Received: 2 May 2020 | Revised: 11 June 2020 | Accepted: 10 August 2020

DOI: 10.1111/jfpp.14876

ORIGINAL ARTILCE

Journal of Food Processing and Preservation | Institute of Food Science + Technology ifst | WILEY

Co-crystallized honey with sucrose: Evaluation of process and product characterization

Leda B. Quast[1] | Sabrina G. Farina[1] | Ernesto Quast[1] | Manoela A. Vieira[2] | Marise B. Queiroz[3]

[1]Federal University of Fronteira Sul – UFFS, Laranjeiras do Sul, Brazil

[2]Federal Institute of Santa Catarina – IFSC, Santa Catarina, Brazil

[3]Food Technology Institute – ITAL, Campinas, Brazil

Correspondence
Leda B. Quast, Federal University of Fronteira Sul - UFFS, Campus Laranjeiras do Sul. Laranjeiras do Sul, PR. 85.301-970, Brazil.
Email: leda.quast@uffs.edu.br

Funding information
Fundação de Amparo à Pesquisa e Inovação do Estado de Santa Catarina, Grant/Award Number: FAPESC 3459

Abstract

Honey is a commercial product that presents difficulties in food industries related to crystallization inside the packages. Dry ingredients are easy to handle. Honey co-crystallized with sucrose is a dry productthat can be used in the food industry as long as fulfillsafety and sensory requirements. The objective of this work was to produce and characterize honey co-crystallized with sucrose using 9 different samples of honey. The process of co-crystallization of honey (15%) with sucrose resulted productswith water activity from 0.38 to 0.51, moisture values ranging from 1.25% to 2.04% (wet basis), good fluidity (repose angles from 23.40 to 32.28°) and apparent density from 0.46 to 0.55 g/cm^3. The products presented morphological structure characteristic of co-crystallization products. Final products showed good overall sensory acceptance, which opens the possibility of using co-crystallized honey in food industries.

Practical applications

The co-crystallization process was used to produce a dry honey-based ingredient, showing good fluidity, stability and sensory acceptance, with honey samples from different origins and physico-chemical properties. The formation of a sucrose-honey matrix can be an achievable process to create a handle, dry and standard product for application in different food systems. Handling, transportation and storage of dry products are easier compared to high viscous products and are achieved in the present product. Economic and industrial applications are greatly expanded for food development.

1 | INTRODUCTION

Honey is a complex food and its composition varies depending on the floral origin, geographic and climatic conditions. The main components of honey are fructose and glucose (60%–85%), maltose and sucrose (7%–10%), natural antioxidants, minerals, flavonoids, vitamins, enzymes and aromatic substances (Ahmed, Prabhu, Raghavan, & Ngadi, 2007; Cui, Sun, Chen, & Sun, 2008; Silva, Gauche, Gonzaga, Costa, & Fett, 2016; Zamora & Chirife, 2006).In the Southern region of Brazil, honey typically has an average acidity of 37.82 meqkg^{-1}, pH of 3.4 and HMF (hydroxymethylfurfural) of 20.58 mgkg^{-1} (Ribeiro & Starikoff, 2019).

All fresh honeys are high viscosity liquid, but they tend to crystallize when stored at temperatures below 37°C due to glucose supersaturation. This crystallization varies according to several factors, such as bee culture, floral origin, sugar content, and time for ripening, which decreases the moisture content (Conforti, Lupano, Malcalza, Arias, & Castells, 2006; Seraglio et al., 2019).

In the food industries, honey is a difficult product to store due to its high viscosity and tendency to crystallize quickly. Its removal from packaging for large-scale use is a limiting factor. The co-crystallization processprovides a dry product, easy to handle and use in many formulations of products with honey or sucrose.

The sucrose co-crystallization process consists of the concentration of a sucrose solution to its supersaturation state and maintained in high temperature to avoid re-crystallization. Then, a predetermined amount of the active material (its quantity depends on the characteristics of the desired final product) in this case honey, is added to the concentrated solution under mechanical stirring, promoting the nucleation of the mixture of sucrose and active material.The final solution iscooled so the mixture reaches the temperature of saturation, when crystallization begins. In this stage, latent heat is released due to the phase change transition, which contributes to the drying of the material. Continuous stirring promotes crystallization until the formation of the agglomerated product. The co-crystallized mixture is dried (if necessary), ground and sieved to obtain granulomery uniformity (Astolfi-Filho, Souza, Reipert, & Telis, 2005; Bhandari, Datta, D'arci, & Rintoul, 1998; Lopez-Cordoba, Gallo, Bucalá, Martino, & Navarro, 2016).

Several co-crystallization processes have been reported in the literature. Studies have been carried out on the encapsulation of fruit juice (Andrade Pizarro, Blanquicett Gónzalez, & Rangel terraza, R., 2017; Astolfi-Filho et al., 2005), essential oils and plant extracts (Beristain, Vazquez, Garcia, & &Vermnon-Carter, E.J., 1996), yerba mate (Ilex paraguariensis) and mineral salts (Lorena, Anbinder, Navarro, & Martino, 2007), zinc sulfate (Lopez-Cordoba et al., 2016) and co-crystallization of cardamomand paprika oleoresin (Federzoni, Alvim, Fadini, Silva, & Queiroz, 2019; Sardar & Singhal, 2013), all using sucrose as a crystallization agent.

The co-crystallization process of honey with sucrose was reported by Bhandari et al. (1998) who used sucrose and honey in proportions of 90:10, 85:15 and 80:20 and resulted formulations similar to honey in terms of aroma and flavor. Cui et al. (2008) reported a study where dried honey was produced using microwave technique associated with vacuum. Jedlinska et al. (2019) and Nurhadi and Roos (2017) used spray drier technique to obtain dried honey with maltodextrin. The productspresented physical and physico-chemical characteristics similar to powders.

Dried honey or a dry honey-based product such as co-crystallized honey with sucrose, can present technical conveniences for applications in the food industry or for the final consumer, in addition provide an alternative for commercialization. The objective of this work was to obtain and characterize honey co-crystallized with sucrose, using samples of honeys from Southern Brazil.

