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FLOW AND THERMAL PROPERTIES OF STEVIA POWDER

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Stevia (*Stevia rebaudiana* Bertoni) has recently received a lot of attention as a sweetener due to its taste and low calorific value. Flow and thermal properties of foods play a significant role in the quantitative analysis of unit operations in the food industry. However, there are no published data available on flow and thermal properties of stevia powder. Powder Flow Tester and KD2 Pro Thermal Properties Analyzer were used to determine the flow and thermal properties of stevia powder, respectively, at different moisture contents (4.96%, 9.68%, 13.99%, 20.08%, and 25.79%, w.b.). Mean angle of internal friction of stevia powder ranged from 41.13° to 46.3°. The mean effective angle of internal friction ranged from 47.8° to 52.5° and the mean flow index ranged from 0.27 to 0.48. Mean thermal conductivity of stevia powder ranged from 0.091 $W \cdot m^{-2} \cdot K^{-1}$ to 0.115 $W \cdot m^{-2} \cdot K^{-1}$. Mean thermal diffusivity ranged from 0.103 $mm^2 \cdot s^{-1}$ to 0.121 $mm^2 \cdot s^{-1}$ and mean volumetric specific heat ranged from 0.865 $MJ \cdot m^{-3} \cdot K^{-1}$ to 1.019 $MJ \cdot m^{-3} \cdot K^{-1}$. Polynomial regression models were developed to predict flow and thermal properties of stevia powder using moisture content of stevia powder.

Keywords: food properties; food processing and storage; food engineering; stevioside; rebaudioside A

Stevia (*Stevia rebaudiana* Bertoni) is a branched bushy shrub belonging to the Asteraceae family and is native to the north eastern part of Paraguay (Lasekan and Naidu, 2013; Lemus-Mondaca et al., 2012). *Rebaudiana* and *phlebophylla* are the only two species that produce steviol glycosides among the 230 species of *Stevia* genus (Brandle and Telmer, 2007). Stevia and stevioside have been used as substitutes for saccharine for the treatment of diabetes mellitus, obesity, and hypertension and also for the prevention of caries (Pól et al., 2007). Stevioside and *rebaudiana* A are the two major sweetening agents that are thermostable up to 200 °C and are suitable for use in cooked foods (Lemus-Mondaca et al., 2012). Stevioside, a white crystalline and odorless powder, which is almost 300 times sweeter than sucrose is extracted from the leaves of *S. rebaudiana* Bertoni (Gasmalla et al., 2014). Rebaudioside A is about 250 to 400 times sweeter than sucrose and has a wide range of food applications (Flavia et al., 2007). In addition, stevia leaves are also a good source of carbohydrates (Gasmalla et al., 2014).

Powder flow properties are essential in handling and processing of food powders primarily related to the flow from hoppers and silos, mixing, transportation, compression, and packaging (Fitzpatrick et al., 2004; Slettengren et al., 2016). The ability of a powder to flow depends on its physical properties (size, density, and surface area), moisture content, and types of equipment used during handling, processing and storage. The moisture content of a powder plays a significant role in its flowability as the liquid bridges and capillary forces acting between powder particles lead to reduced flowability (de Campos and do Carmo Ferreira, 2013).

Thermal processes such as drying, heating, cooling, sterilization, cooking, and refrigeration are commonly used in food processing, transportation and preservation operations. Thermal conductivity, thermal diffusivity and specific heat are three important engineering properties of a food material related to heat transfer characteristics (Božiková et al., 2015). Hence, the response of stevia powder to heat transfer is dependent on these properties. Knowledge of thermal properties of stevia powder is important not only for designing optimal processing systems and developing equipment for drying, but also for the prediction and control of various changes occurring in stevia powder during thermal processing and storage. The objective of this research was to determine the flow and thermal properties of stevia powder and evaluate the effect of moisture content on those properties.

