s; $p > 0.05$), while H2 exhibited the lowest viscosity. For comparison, *Apis mellifera* honey evaluated by Ozmen *et al.* (2025) exhibited $\eta 50 = 13.1$ Pa s at 25 °C, substantially higher than values observed in the present study. The consistency index (k) values (Table 2) were also low, in agreement with the low viscosity, and below those reported in previous studies (Suarez-Ramos *et al.*, 2023; Trávníček and Přidal, 2017).

The relatively low viscosity and consistency index values are consistent with the high moisture content of the samples (>20%, Table 1), which reduces intermolecular interactions and facilitates flow. Under these conditions, the rheological behavior is primarily governed by the liquid phase, where sugar-water interactions dominate and limit the development of structural complexity (Trávníček and Přidal, 2017; Yanniotis *et al.*, 2006; Yoo, 2004).

Table 2. Apparent viscosity at 50 s^{-1} (η50) and fitted parameters from flow and oscillatory rheological models of *Scaptotrigona mexicana* honey.

Variable		Honey			
		H1	**H2**	**H3**	**H4**
η50 (Pa s)		0.44 ± 0.01^{ab}	0.27 ± 0.08^{b}	0.70 ± 0.09^{a}	0.60 ± 0.05^{a}
Flow parameters	***k*** **(Pa s^n)**	2.05 ± 0.08^{a}	2.97 ± 1.40^{a}	1.27 ± 0.19^{a}	1.43 ± 0.06^{a}
	n	1.03 ± 0.0^{a}	1.10 ± 0.0^{a}	1.01 ± 0.0^{a}	1.05 ± 0.0^{a}
	R^2	1.00 ± 0.0^{a}	0.99 ± 0.0^{a}	1.00 ± 0.0^{a}	1.00 ± 0.0^{a}
Oscillatory parameters	***n'***	0.63 ± 0.01^{a}	0.45 ± 0.14^{a}	0.65 ± 0.05^{a}	0.68 ± 0.07^{a}
	S′	0.03 ± 0.01^{a}	0.02 ± 0.00^{a}	0.05 ± 0.02^{a}	0.02 ± 0.01^{a}
	R^2	0.96 ± 0.02^{a}	0.74 ± 0.05^{b}	1.00 ± 0.00^{a}	0.95 ± 0.06^{a}
	n''	0.95 ± 0.02^{a}	0.96 ± 0.01^{a}	0.94 ± 0.01^{a}	0.96 ± 0.00^{a}
	S′′	0.03 ± 0.01^{a}	0.02 ± 0.00^{a}	0.05 ± 0.02^{a}	0.02 ± 0.01^{a}
	R^2	1.00 ± 0.0^{a}	1.00 ± 0.0^{a}	1.00 ± 0.0^{a}	1.00 ± 0.0^{a}

Reported values are the mean ± standard deviation ($n = 2$). In the same row, means that do not share a superscript letter are significantly different according to Tukey's test ($p < 0.05$).

Overall, *S. mexicana* honey can be characterized as a low-viscosity Newtonian fluid under steady shear, with variations among samples mainly associated with compositional differences, particularly moisture content.

3.2.2 Viscoelastic properties

Although all samples exhibited Newtonian behavior under steady shear, oscillatory measurements were conducted to evaluate their time-dependent structural response under small deformations. Figure 2 shows the variation of storage modulus (G') and loss modulus (G' ') as a function of angular frequency (ω, rad s^{-1}).

In all cases, G' ' was higher than G', indicating that viscous behavior predominates over elastic contributions (Witczak *et al.*, 2011). This response is characteristic of weakly structured liquids, where transient intermolecular interactions (such as hydrogen bonding and sugar-water associations) can produce a measurable, yet limited, elastic component under oscillatory conditions. Thus, the observed viscoelastic response does not contradict the Newtonian behavior identified in steady shear, but rather complements it by evidencing the absence of a persistent structural network. Similar behavior has been reported for other honey systems, which have been described as weakly viscoelastic fluids (Suarez-Ramos *et al.*, 2023; Witczak *et al.*, 2011; Yoo, 2004).