2 | MATERIAL AND METHODS

2.1 | Materials

For the co-crystallization tests, 9 samples (identified as samples 1 to 9) of honey (*Apis mellifera*) from different producers in the South Region of Brazil (latitude from −26,7,833 to −27,7,539°; longitude from −53,5,131 to −49,9,678°; altitude from 622 to 934 m; monthly average temperature minimum of 12 and maximum of 30°C with thermal amplitude of 10°C; monthly average rainfall of 140 mm) and refined commercial sucrose (Usina Alto Alegre®) were used. The reagents used for the physico-chemical analyzes were of analytical grade.

2.2 | Physico-chemical characterization of honey samples

Moisture analyzes were determined using the refractometric method (AOAC, 2000) and the water activity (α_w) using a dew point electronic analyzer (LabMaster—Novasina) at 25°C. The analysis of acidity, apparent sucrose, reducing sugars, and fixed mineral residue were carried out according to official methodology of Brazilian legislation (Brasil, 2000).

The HMF index was determined according to the Fiehe method (Bera & Almeida-Muradian, 2007; Kumar et al., 2018), which is a qualitative test where the HMF in the sample reacts with resorcin in acid, presenting a red condensation compound. Analyzes were performed in triplicate.

2.3 | Production of honey co-crystallized with sucrose

In the co-crystallization process, 9 honey samples were used individually. Honey may present physico-chemical differences on its composition, as well as different crystallization and viscosity behavior, which can influence its use (Boussaid et al., 2015; Santos et al., 2014).

The co-crystallizationtestsofhoneywithsucrosewerecarried out following the procedure described by Bhandari et al. (1998) with some modifications. The heating was carried out on an electronic plate with controlled temperature, and after 30 min the permanent regime was established at 170°C. After this period, the co-crystallization procedure began.

Co-crystallization was carried out in an open system, in batches of 300 g of sucrose with 50 g of water, mixed and heated for 8 min from 18 to 124°C. At the end of heating, 15% (45 g) of honey was added to the solution under manual stirring until a crystallized mass was obtained. This amount was determined based on previous tests using honey ranging from 10% to 20%, being 15% the best result with the largest quantity of honey used. The addition of 20% honey made the product "sticky" and for this reason not used for the experiments, since one of the advantages of dry products to rage and management consists in its flow ability. The co-crystallized product was dried in an oven with forced circulation and air renovation at 40°C for 48 hr and crushed in a knife mill (Willye Starft-50) with 4 fixed and 4 adjustable knives. The ground product was sieved to obtain particles smaller than 1 mm. The samples were stored in appropriate flask sat 25°C. The co-crystallization tests were performed in duplicate for each honey sample.

2.4 | Physico-chemical characterization of the co-crystallized product

The co-crystallized samples were evaluated by moisture analysis using the Karl Fisher® titration method (CombiTitrant 5, Merck S.A) and the α_w according to the previously reported methodology. The apparent density was determined using 50 g of product deposited in a 250 ml beaker on a flat surface. The static repose angle was determined by slowly pouring the product from a fixed height of 9 cm through a stainless funnel placed on a support and the product was collected in a petri dish with a radius of 4.75 cm. The repose angle was determined using the radius of the petri dish and the height of the cone formed by the powder (Astolfi-Filho et al., 2005; Bhandari et al., 1998; Karangutkar & Ananthanarayan, 2020). The analysis were performed in quadruplicate.

The size distribution and the average diameter of the co-crystallized were determined by laser diffraction (LA 950-V2, Horiba). The particles were dispersed in absolute ethanol and the results determined for an average fraction of 0.1000 g per sample, in triplicate. The average size was expressed as the particle diameter (D50%) and the polydispersity given as the Span index, calculated according to Equation (1) (Alvim & Grosso, 2010; Oriani et al., 2016; Sartori, Consoli, Hubinger, & Menegalli, 2015):

$$\text{Span index} = \left(D_{90\%} - D_{10\%}\right) / D_{50\%} \tag{1}$$

where $D_{10\%}$, $D_{50\%}$ and $D_{90\%}$ correspond to 10, 50 and 90% of the accumulated size distribution. The morphology was analyzed by observing images generated by stereoscopy (MZS-250 Stereoscope, Dimex, Mexico) and captured using a digital camera.

The sorption isotherms were performed in duplicate, at 25°C following the static method described by Park, Bin, and Brod (2001) and by Oliveira, Afonso, and Costa (2011). The following salts with their corresponding relative humidity were used: lithium chloride (0.122), potassium acetate (0.226), magnesium chloride (0.327), potassium carbonate (0.438), magnesium nitrate (0.529), sodium bromide (0.577), sodium nitrite (0.650), sodium iodide (0.715) and sodium chloride (0.753).

The GAB model (Gugghenheim, Anderson and Bôer) was used to adjust the sorption isotherms, according to Equation (2):

$$X_e = \frac{X_m C K \alpha_w}{\left(1 - K\alpha_w\right)\left(1 - K\alpha_w + CK\alpha_w\right)} \tag{2}$$

where X_e is the equilibrium humidity, X_m is the molecular monolayer moisture (kg/kg), C and K are adsorption constants and α_w is the water activity.

2.5 | Sensory analysis

Prior to sensory analysis, an online survey on consumption habits was carried out with 99 people (over 18, male/female) who answered the questions shown in Figure 1.

Sensory analysis was performed in an appropriate place using hedonic scale with 57 voluntary judges, male/female, untrained, usual consumers of honey and sucrose, between 18 and 50 years old, according to the methods described by Meilgaard, Civille, and Carr (2007).

The panelists received 10 g of co-crystallized product to be added in 150 ml of lemon juice. The lemon juice was prepared at a concentration of 6.67% (v/v) served at a temperature between 8 and 10°C.