Material and methods

Sample preparation

Stevia plants were harvested from the Fort Valley State University research field, put in brown harvesting paper bags and dried at 60 °C in a convection oven (Thermal Product Solutions, White Deer, PA) for 72 h. Leaves were separated from the twigs and further ground to fine powder with a Thomas-Wiley laboratory mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA). Fine powder was packed into Ziploc bags, sealed tightly and stored in a refrigerator at 4 °C (VWR, Model GDM-47, True Manufacturing, Inc., O'fallon, MO). Assessment of the effect of moisture content on flow

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and thermal properties of stevia powder was conducted at five levels of moisture contents (4.96%, 9.68%, 13.99%, 20.08%, and 25.79%, w.b.). Moisture content of stevia powder was determined in triplicates according to the ASABE Standard S358.2 (ASABE, 2011) by drying in an oven at 103 °C for 24 h. The initial moisture content of stevia powder was 9.68%. The samples at moisture contents above 9.68% and below 9.68% were prepared following the procedures described in previous work (Mahapatra et al., 2011, 2013, 2017). Bulk density was calculated by dividing the sample weight by sample volume (10 replicates at each moisture content, $n = 10$).

Flow properties measurement

A Powder Flow Tester (PFT) (Brookfield Engineering Laboratories, Inc., Middleborough, MA) was used to determine the flow properties of stevia powder. The PFT uses the annular and Jenike shear tests techniques and is in compliance with the ASTM D6128 test procedures (Slettengren et al., 2016). Flow function tests were conducted using a vane lid and running standard flow function test program (max. stress: 4.82 kPa; no. of consolidation levels: 5; no. of stresses: 3; axial speed: 1.0 mm·s^{-1}; flow index stress: 10 kPa; arching flow factor: 1.40). Software provided by PFT manufacturer automatically calculated the following: cohesion; angle of internal friction; effective angle of internal friction, and flow index.

Thermal properties measurement

Thermal properties of stevia powder were measured using a KD2 Pro Thermal Properties Analyzer (Decagon Devices, Inc., Pullman, WA) as described by Mahapatra et al. (2017). Thermal properties were measured in triplicate and repeated 10 times ($n = 30$).

Statistical analysis and modeling procedures

Flow and thermal properties were measured at five moisture contents and the mean values were calculated at each moisture content. Data were analyzed using the general linear models (GLM) procedures of the Statistical Analysis System (Version 9.4, SAS Institute Inc., Cary, NC) and the least significant difference (LSD) among means was calculated at 5% significant level ($p < 0.05$). Regression techniques were used to assess the relationship between moisture content and both the properties. Second degree polynomial models were developed using PROC REG (regression procedure) and GLM (general linear models) procedures of SAS. Five statistical indices including correlation coefficient (R), mean relative percentage residual (MRPR), bias factor, accuracy factor, and root mean square residual (RMSR) were calculated to assess performance of the models (Gosukonda et al., 2017; Jeyamkondan et al., 2001). Measured and predicted values were averaged for plotting the graphs.

Results and discussion

Flow and thermal properties of stevia powder were determined at different moisture contents (4.96%, 9.68%, 13.99%, 20.08%, and 25.79%, w.b.). Mean room temperature recorded was 23 ± 2 °C. Mean bulk density of stevia powder ranged from 302.66 ± 8.09 to 375.53 ± 5.47 kg·m^{-3}.

Flow properties of stevia powder

Cohesion

Mean cohesion of stevia powder ranged from 0 to 0.012 ± 0.008. Cohesion in a powder is the result of either inter-particle forces (electrostatic, moisture) or mechanical interlocking between adjacent particles. Moisture content increase results in increased distance between stevia powder particles, reduced electrostatic and molecular interactions, and, therefore, lower cohesion. Cohesion tends to decrease at moisture content heading towards the liquid limit and increases towards the shrinkage limit. Stevia powder indicated zero cohesion above 14% moisture content with an angle of internal friction ranging from 44 to 46° (Table 1).

Angle of internal friction

Mean angle of internal friction of stevia powder ranged from 41.13 ± 0.45° to 45.83 ± 1.09° (Fig. 1, Table 1) and was significantly ($p < 0.0001$, $R^2 = 0.77$) affected by moisture content. Increasing the moisture content of stevia powder from 5 to 14% increased the angle of internal friction by 8.4%. However, for moisture content above 14%, the value of angle of internal friction remained flat or decreased slightly with increasing moisture content (Fig. 1). Kamath et al. (1993) reported lower value of angle of internal friction for sugar (31.3 to 34.6°). Fitzpatrick et al. (2004) reported the angle of internal friction for 13 food powders that varied from 42 to 65°. The measured values for angle of internal friction of stevia powder at all moisture content levels were greater than the critical value of less than 30°, hence, gravity discharge cannot be used to unload stevia powder from storage bins and silos (Fasina, 2006; Puri, 2002).