Additionally, both G' and G' ' increased with angular frequency, consistent with the behavior of concentrated liquid systems. No crossover between moduli was observed within the evaluated range, further supporting the lack of gel-like or highly structured organization. No significant differences were detected among samples in their viscoelastic parameters ($p > 0.05$) (Table 2), indicating similar molecular organization. The low values of G', G' ', and gel-related parameters (S', S' ', n', n' ') reinforce that the elastic contribution is minimal and that *S. mexicana* honey behaves as a predominantly viscous system. Furthermore, these values were lower than those reported in previous studies (Suarez-Ramos *et al.*, 2023; Witczak *et al.*, 2011), which is consistent with the inverse relationship between water content and gel strength (Yoo, 2004).

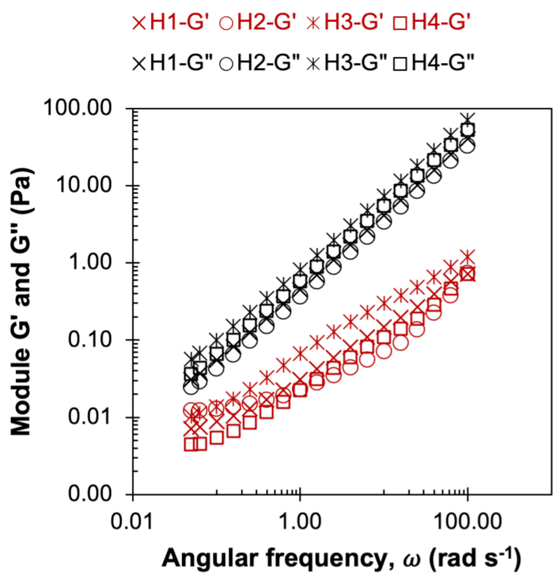

Figure 2. Storage shear modules (G', red symbols) and loss modules (G' ', black symbols) as a function of angular frequency (ω), for different *Scaptotrigona mexicana* honeys studied: H1, H2, H3 and H4. Temperature: 25 °C. Reported values are the mean ($n = 2$).

Table 3. Pearson correlations between physicochemical and rheological properties of *Scaptotrigona mexicana* honeys, spray drying yield and physicochemical properties of powdered honeys.

		Spray drying yield and dry particle characteristics						
		L	**C***	**h***	**Moisture**	**Higroscopicity**	**Solubility**	**Yield**
Properties of *S. mexicana* honeys	**L**	**0.086**	-0.384	0.255	**-0.553**	0.288	0.036	-0.254
	C*	-0.278	0.448	-0.223	0.504	-0.337	-0.150	0.362
	h*	0.102	-0.405	0.269	**-0.509**	0.307	0.150	-0.341
	pH	-0.017	-0.355	0.311	-0.387	0.284	0.220	-0.450
	Free acidity	0.249	0.158	-0.221	0.356	-0.100	0.117	0.037
	Moisture	-0.028	0.294	-0.212	0.254	-0.257	-0.158	0.406
	Soluble solids	0.033	-0.372	0.281	-0.404	0.290	0.168	-0.424
	η_{50}	0.059	-0.344	0.220	-0.280	0.310	0.158	-0.381
	MD:TS ratio	-0.188	**-0.838**	**0.899**	**0.509**	**0.606**	**0.785**	**0.740**

In bold, significant values ($p < 0.05$).

In general, the dynamic measurements are consistent with the steady shear results, confirming that *S. mexicana* honey behaves as a low-viscosity, weakly structured liquid, whose rheological response is largely governed by its high moisture content and the resulting reduction in intermolecular interactions.

3.3 Spray-drying yield and properties of powders

This section presents the results obtained from the spray drying of *S. mexicana* honey using different carrier agent formulations. Pearson correlation coefficients among process variables and powder properties are summarized in Table 3.

3.3.1 Color of spray-dried powders

The color parameters of the dry particles are presented on the LCH scale (Table 4). In all cases, the luminosity (L*) of the powders was higher than that of the fresh honeys, indicating a lighter appearance after drying. This effect is mainly attributed to the incorporation of carrier agents, particularly maltodextrin, which possesses high intrinsic luminosity and dilutes the natural pigments of honey.