The co-crystallized product was evaluated using the appearance, color, taste and flavor attributes when dissolved into drink, using a 9 point structured hedonic scale, anchored at the ends 1: extremely disliked and 9: extremely liked. The consumption intention of the co-crystallized product was assessed using a five point

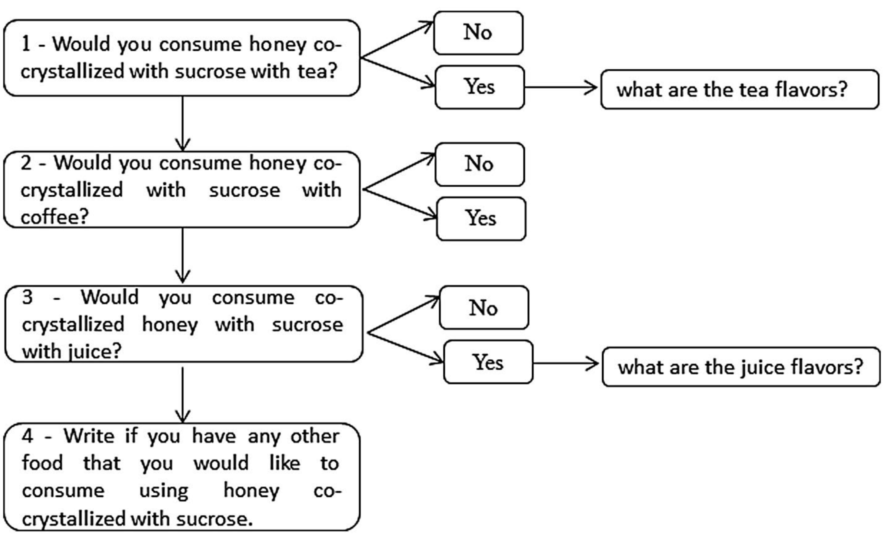

FIGURE 1 Questions for consumption habits

scale, "definitely buy" and "definitely not buy" corresponding to the highest and lowest score "5" and "1", respectively. The acceptability index was evaluated for the aroma of dry co-crystallized product and juice taste with co-crystallized product using Equation (3):

$$\text{Acceptability Index}\,(\%) = (A/B) \times 100 \quad (3)$$

where *A* is the average obtained for the attribute and *B* the maximum score obtained for the attribute (Dutcoski, 2011).

The consumption habits survey and the sensory analysis tests were previously approved by the ethics committee of the Federal University of FronteiraSul: CAAE: 32327414.0.0000.5564.

3 | RESULTS AND DISCUSSION

3.1 | Physico-chemical characterization of honey

Table 1 shows the results of the physico-chemical analyzes of the 9 honey samples used.

The analyzes of moisture, acidity, apparent sucrose and reducing sugars are following the legislation (Commission and (CAC) on Honey, 1987; Brasil, 2000) classifying the samples as Blossom honey.

Water is the second component present in the greatest amount in honey. Moisture is an indicator of its quality, as it directly affect the characteristics of shelf life, product storage, viscosity and crystallization. Moisture levels above 20% (wet basis) may indicate risk of fermentation by osmophilic yeasts. In this study, moisture values ranged from 16.38 ± 0.43 to 19.2 ± 0.06% (wet basis) and are similar to honey samples from different countries as reported by Seraglio et al. (2019).

Water activity is not a mandatory parameter by law, however, its measurement is important considering that yeasts can grow with α_w above 0.60 (Silva et al., 2016). It is observed that samples 6 and 7 should be monitored for their quality, as they presented α_w of 0.60 and 0.64 respectively. However, their humidity values were 17.04 ± 0.41 and 18.75 ± 0.24% (wet basis). Thus, it is observed that α_w is an important measure in the analysis of honey quality, since during the process of glucose crystallization there is a reduction of soluble solids content, resulting in the dilution of the amorphous solution that will lead to an increase of the α_w value (Silva et al., 2016).

The acidity in honey is due to the presence of organic acids that are derived from the enzymatic reactions of sugars present in honey and depend on its botanical origin (Ribeiro & Starikoff, 2019; Silva et al., 2016). In the present study, acidity was the parameter that showed the greatest variation, from 7.63 ± 0.64 to 29.27 ± 2.46 meq/kg^1. The values are below of the limit legislation, which is 50 $meqkg^{-1}$ (Commission and (CAC) on Honey, 1987; Brasil, 2000), which suggest that these honey samples did not show fermentation. The obtained results in this work are similar to those reported by Kumar et al. (2018) in the study of Indian honeys and in a review article on the chemical composition of honey reported by Silva et al. (2016).

The HMF index in this work showed negative valuesfor all samples, indicating no degradation of enzymes presented in the honeys. A high HMF value represents a decrease on its nutritional value (Almeida-Filho et al., 2011).

3.2 | Co-crystallization tests

Figure 2 shows the heating curves of the 9 samples during the co-crystallization tests of honey with sucrose.

The starting temperature of water and sucrose solutions was 20°C (Figure 2). In the first 4 min of heating, the temperature rise is linear pattern and is caused by the transfer of sensitive heat in the solution. After 4 min, the temperature increases, with a tendency to stabilize, which occurs after 7 min at 120°C. This situation already indicates that the heat transfer is given by the latent heat,- moment when crystallization occurs, at 8 min (124°C). At that point, the samples were removed from heating and the honey was added, remaining under agitation until the formation of crystal granules. Technically, it is not recommended to keep the samples under heating for a long period, due to undesirable thermal degradation and caramelization process (Quintas, Fundo, & Silva, 2010).

TABLE 1 Physico-chemical analysis of honey samples collected in the southern region of Brazil

Samples of honey	Moisture (%) (wet basis)	α_w	Acidity (meq kg^{-1})	Apparent sucrose (%)	Reducing sugar (%)	Ash (%)
1	17.9 ± 0.00^{cd}	0.56 ± 0.0^{f}	7.63 ± 0.64^{d}	5.05 ± 0.93^{a}	68.82 ± 2.71^{a}	0.04 ± 0.01^{d}
2	19.2 ± 0.06^{a}	0.58 ± 0.0^{d}	15.75 ± 1.32^{b}	4.63 ± 0.86^{ab}	69.80 ± 2.75^{a}	0.44 ± 0.06^{ab}
3	18.4 ± 0.06^{bc}	0.56 ± 0.0^{e}	8.02 ± 0.67^{cd}	3.69 ± 0.68^{abc}	68.68 ± 2.71^{a}	0.10 ± 0.02^{cd}
4	16.38 ± 0.43^{f}	0.59 ± 0.0^{c}	17.77 ± 1.49^{b}	3.16 ± 0.59^{bc}	67.27 ± 2.65^{a}	0.53 ± 0.07^{a}
5	17.63 ± 0.24^{de}	0.58 ± 0.0^{d}	11.49 ± 0.97^{c}	1.20 ± 0.22^{de}	71.71 ± 2.83^{a}	0.11 ± 0.02^{cd}
6	17.04 ± 0.41^{ef}	0.60 ± 0.0^{b}	15.65 ± 1.32^{b}	3.63 ± 0.67^{abc}	71.69 ± 2.82^{a}	0.35 ± 0.02^{b}
7	18.75 ± 0.24^{ab}	0.64 ± 0.0^{a}	15.46 ± 1.30^{b}	1.24 ± 0.23^{de}	71.68 ± 2.83^{a}	0.37 ± 0.01^{b}
8	17.24 ± 0.07^{de}	0.59 ± 0.0^{c}	29.27 ± 2.46^{a}	0.58 ± 0.11^{e}	70.73 ± 2.79^{a}	0.19 ± 0.05^{c}
9	18.8 ± 0.1^{ab}	0.57 ± 0.0^{d}	10.63 ± 0.89^{cd}	2.41 ± 0.45^{cd}	70.38 ± 2.78^{a}	0.10 ± 0.07^{cd}

Note: The qualitative HMF index for all samples was negative. Tukey test with $p < 0.05$, equal letters in the column do not differ statistically.