Table 1 Flow properties of stevia powder (mean ± SD, $n = 3$)

Moisture content, w.b. (%)	Angle of internal friction (°)	Effective angle of internal friction (°)	Cohesion (kPa)	Flow index
4.96	41.13 ± 0.45 c	47.80 ± 2.17 a	0.002 ± 0.003 b	0.27 ± 0.01 b
9.68	42.10 ± 0.10 c	51.87 ± 1.11 a	0.012 ± 0.008 a	0.30 ± 0.01 b
13.99	44.60 ± 0.27 a,b	52.30 ± 2.46 a	0	0.47 ± 0.02 a
20.08	45.83 ± 1.09 a	52.50 ± 2.86 a	0	0.48 ± 0.05 a
25.79	44.13 ± 0.51 b	47.67 ± 2.52 a	0	0.48 ± 0.05 a

Values in the same column with different letter are significantly different ($p < 0.05$)

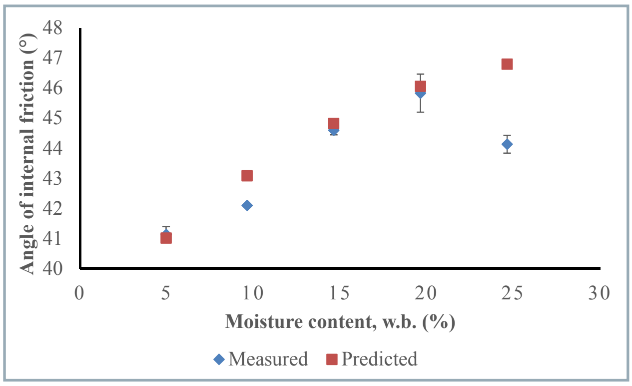

Fig. 1 Measured and predicted angle of internal friction of stevia powder

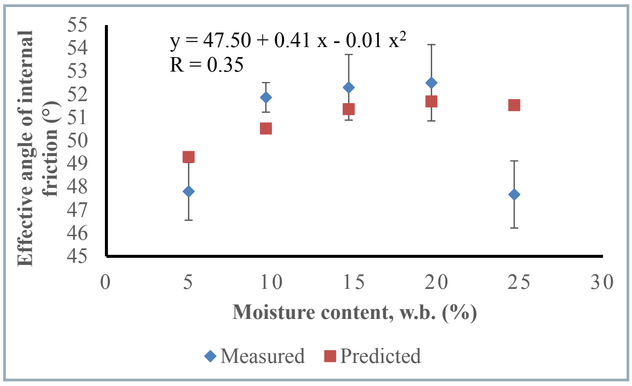

Fig. 2 Measured and predicted effective angle of internal friction of stevia powder