No significant differences ($p > 0.05$) were observed among L* values of the powders (Table 4). Although a statistically significant correlation was found between the L* values of honeys and powders, the correlation coefficient was very low ($r = 0.086$), indicating that this relationship lacks practical relevance. This result confirms that powder luminosity is governed primarily by the carrier materials rather than the original honey color.

In contrast, chroma (C*) and hue angle (h*) showed significant differences among treatments ($p < 0.05$, Table 4). The MD:TS ratio was the only variable strongly correlated with these parameters (Table 3). Increasing the maltodextrin fraction led to lower chroma values, indicating reduced color saturation, and higher h* values, reflecting a shift toward yellow tones. Conversely, formulations containing higher proportions of taro starch resulted in powders with more intense coloration and a noticeable shift toward orange hues.

These results suggest that the type and proportion of carrier agents play a dominant role in defining the visual attributes of the powders. The reduction in color intensity observed with higher maltodextrin content can be explained by a dilution effect, where the carrier masks the intrinsic pigments of the honey. In contrast, the incorporation of taro starch appears to preserve, to some extent, the characteristic color of *S. mexicana* honey.

Additionally, the observed differences in color may be associated with structural variations in the particles formed during spray drying. Systems containing maltodextrin typically produce powders with more uniform surfaces, which enhance light reflection and result in higher luminosity but lower color saturation (Carpintero-Tepole *et al.*, 2024; Sobulska and Zbicinski, 2021). In contrast, formulations with taro starch may promote less homogeneous structures (Hoyos-Leyva *et al.*, 2018a; Hoyos-Leyva *et al.*, 2018b), allowing greater light scattering and a more pronounced expression of the honey's inherent color. The morphological study of the dry particles obtained represents a relevant line of future research.

Overall, the color of spray-dried *S. mexicana* honey powders is primarily determined by the composition of the carrier system, particularly the maltodextrin:taro starch ratio, which modulates both luminosity and color saturation.

Table 4. Spray-drying yield and physicochemical properties of powdered honeys of *Scaptotrigona mexicana*.

Treatment	Honey	MD:TS ratio	Color parameters L	C*	h* (°)	Color sample	Moisture (% wb)	Hygroscopicity (g H_2O/100 g dm)	Solubility (%)	Yield (%)
1	H1	1:0	91.91 ± 3.56^{a}	6.25 ± 0.03^{bcd}	83.73 ± 0.05^{a}		4.97 ± 0.79^{a}	22.25 ± 0.93^{a}	99.08 ± 2.44^{a}	59.04 ± 1.56^{ab}
2	H2	1:0	95.57 ± 4.82^{a}	6.03 ± 0.40^{bcd}	80.41 ± 4.07^{ab}		4.98 ± 0.85^{a}	21.76 ± 1.50^{a}	92.11 ± 2.05^{ab}	66.59 ± 1.93^{a}
3	H3	1:0	94.77 ± 0.11^{a}	4.28 ± 0.06^{cd}	86.57 ± 0.86^{a}		4.88 ± 0.14^{a}	22.84 ± 1.17^{a}	99.09 ± 1.15^{a}	56.97 ± 6.08^{ab}
4	H4	1:0	95.59 ± 0.98^{a}	3.54 ± 0.23^{d}	86.00 ± 0.91^{a}		4.68 ± 0.40^{a}	22.77 ± 0.16^{a}	96.32 ± 2.78^{a}	61.82 ± 4.61^{ab}
5	H1	1:1	92.84 ± 1.12^{a}	11.47 ± 0.06^{a}	75.22 ± 0.30^{b}		4.88 ± 0.16^{a}	20.53 ± 0.55^{a}	80.63 ± 4.00^{c}	56.58 ± 1.51^{ab}
6	H2	1:1	97.11 ± 3.08^{a}	9.98 ± 2.88^{ab}	73.18 ± 3.87^{b}		4.64 ± 0.12^{a}	21.49 ± 1.06^{a}	90.42 ± 1.30^{ab}	51.09 ± 0.75^{bc}
7	H3	1:1	95.72 ± 0.24^{a}	8.26 ± 0.79^{abc}	75.02 ± 0.83^{b}		4.10 ± 0.15^{a}	21.45 ± 0.57^{a}	90.65 ± 2.62^{ab}	40.78 ± 1.08^{c}
8	H4	1:1	95.71 ± 0.30^{a}	8.29 ± 0.14^{abc}	75.11 ± 0.11^{b}		3.29 ± 0.42^{a}	21.53 ± 0.03^{a}	84.60 ± 1.47^{bc}	49.16 ± 4.82^{bc}