Journal of Food Processing and Preservation

During the co-crystallization processes, the variation in the mass content of the water was monitored. At the beginning of the process, 50 ± 0.02 g of water were added. After the co-crystallization process, was observed 92% loss (46.00 ± 3.08 g) of water by evaporation, leaving 4 g of water remaining. At the end of the drying process, the amount of evaporated water was 7.40 ± 2.14 g, indicating that a certain amount of water present in honey and sugar was partially removed.

3.3 | Physico-chemical tests of co-crystallized products

Table 2 presents the results of the physical and chemical analyzes from co-crystallized products, of the 9 samples.

The α_w of co-crystallized products were below 0.6 (Table 2), which indicates that this product can be stored in room conditions. The moisture content of the co-crystallized honey showed statistical variations between them ($p < 0.05$) and were higher than commercial sucrose. The moisture ranged from 1.25 ± 0.03 to 2.04 ± 0.04% (wet basis) higher than those determined by Astolfi-Filho et al., (2005) in the co-crystallization of 15% of passion fruit juice with sucrose (1.02 and 0.95% (wet basis)) and lower than the values obtained by Bhandari et al. (1998) and Beristain, Mendoza, Garcia, and Vazquez (1994) for 15% of co-crystallized honey with sucrose (6.99% (wet basis)) and co-crystallization of Jamaica (*Hibiscus sabdarifa* L.), 10% extract with pH of 4.3, with 3.73% (wet basis).

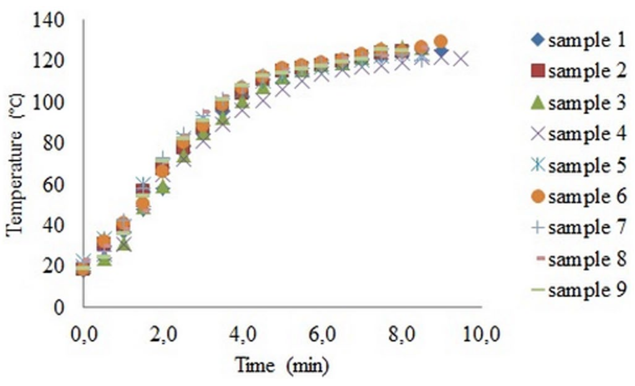

FIGURE 2 Heating curves during co-crystallization process

Co-crystallized products (Table 2) showed similar apparent density values ($p < 0.05$) ranging from 0.46 to 0.49 g/cm^3 for the 9 experiments performed. These values are below the value determined by Astolfi-Filho et al. (2005) in their study with 15% passion fruit juice co-crystallized with sucrose, whose value was 0.638 g/cm^3. On the other hand, the values found in this work are identical to those determined by Beristain et al. (1994) in the co-crystallization of extract of Jamaica (*Hibiscus sabdarifa* L) with sucrose, in concentrations of 10 to 16%, obtaining values ranging from 0.47 to 0.56 g/cm^3. The apparent density values were statistically lower ($p < 0.05$) when compared with commercial sucrose, which was 0.76 ± 0.01 g/cm^3 (Table 2). This indicates that co-crystallized products had a presence of empty spaces among their particles, and in an industrial process, a vibration step could be suggested to remove air between the particles.

Regarding the repose angle, the co-crystallized samples showed values ranging from 23.40 ± 1.69 to 32.28 ± 1.02°, all values were below 35°, including commercial sucrose, which indicates good or excellent flow at free flow. Products with repose angles above 35° show cohesiveness of the particles, interfering their flow (Bhandari et al., 1998; Wells, 2005).

In a study reported by Astolfi-Filho et al. (2005) with 15% passion fruit juice co-crystallized with sucrose, the authors determined repose angles of 28.45 and 31.60°, similar to those obtained in this work. In a study of Bhandari et al. (1998), the authors reported a repose angle from 39.5° of 15% co-crystallized honey with sucrose, similar to the value of 39.7° for yerba co-crystallized with sucrose (Lorena et al., 2007).

Considering α_w and repose angle values, the co-crystallized honey with sucrose obtained in this work has similar properties to commercial sucrose, and can be used as a sweetener in foods that traditionally contains sucrose as drinks, cakes and cookies.

TABLE 2 Physico-chemical analyzes of co-crystallized samples

Co-crystallized samples	Moisture (%) (wetbasis)	α_w	Apparent density (g/cm^3)	Repose Angle (°)
1	1.34 ± 0.05^{cd}	0.42 ± 0.01^{bcd}	0.50 ± 0.01^{b}	29.98 ± 2.71
2	1.39 ± 0.09^{cd}	0.40 ± 0.01^{cde}	0.52 ± 0.01^{b}	23.40 ± 1.69
3	2.04 ± 0.04^{a}	0.51 ± 0.01^{a}	0.48 ± 0.01^{b}	32.02 ± 1.14
4	1.35 ± 0.12^{cd}	0.39 ± 0.01^{de}	0.52 ± 0.02^{b}	32.28 ± 1.02
5	1.25 ± 0.03^{d}	0.43 ± 0.00^{bc}	0.52 ± 0.02^{b}	26.58 ± 1.82
6	1.47 ± 0.09^{cd}	0.38 ± 0.01^{e}	0.49 ± 0.03^{b}	32.07 ± 3.47
7	1.43 ± 0.09^{cd}	0.42 ± 0.02^{bcd}	0.47 ± 0.03^{b}	29.54 ± 2.71
8	1.54 ± 0.12^{bc}	0.41 ± 0.01^{bcde}	0.46 ± 0.03^{b}	30.17 ± 1.21
9	1.76 ± 0.09^{b}	0.45 ± 0.00^{b}	0.49 ± 0.03^{b}	30.17 ± 0.47
Commercialsucrose	0.55 ± 0.01^{e}	0.49 ± 0.03^{a}	0.76 ± 0.00^{a}	34.62 ± 1.41

Note: Tukey test with $p < 0.05$, equal letters in the column do not differ statistically.

