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Effect of moisture content and particle size on grinding kinetics and flowability of balloon flower (*Platycodon grandiflorum*)

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Abstract In this study, the grinding kinetics and the flowability of balloon flowers (BFs) with various moisture contents (8, 12, and 20%) were determined. Three semi-empirical grinding models (Bond, Kick, and Rittinger) were applied to describe the BFs' grinding process. A lower moisture content resulted in a decreased grinding constant value (Bond's index). Based on the kinetics of particles during grinding, a sigmoid model was developed which successfully described changes in the particle sizes of BFs with various moisture contents during the grinding process except for smaller ones (< 0.60 mm) with a high moisture content (20%). The flow function at different particle sizes was not consistently correlated with results regarding the internal friction angle. This might be due to different particle shapes and sizes of BFs. The poorest flowability was observed for BF powder with the smallest particle size.

Keywords Balloon flower · Powder · Grinding · Kinetics · Flowability

Introduction

The balloon flower (BF, *Platycodon grandiflorum*) is an herbaceous perennial belonging to the *Campanulaceae* family. It contains many nutritional components such as fiber and triterpenoid saponins [1]. In Korea, this plant is known as *Doraji* (Japanese name, '*Kikyo*'; Chinese name, '*Jiegeng*'). The BF is a popularly consumed food. Many Asian countries use it as an ingredient of medicine in its dried form because of various contained bioactive components [1]. Flour or powder forms of BF are in high demand by processed-food companies and the pharmaceutical industry for producing oriental medicines due to its handling and manufacturing convenience. The bioactive components in the powder forms of BFs are highly efficiently extracted which is why they are more preferred to use in liquid types of oriental medicine. Commercially used BF powder is obtained after grinding dried roots of BF.

Grinding is a widely used process for size reduction in the food industry [2]. Dried grains and roots may be broken down in many different ways, including compression, impact, attrition, rubbing, and cutting [3]. The grinding process requires high energy—depending on the grains' mechanical properties [4]—to yield certain particle sizes suitable for many applications in food processing. Many BF grinding process parameters can affect flour powder characteristics, including the specific grinding method, machinery, as well as the hardness and the cultivar of BFs. The moisture content in the grain is a particularly important factor that determines the required particle sizes and energy during grinding because there is a direct relationship between moisture content and the grains' mechanical properties [5–7]. In addition, size reduction can generate a new surface area of a particle which will increase when a grain's particle size diminishes. Many unit operations such as leachings, extractions, and biochemical reactions conducted in liquid–solid mixture can be optimized by reducing particle sizes. In addition, the thermal processing time might be shortened when the sizes of solid particles are small [7, 8].

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Despite many benefits of size reduction, when particle sizes are smaller, their flowability generally worsens. It has been known that when particles are exiting hoppers or feeders, the flowability is highly dependent on their sizes [9, 10]. Bulk properties of food powders are specifically affected by moisture content, particle shape or dimension, and particle surface characteristics. These are essential properties that affect the storage and transfer of particles in bulk [8, 11]. When bulk powders stream through a hopper or a silo, either core or mass flows will occur. A core flow happens when the powder floats towards a silo outlet in a channel formed within the powder itself. In a mass flow, all powders in a silo are in motion whenever any powder is drawn from the outlet [12]. Stresses are generally low throughout the solid mass and a low powder compaction is generated in a mass flow; particles move in a first-in-first-out fashion. Therefore, the residence time for materials in a silo is short. However, arching can occur in the mass flow of powder from a hopper.

The objectives of this study were (1) to investigate the application of kinetic modeling on the BFs' grinding process, (2) to determine the time dependence of BF particle sizes during grinding, and (3) to evaluate the flowability of BF powder with various particle sizes.

Materials and methods

Sample preparation and analysis of general chemical compositions

Balloon flowers (BFs, *Platycodon grandiflorum*) were purchased from a local market in Gangwon Province, Republic of Korea. General compositions, such as moisture content, crude carbohydrate, crude protein, crude fat, crude ashes, and crude fiber of fresh and dried BFs (i.e., before and after drying up to 12% of the moisture content) were analyzed according to AOAC criteria [13]. The analysis was conducted with three different BF samples (> 70 g each) and the BF parts were randomly mixed before analysis. The general compositions of dried BFs were analyzed with a 12% moisture content which could represent the average for dried BFs used in this study since the evaluation of the grinding properties and the particle sizes of BF powder was conducted at 8, 12, and 20% of moisture content. The temperature of the dryer for moisture measurement was set at 105 °C. The Kjedahl protein analysis system MBC-20 (Kjeltec, Barcelona, Spain) was used for the protein measurement and the Soxhlet method for lipid analysis. The temperature of the furnace for ash analysis was set at 550 °C.