MD: DE-10 maltodextrin. TS: taro starch. Inlet temperature: 120 ºC. Outlet temperature: 63.6 ± 1.1 °C. Ratio of dry honey to carrier material mixture: 1:1 w:w. Reported values are mean ± standard deviation ($n = 2$). In the same column, means that do not share a superscript letter are significantly different according to Tukey's test ($p < 0.05$).

3.3.2 Moisture content, hygroscopicity and solubility of spray-dried powders

Table 4 shows the moisture content, solubility and hygroscopicity of the spray-dried honey powders. No significant differences ($p > 0.05$) were observed in the moisture content among treatments. This result suggests that the spray-drying conditions promoted rapid and uniform water removal, leading to powders with similar residual moisture levels (Carpintero-Tepole *et al.*, 2024; Jedlińska *et al.*, 2019; Toniazzo *et al.*, 2023a). The values obtained are consistent with those reported for stingless bee honey powders produced under comparable conditions (Cuevas-Glory *et al.*, 2017; Leyva-Moguel *et al.*, 2022).

Similarly, no significant differences ($p > 0.05$) were found in hygroscopicity among treatments. The absence of variability in both moisture and hygroscopicity indicates that the physicochemical and rheological differences of the original honeys had a limited influence on these properties after drying. This observation is supported by the Pearson correlation analysis (Table 3), where the MD:TS ratio was the only variable significantly correlated with moisture (r = 0.509), hygroscopicity (r = 0.606), and solubility (r = 0.785). These results suggest that the incorporation of carrier materials attenuated the intrinsic variability of the honeys, yielding powders with relatively homogeneous physical properties.

The hygroscopicity values obtained (Table 4) fall within the typical range reported for honey powders (Cuevas-Glory *et al.*, 2017; Leyva-Moguel *et al.*, 2022). This behavior is expected due to the high sugar content of honey, which promotes water adsorption (Samborska *et al.*, 2019; Toniazzo *et al.*, 2023a). From a practical standpoint, these values indicate that the powders may be sensitive to moisture uptake during storage, particularly under high relative humidity conditions (Ligarda-Samanez *et al.*, 2023).

Powder solubility is a critical parameter for reconstitution and end-use applications (Leyva-Moguel *et al.*, 2022; Samborska, 2019; Toniazzo *et al.*, 2023b). The solubility values observed in this study are comparable to those reported for spray-dried honey powders produced with maltodextrin (Ligarda-Samanez *et al.*, 2023; Mutlu and Erbas, 2023). According to the Pearson analysis, solubility was strongly correlated with the MD:TS ratio (r = 0.785), indicating that the carrier composition plays a dominant role in this property.

Increasing the maltodextrin proportion improved powder solubility, whereas the incorporation of taro starch reduced it. This behavior can be explained by the highly amorphous nature of maltodextrin, which promotes rapid dissolution in water (Badin *et al.*, 2025), in contrast to the partial crystallinity and lower solubility of native starches (Aparicio-Saguilán *et al.*, 2024; Martínez-Cigarroa *et al.*, 2025; Roldán-Cruz *et al.*, 2026). Therefore, the inclusion of taro starch limits the overall dissolution capacity of the powders.

From a technological perspective, formulations with higher maltodextrin content are more suitable for applications requiring rapid reconstitution, such as instant beverages (Samborska, 2019; Sobulska and Zbicinski, 2021). In contrast, the incorporation of taro starch could be advantageous in systems where slower dissolution or structural functionality is desired (Hoyos-Leyva *et al.*, 2018a; Hoyos-Leyva *et al.*, 2018b).