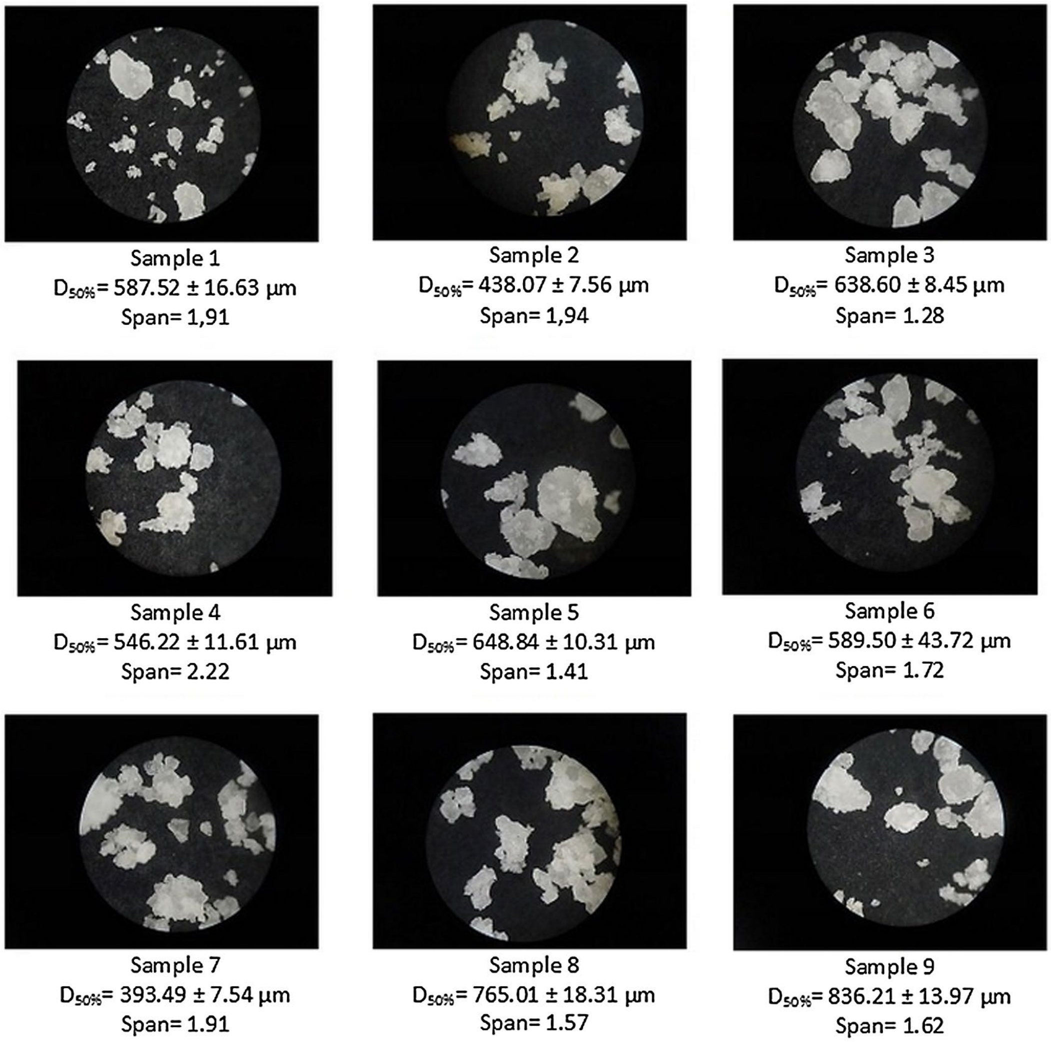

FIGURE 3 Images obtained by stereoscopy (×4 magnification), mean diameter and span index for the 9 samples of co-crystallized honey

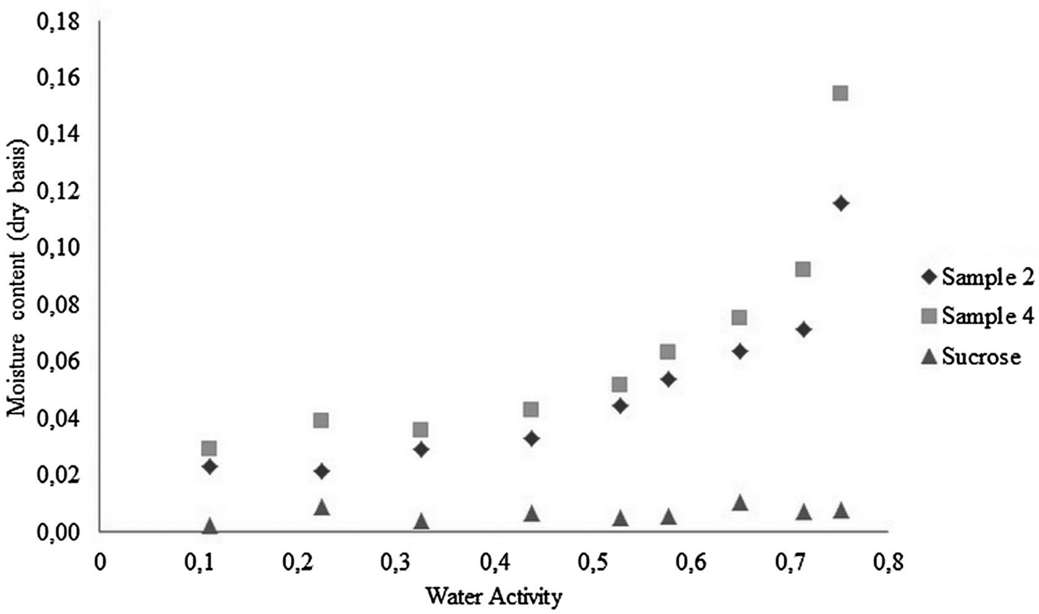

FIGURE 4 Isotherms profile of samples 2, 4 and commercial sucrose

Figure 3 presents the results for the average diameter (D50%), the Span index and the images obtained in the morphological analysis for the 9 samples of co-crystallized honey.