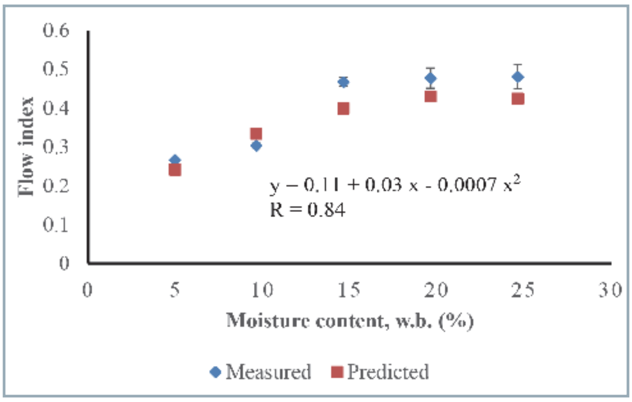

Fig. 3 Measured and predicted flow index of stevia powder

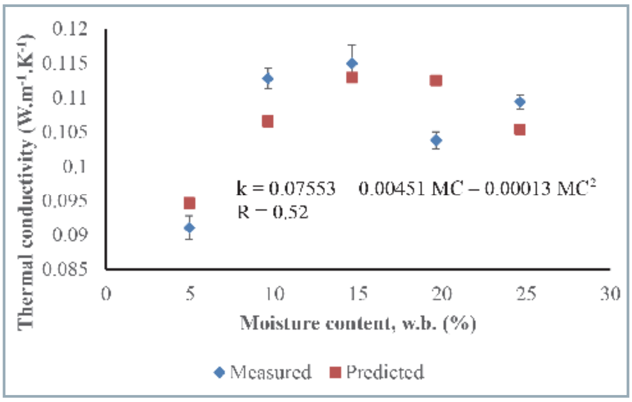

Fig. 4 Measured and predicted thermal conductivity of stevia powder

Effective angle of internal friction

The effective angle of internal friction of stevia powder, a measure of inter-particle interactions, were in the range of 47.8 ± 2.2° to 52.3 ± 2.5° (Fig. 2, Table 1). Statistical analysis of data showed that moisture content did not significantly (p = 0.32, R^2 = 0.14) affect the effective angle of internal friction.

Flow index

Mean flow index values of stevia powder were in the range of 0.27 ± 0.01 to 0.48 ± 0.05 (Fig. 3, Table 1) and were significantly p < 0.0001, R^2 = 0.83) affected by moisture content. Increasing the moisture content of stevia powder from 5 to 26% increased the flow index by 78%. From the flow index values, stevia powder can be classified as cohesive material (difficult to flow) and, therefore, low aids will be needed during discharging of stevia powder from storage bins, silos, and hoppers. Poor flowability of stevia powder could be due to particle shape, small particle size, and wider particle size distribution.

Thermal properties of stevia powder

Thermal conductivity

Mean thermal conductivity values of stevia powder ranged from 0.0910 ± 0.0095 to 0.1150 ± 0.0146 W·m^{-1}·K^{-1} (Fig. 4, Table 2). Carson (2015) reported that thermal conductivity of particulate foods should range between 0.03 and 0.30 W·m^{-1}·K^{-1}. Statistical analysis indicated that moisture content had a significant (p < 0.0001) effect on thermal conductivity values. The lowest thermal conductivity was obtained at moisture content of 5% and the highest value was obtained at moisture content of 14%. Thermal conductivity increased with increase in moisture content from 5 to 14%, but above 14% moisture content, thermal conductivity remained about constant or decreased slightly with increasing moisture content.

Thermal diffusivity

Thermal diffusivity of stevia powder ranged from 0.1032 ± 0.0087 to 0.1206 ± 0.0097 mm^2·s^{-1} (Fig. 5, Table 2). Statistical analysis indicated that moisture content had a significant (p < 0.0001) effect on thermal diffusivity values of stevia powder. The lowest thermal diffusivity was obtained at moisture content of 5% and the highest value was obtained at moisture content of 20%. The thermal diffusivity increased with increase in moisture content up to a peak at 20%. Further increase beyond this level resulted in a decrease in thermal diffusivity (Fig. 5). As moisture content of stevia powder increased, the pores and capillaries of stevia powder that were initially filled with air were gradually filled up by absorbing water. Heat released due to water adsorption in stevia powder resulted in the increased thermal diffusivity (Kostaropoulos and Saravacos, 1997; Raigar and Mishra, 2015). For most food and agricultural products, thermal diffusivity values range from 0.1 to 2.0 × 10^{-7} m^2·s^{-1} (Huang and Liu, 2009).

Table 2 Thermal properties of stevia powder (mean ± SD, $n = 30$)

Moisture content, w.b. (%)	Thermal properties		
	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	thermal diffusivity ($mm^2 \cdot s^{-1}$)	specific heat ($MJ \cdot m^{-3} \cdot K^{-1}$)
4.96	0.091 ± 0.009 c	0.103 ± 0.009 c	0.908 ± 0.071 b
9.68	0.113 ± 0.008 a	0.111 ± 0.008 b	1.019 ± 0.044 a
13.99	0.115 ± 0.015 a	0.116 ± 0.012 a,b	0.988 ± 0.054 a
20.08	0.104 ± 0.007 b	0.121 ± 0.009 a	0.865 ± 0.044 b
25.79	0.109 ± 0.006 a,b	0.110 ± 0.003 b	0.958 ± 0.185 a