3.3.3 Process yield

Process yield values obtained for the spray drying of *S. mexicana* honey are presented in Table 4. In all cases, except for treatments 7 and 8, yields exceeded 50%, indicating acceptable process efficiency under the evaluated conditions. Despite the well-known challenges associated with spray drying of high-sugar matrices, such as stickiness and wall deposition, the results demonstrate that the selected formulation and operating conditions allowed stable powder production. This behavior is primarily related to the incorporation of carrier agents, which reduced stickiness and improved particle recovery (Carpintero-Tepole *et al.*, 2024; Samborska, 2019; Suhag *et al.*, 2018; Vázquez-León *et al.*, 2021).

Pearson correlation analysis (Table 3) indicated that the MD:TS ratio was the variable most strongly associated with process yield (r = 0.740). Higher yields were obtained as the proportion of maltodextrin increased, confirming its key role in enhancing drying performance. This effect can be attributed to the high glass transition temperature (Tg) of maltodextrin, which promotes the formation of particles in a stable glassy state during drying, reducing adhesion to dryer surfaces (Samborska, 2019; Suhag *et al.*, 2018). In contrast, the incorporation of taro starch negatively affected process yield. Although taro starch can act as a drying aid, its composition (particularly its protein fraction) may promote particle aggregation and flocculation, potentially leading to partial obstruction of the atomizer and reduced process efficiency (Hoyos-Leyva *et al.*, 2018a; Hoyos-Leyva *et al.*, 2018b).

The outlet air temperature in this study (63.6 ± 1.1 °C) remained below the reported Tg values of honey-maltodextrin systems (68.26 °C) (Suhag *et al.*, 2018), which likely contributed to maintaining the particles in a glassy state and minimizing stickiness. This condition is critical, as operating above Tg promotes a transition to a rubbery state, increasing particle adhesion and reducing yield (Samborska, 2019; Sobulska and Zbicinski, 2021). Therefore, determining Tg from different carrier systems is a promising line of research.

Compared with previous studies on stingless bee honey (Cuevas-Glory *et al.*, 2017; Osés *et al.*, 2021), the yields obtained in this study are within or above the typical reported range (22.6-72%), despite the relatively high solids content (30%) used in the feed mixture. From a technological perspective, achieving yields above 50% at this solids level is particularly relevant, as it improves process efficiency and reduces production costs.

Overall, process yield in the spray drying of *S. mexicana* honey is strongly governed by the carrier composition and its influence on the thermal and physical state of the particles during drying. Increasing the maltodextrin proportion enhances yield, whereas higher levels of taro starch may compromise process efficiency.

Conclusions

The physicochemical and rheological characterization of four *Scaptotrigona mexicana* honeys revealed differences in moisture content, soluble solids, viscosity, and color parameters, which are typical of stingless bee honeys and reflect the natural variability of this product. Despite these differences, the intrinsic properties of the honeys did not show a direct influence on spray-drying yield or powder characteristics under the experimental conditions evaluated. In contrast, the composition of the carrier system had a significant effect on the process performance and the properties of the resulting powders. In particular, higher proportions of maltodextrin improved powder recovery and solubility, indicating that carrier selection plays a critical role in enhancing spray-drying performance when processing stingless bee honeys.

The results demonstrate that spray-drying can be used as a viable strategy to convert *S. mexicana* honey into a powdered ingredient. This approach may contribute to improving the handling, storage, and potential applications of stingless bee honeys by reducing the limitations associated with their high moisture content.

Overall, this study provides experimental evidence on the behavior of *S. mexicana* honeys during spray-drying and on the influence of carrier composition on process efficiency and powder properties. These findings contribute to the technological knowledge required for the stabilization and valorization of stingless bee honeys. Future research should explore alternative carrier systems, optimize drying conditions, and evaluate the storage stability of the resulting powders to further support their potential industrial applications.

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AI tool use statement

AI-based tools were used for grammar correction and style enhancement. No AI systems were used to create, analyze, or interpret the scientific content of this manuscript. The experimental design, data analysis, discussions, and conclusions were developed exclusively by the authors.

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