Samples showed a morphological structure characteristic of co-crystallization, with clusters of typical polygonal shape and irregular appearance. The results also showed a monomodal size distribution behavior with a high polydispersity in most of the time, with a Span index greater than 1.5, except for samples 3 and 5. The average diameters varied in a range from 393.49 (sample 7) to 836.21 μm (sample 9).

Figure 4 shows the isotherms profile of samples 2, 4 and commercial sucrose.

For the realization of sorption isotherms and sensory analysis, samples of numbers 2 and 4 were chosen due its physico-chemical results and visual aspect of the co-crystallized product.

The samples of co-crystallized honey with sucrose showed X_e higher than sucrose (Figure 4). This indicates that, even in small amounts of honey in the product (15%), important changes occur in its X_e, indicating that the hygroscopicity of the co-crystallized samples is greater than the sucrose. Through visual observation, it was possible to notice that in the α_w of 0.327 (magnesium chloride), in the equilibrium condition, the co-crystallized samples already showed change in their physical structure, with a tendency to the formation of aggregations, indicating absorption of moisture. This fact is a strong indication that the packaging to be used for the conservation of this product must provide barrier to water vapor.

The sorption isotherms of co-crystallized honey with 15% sucrose (samples 2 and 4) were adjusted according to the GAB model. The results are shown in Table 3.

The curves of the co-crystallized samples showed a mathematical fit for GAB equation, with a determination coefficient above 0.98. The values of the constant K are close to 1, in this case, the GAB equation could be reduced to the BET equation (Brunauer, Emmett and Teller) and linearized (Park, Park, Cornejo, & Fabbro, 2008). The shape of the obtained curves suggests a sigmoid behavior, typical for soluble products, where the water activity grows asymptotically with the increase in relative humidity (Mathlouthl & Rogé, 2003). The X_m (monolayer moisture) of samples 2 and 4 were 0.017 and 0.021 g/g (dry basis), respectively. These values are expected for powder or dehydrated food products (Astolfi-Filho et al., 2005). The X_m means that this moisture at 25°C provides maximum physico-chemical stability. Below these values, energy required is high and stability is affected negatively due to fats oxidation (Goula, Karapantsios, Achilias, & Adamopoulos, 2008).

TABLE 3 Evaluation of isotherm adjustment parameters using GAB method

Samples	K	C	X_m (g/g dry basis)	R^2
2	1.1150	1503835	0.017	0.989
4	1.1369	55077324	0.021	0.987

3.4 | Sensory analysis

The online analysis of the consumption habits questionnaire showed that 67.68% answered that they would like to consume the co-crystallized product with tea or juice and 40.40% would consume with coffee. The most cited tea flavors were chamomile, mint, mate, fennel and fruit. Regarding juices, the preferred flavors were lemon, orange, pineapple, passion fruit and acerola (*Malpighiaemarginata*). Consumers indicated that they would like to taste the co-crystallized product in the preparation of cakes, cereals, yogurts and vitamins. Based on the results, the sensory analyses were performed using lemon juice with co-crystallized samples numbers 2 and 4.

The sensory analysis results are shown in Table 4.

Taste, color, flavor and appearance attributes of co-crystallized samples 2 and 4 did not show significant difference ($p < 0.05$).

The acceptability index (Equation 3) for flavor attribute was 91.44% (sample 2) and 89.67% (sample 4). These results indicate a good acceptability by consumers, as it is greater than 70%, a minimum value to be considered for good acceptability (Dutcoski, 2011).

The intention to purchase of co-crystallized honey with sucrose are shown in Figure 5.

The two formulations of co-crystallized honey were evaluated between "certainly would buy" and "possibly would buy", confirming the results of the sensory analysis and the acceptability index for flavor attribute.

TABLE 4 Appearance, taste and color of co-crystallized honey samples and flavor in lemon juice added with co-crystallized product

	Co-crystallized product			
Attributes	Sample 2	Sample 4	F_{calc}	p-value
Appearance in co-crystallized dry product	7.84 ± 0.65	7.44 ± 0.93	1.70	0.05
Flavor in co-crystallized dry product	7.96 ± 0.75	7.75 ± 0.78	0.85	0.55
Color in co-crystallized dry product	8.00 ± 0.67	7.79 ± 0.83	1.12	0.66
Taste in lemon juice with co-crystallized product	8.23 ± 0.65	8.07 ± 0.78	1.52	0.12

Note: Fisher Test at 95% confidence level.

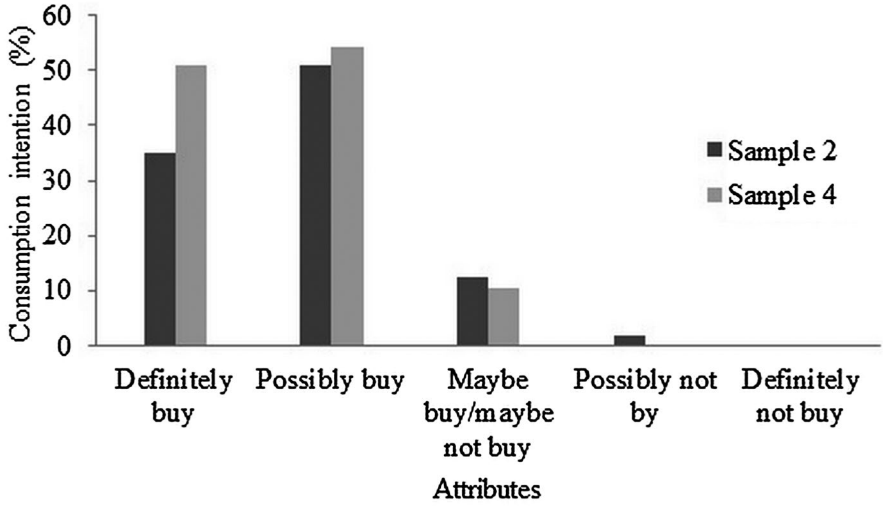

FIGURE 5 Intention to purchase of co-crystallized products. Percentage values for 57 judges. Purchase intention scores: 5 = would certainly buy and 1 = would certainly not buy.