Values in the same column with different letter are significantly different ($p < 0.05$)

Table 3 Selected statistical indices of polynomial regression models

Flow and thermal properties	MRPR (%)	Bias factor	Accuracy factor	RMSR
Angle of internal friction	-1.82	1.02	1.02	1.37
Angle of effective internal friction	-1.20	1.01	1.05	2.76
Flow index	6.78	0.93	1.12	0.06
Thermal conductivity	-0.99	1.01	1.07	0.01
Thermal diffusivity	-0.55	1.00	1.05	0.01
Volumetric specific heat	-0.66	1.00	1.07	0.08

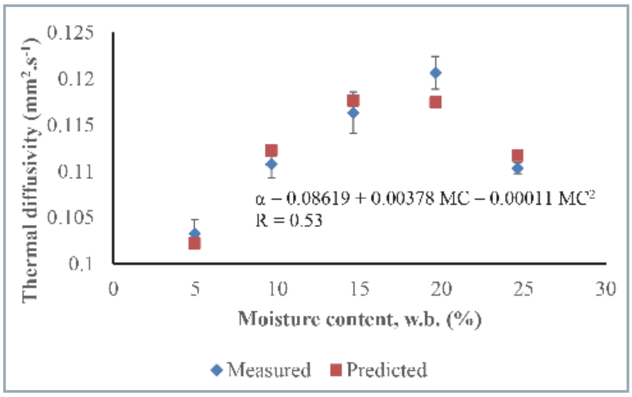

Fig. 5 Measured and predicted thermal diffusivity of stevia powder

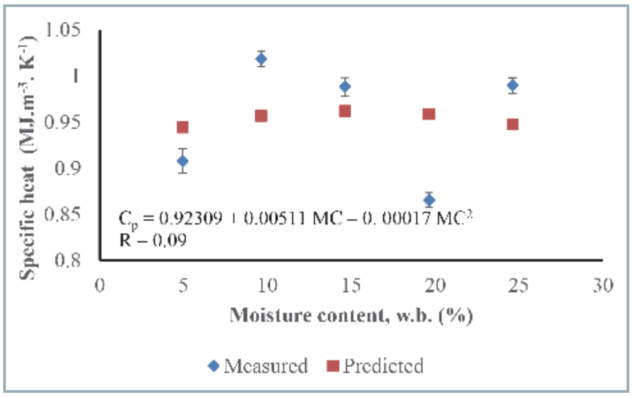

Fig. 6 Measured and predicted specific heat of stevia powder

Specific heat

Specific heat of stevia powder ranged from 0.8654 ± 0.0436 to 1.0185 ± 0.0445 $MJ \cdot m^{-3} \cdot K^{-1}$ (Table 2). Statistical analysis indicated that moisture content had no significant ($p = 0.26$) effect on specific heat values of stevia powder. It can also be seen from Fig. 6 that the specific heat is independent of moisture content in the range studied and did not show any specific trend with moisture content.

Performance of polynomial models

Table 3 shows the selected statistical indices. The MRPR values indicate that models have over-predicted angle of internal friction (1.8%) and angle of effective internal friction (1.2%), whereas, under-predicted flow index (7%). The MRPR values for thermal properties indicate that models have over-predicted the thermal properties in the range of 0.6% to 1%. The bias factor values for flow and thermal properties are close to one indicating that there is no systemic bias. Accuracy factors ranged from 1.02 to 1.12. A value of 1.02 suggests that deviation of predicted value from experimental value is about 2%.

Conclusions

This paper presents the measured flow and thermal properties of stevia powder at a range of moisture contents. The angle of internal friction measured at different moisture contents were more than 30° for stevia powder indicating that stevia powder cannot be discharged from silos and bins by gravity. Based on the measured values of flow index, stevia powder can be classified as cohesive/poor flowing material. The study showed a positive correlation between thermal conductivity and moisture content. A positive correlation was also observed between thermal diffusivity and moisture content. However, moisture content had no significant effect on specific heat for the measured moisture range of 5 to 26%. The data extends the range of knowledge of flow and thermal properties of stevia powder to moisture contents that have not previously been reported.

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