The sensory analysis results showed that the co-crystallized honey with sucrose was accepted by the samplers, leading to new possibilities of using this product as a sweetener in different types of foods that traditionally use pure sucrose.

4 | CONCLUSIONS

The physico-chemical analysis showed that there are differences in the composition of the honey samples from different production places, but with processing, these differences were reduced and the co-crystallized presented similar characteristics. The process of co-crystallization of honey (15%) with sucrose resulted in dry products, with good fluidity and more hygroscopic when compared to commercial sucrose. Co-crystallized products showed good sensory acceptance, acceptability index and purchase intention, which may indicate the use as ingredient for food containing sucrose.

ACKNOWLEDGMENTS

We would like to thank Fundação de Amparo à Pesquisa e Inovação do Estado de Santa Catarina (FAPESC Brazil) for the financial support and UFFS for the scholarships awarded.

CONFLICT OF INTEREST

The authors declares that there is no conflict of interest.

ORCID

Leda B. Quast https://orcid.org/0000-0002-6938-3666

Marise B. Queiroz https://orcid.org/0000-0002-5123-7273

REFERENCES

Ahmed, J., Prabhu, S. T., Raghavan, G. S. V., & Ngadi, M. (2007). Physico-chemical, rheological, calorimetric and dielectric behavior of selected Indian honey. *Journal of Food Engineering*, *79*(4), 1207–1213. https://doi.org/10.1016/j.jfoodeng.2006.04.048

Almeida-Filho, J. P., Machado, A. V., Alves, F. M. S., Queiroga, C. H., & Cândido, A. F. M. (2011). Estudo físico-químico e de qualidade do mel de abelha comercializado no município de pombal – PB. *Revista Verde De Agroecologia E Desenvolvimento Sustentável*, *6*(3), 83–90.

Alvim, O. D., & Grosso, C. R. F. (2010). Microparticles obtained by complex coacervation Onfluence of the type of reticulation and the drying process on the release of the core material. *Food Science and Technology (Campinas)*, *30*(4), 1069-1076. https://doi.org/10.1590/S0101-0612010000400036

Andrade Pizarro, R. D., Blanquicett Gónzalez, K., & Rangel terraza, R., (2017). Propiedades físicas de naranja agria cocristalizada: Efecto del pH, sólidos solubles y zumo adicionado. *Agronomía Mesoamericana*, *28*(2), 427. https://doi.org/10.15517/ma.v28i2.23833

AOAC. (2000). Official methods of analysis of AOAC international. 17 ed. Horwitz, W. Gaithersburg, MD: Association of Official Analytical Chemists, Chapter 44, 22–33.

Astolfi-Filho, Z., Souza, A. C., Reipert, E. C. D., & Telis, V. R. N. (2005). Encapsulaçãodesucodemaracujáporco-cristalizaçãocomsacarose: cinéticadecristalizaçãoepropriedadesfísicas. *Ciênciae Tecnologiade Alimentos*, *25*(4), 795–801.

Bera, A., & Almeida-Muradian, L. B. (2007). Propriedades físico-químicas de amostras comerciais de mel com própolis do estado de São Paulo. *Ciência E Tecnologia De Alimentos*, *27*(1), 49–52. https://doi.org/10.1590/S0101-20612007000100009

Beristain, C. I., Mendoza, R. E., Garcia, H. S., & Vazquez, A. (1994). Cocrystallization of Jamaica (*Hibiscus sabdarifa* L.) Granules. *LWT—Food Science and Technology*, *27*(4), 347–349. https://doi.org/10.1006/fstl.1994.1071

Beristain, C. I., Vazquez, A., Garcia, H. S., & Vermnon-Carter, E. J. (1996). Encapsulationoforangepeeloilbyco-crystallization. *LWT—Food Science and Technology*, *29*(7), 645–647. https://doi.org/10.1006/fstl.1996.0098

Bhandari, R. B., Datta, N., D'arci, B. R., Rintoul, G. B., (1998). Co-crystallizationofhoneywithsucrose. *Lebensmittel – Wissenschaftund Technologie*, *31*,138–142.

Boussaid, A., Chouaibi, M., Rezig, L., Missaoui, R., Donsí, F., Ferrari, G., & Hamdi, S. (2015). Physicochemical, rheological, and thermal properties of six types of honey from various floral origins in Tunisia. *International Journal of Food Properties*, *18*(12), 2624–2637. https://doi.org/10.1080/10942912.2014.1001072

Brasil. (2000). Ministério da Agricultura, Pecuária e Abastecimento. Secretaria Nacional de Defesa Agropecuária. InstruçãoNormativan 11, de20deoutubrode 2000. Laboratório Nacional de Referência

Animal, LANARA. Métodos Analíticos Oficiais para Controle de Produto de Origem Animal e seus Ingredientes. Ministério da Agricultura. Brasília, DF.

Codex Alimentarius Commission (CAC) on Honey. (1987). Revised Codex Standard for Honey, CXS 12-1981.

Conforti, P. A., Lupano, C. E., Malcalza, N. H., Arias, V., & Castells, C. B. (2006). Crystallization of honey at −20°C. *International Journal of Food Properties*, *9*, 99–107.

Cui, Z. W., Sun, L. J., Chen, W., & Sun, D. W. (2008). Preparation of dry honey by microwave-vacuum drying. *Journal of Food Engineering*, *84*, 582–590.

Dutcoski, S. V. (2011). *Análise sensorial de alimentos*, 3th. ed. Curitiba: Champagnat. p. 426.

Federzoni, V., Alvim, I. D., Fadini, A. L., Silva, L. B., & Queiroz, M. B. (2019). Co-crystallization of paprika oleoresin and storage stability study. *Food Science and. Technology*, *39*(1), 182–189. https://doi.org/10.1590/fst.41617

Goula, A. M., Karapantsios, T. D., Achilias, D. S., & Adamopoulos, K. G. (2008). Water sorption isotherms and glass transition temperature of spray dried tomato pulp. *Journal of Food Engineering*, *85*(1), 73–83. https://doi.org/10.1016/j.jfoodeng.2007.07.015

Jedlinska, A., Samborska, K., Wieczorek, A., Wiktor, A., Ostrowska-Ligeza, E., Jamróz, W., … Witrowa-Rajchert, D. (2019). The application of dehumidified air in rapeseed and honeydew honey spray drying – Process performance and powers properties considerations. *Journal of Food Engineering*, *245*, 80–87. https://doi.org/10.1016/j.jfoodeng.2018.10017

Karangutkar, A., & Ananthanarayan, L. (2020). Co-crystallization of Basella rubra extract with sucrose: Characterization of co-crystals evaluating the storage stability of betacyanin pigments. *Journal of Food Engineering*, *271*, 109776. https://doi.org/10.1016/j.jfoodeng.2019.109776

Kumar, T., Gill, J. P. S., Bedi, J. S., Manav, M., AnsarI, M. J., & Walia, G. S. (2018). Sensory and physicochemical analysis of Indian honeys for assessment of quality and floral origin. *Food Research International*, *108*, 571–583. https://doi.org/10.1016/j.foodres.2018.04.005

López-Córdoba, A., Gallo, L., Bucalá, V., Martino, M., & Navarro, A. (2016). Co-crystallization of zinc sulfate with sucrose: A promissory strategy to render zinc solid dosage forms more palatable. *Journal of Food Engineering*, *170*, 100–107. https://doi.org/10.1016/j.jfoodeng.2015.09.024

Lorena, D., Anbinder, P. S., Navarro, A. S., & Martino, M. (2007). Co-crystallization of yerba mate extract (Ilex paraguariensis) and mineral salts within a sucrose matrix. *Journal of Food Engineering*, *80*, 573–580. https://doi.org/10.1016/j.jfoodeng.2006.06.016

Mathlouthl, M., & Rogé, B. (2003). Water vapour sorption isotherms and the caking of food powders. *Food Chemistry*, *82*(1), 61–71. https://doi.org/10.1016/S0308-8146(02)00534-4

Meilgaard, M., Civille, G. V., & Carr, B. T. (2007). *Sensory evaluation techniques*, 4th ed. Boca Raton: CRCPress. p. 387.

Nurhadi, B., & Roos, Y. H. (2017). Influence of anti-caking agent on the water sorption isotherm and flow-ability properties of vacuum dried honey powder. *Journal of Food Engineering*, *210*, 76–82. https://doi.org/10.1016/j.jfoodeng.2017.04.020

Oliveira, V. S., Afonso, M. R. A., & Costa, J. M. C. (2011). Caracterizaçãofísico-químicae comportamento higro scópicode-sapotiliofilizado. *Revista Ciência Agronômica*, *42*(2), 342–348. https://doi.org/10.1590/S1415-43662013001000011

Oriani, V. B., Alvim, O. D., Consoli, L., Molina, G., Pastore, G. M., & Hubinger, M. D. (2016). Solid lipid microparticles produced by spray chilling technique to deliver ginger oleoresin: Structure and compound retention. *Food Research International*, *80*, 41–49. https://doi.org/10.1016/j.foodres.2015.12.015

Park, K. J., Bin, A., & Brod, F. P. R. (2001). Obtenção das isotermas de sorção e modelagem matemática para a pêra bartlett (Pyrus sp.) Com e sem desidratação osmótica. *Ciência E Tecnologia De Alimentos*, *21*(1), 73–77. https://doi.org/10.1590/S0101-20612001000100016

Park, K. J. B., Park, K. J., Cornejo, F. E. P., & Fabbro, I. M. D. (2008). Review Considerações termodinâmicas das isotermas. *Revista Brasileira De Produtos Agroindustriais*, *10*(1), 83–94.

Quintas, M. A. C.Fundo, J. F., Silva, C. M. L. (2010). Sucrose in the Concentrated Solution or the Supercooled "State": A Review of Caramelisation Reactions and Physical Behaviour. *Food Engineering Reviews*, *2*(3), 204–215. https://doi.org/10.1007/s12393-010-9022-4

Ribeiro, R., & Starikoff, K. R. (2019). Avaliação da qualidade fpisico-química e microbiológica de mel comercializado. *Revista De Ciências Agroveterinárias*, *18*(1), 111–118. https://doi.org/10.5965/223811711812019111

Santos, F. K. G., Dantas Filho, A. N., Leite, R. H. L., Aroucha, E. M. M., Santos, A. G., & Oliveira, T. A. (2014). Rheological and some physicochemical characteristics of selected floral honeys from plants of caatinga. *Anais Da Academia Brasileira De Ciencias*, *86*(2), 981–994. https://doi.org/10.1590/0001-3765201420130064

Sardar, B. R., & Singhal, R. S. (2013). Characterization of co-crystallized sucrose entrapped with cardamom oleoresin. *Journal of Food Engineering*, *117*, 521–529. https://doi.org/10.1016/j.jfoodeng.2012.12.011

Sartori, T., Consoli, L., Hubinger, M. D., & Menegalli, F. C. (2015). Ascorbic acid microencapsulation by spray chilling: Production and characterization. *LWT—Food Science and Technology*, *63*(1), 353–360. https://doi.org/10.1016/j.lwt.2015.03.112

Seraglio, S. K. T., Silva, B., Bergamos, G., Brugnerotto, P., Gonzaga, L. V., Fett, R., & Costa, A. C. O. (2019). An overview of physicochemical characteristics and heath-promoting properties of honeydew honey – Review. *Food Research International*, *119*, 44–66. https://doi.org/10.1016/j.foodres.2019.01.028

Silva, M. P., Gauche, C., Gonzaga, L. V., Costa, A. C. O., & Fett, R. (2016). Honey: Chemical composition, stability and authenticity. *Food Chemistry*, *196*, 309–323. https://doi.org/10.1016/j.foodchem.2015.09.051

Wells, J. (2005). Pre-formulação farmacêutica. In M. Aulton (Ed.), *Delineamento de formas farmacêuticas* (pp. 125–148). Porto Alegre: Artmed.

Zamora, M. C., & Chirife, J. (2006). Determination of water activity change due to crystallization in honeys from Argentina. *Food Control*, *17*(1), 59–64. https://doi.org/10.1016/j.foodcont.2004.09.003

How to cite this article: Quast LB, Farina SG, Quast E, Vieira MA, Queiroz MB. Co-crystallized honey with sucrose: Evaluation of process and product characterization. *J Food Process Preserv*. 2020;44:e14876. https://doi.org/10.1111/jfpp.14876