Before drying and grinding, the BFs were washed, cut into cylindrical form (diameter 1 cm; height 7 cm), and then placed at room temperature (25 °C) for 12 h to obtain moisture equilibrium. The BF moisture contents were adjusted to 8, 12, and 20% using a tray dryer (Dong Yang Machinery Co., Siheung, Republic of Korea) and the periods for the balloon flowers to reach those moisture levels were 1010, 1180, and 1440 min, respectively. Changes in the BF moisture contents were determined with the moisture analyzer HS200M (Hansung Co., Ltd., Seoul, Republic of Korea).

Grinding studies

Grinding was carried out for 75 g of BFs for 5, 10, 15, 20, 30, 40, 50, 60, and 90 s using the 500 W dry grinder HMF-3000S (Hanil Electric Co., Ltd., Seoul, Republic of Korea). After each grinding period, the particle sizes of all samples were determined with standard screen mesh sieves (2, 1.4, 1.18, 1, 0.6, 0.425, 0.25, and 0.15 mm) stacked on each other with the smallest mesh screen at the bottom and the largest one on the top. In each case, the sample was placed on the top screen and the stack was mechanically shaken for 10 min using the motorized sieve shaker CG-211-8 (Chunggye, Seoul, Korea). Screens with retained particles were removed and weighed. The mass of individual screen increments was converted to a mass fraction of the total sample using the following formula [14].

$$L_2 = \sum_{i=1}^{n} \Phi_i d_i \tag{1}$$

where L_2 is the final particle size of BFs after grinding (mm) and Φ_i the differential weight fraction of particles passing through an aperture with the size d_i, which was the average mesh's aperture size in mm [5].

Based on the initial and final particle sizes of the BF powder, Rittinger's law, Kick's law, and Bond's law constants as well as the Bond Work Index were calculated using the following Eq. (3).

Rittinger's law

$$E = K_r \left[\frac{1}{L_2} - \frac{1}{L_1} \right] \tag{2}$$

Kick's law

$$E = K_k \ln \left[\frac{L_1}{L_2} \right] \tag{3}$$

Bond's law

$$E = K_b\left[\frac{1}{\sqrt{L_2}} - \frac{1}{\sqrt{L_1}}\right] \tag{4}$$

Work index

$$W_{ind} = \frac{K_b}{0.3162} \tag{5}$$

where L_1 and L_2 are the mean diameters of the initial and ground samples, respectively. K_r, K_k, and K_b are Rittinger's, Kick's, and Bond's constants, respectively. E is the energy required for grinding and W_{ind} the work index which was defined as the energy required to grind materials to a size capable for passing through a 100 µm mesh.

Grinding kinetics

Generally, a plot of powder yield and the grinding time displays the shape of a Sigmoidal curve. A differential equation derived from grinding kinetics can be used to predict the quantity of ground particles with a size i at a given time using the following kinetic equation:

$$BF_i(t) = \frac{BF_{max}}{1 + e^{-\frac{1}{a}(t-b)}} \tag{6}$$

where coefficient a is a grinding ability constant and b the required grinding time to obtain 50% of BFs with a specific particle size, i. The amount of ground particles containing a specific size at various grinding times can be empirically measured. A kinetic model for BF grinding was then developed based on these amounts.

Flowability measurement

The flowability of BF powder was measured using a powder flow tester (Brookfield, Middleboro, MA, USA). The bulk density, the effective angle of internal friction, and the flow function were measured. These three are important factors that can characterize the flow property of powder. A PFT-500 Vane lid component was used to evaluate standard flow functions. The maximum stress applied was at 4.819 kPa. Five different consolidation levels (0.289, 0.584, 1.180, 2.385, and 4.819 kPa) of stress were then applied. Easy or difficult flows were classified based on the direction of the flow function represented in a flow function graph [11]. An inverse slope of the flow function, also called flow index, was used to classify flowability [15].

Statistical analysis

All variables were measured in triplicate. Their average values were used for analysis. The curve fitting tool of Matlab (R2011b, Mathworks, Natick, MA, USA) was used to analyze and to develop a model of grinding kinetics. Significant differences were evaluated by one-way analysis of variance (ANOVA) using Microsoft Excel 2013 (Microsoft Corp., Redmond, WA, USA).

Results and discussion

General compositions of balloon flowers (BFs)

The general compositions of BF were analyzed and summarized in Table 1. The initial moisture content of the fresh BF was 76.63% and it was dried to 12%. Since the moisture content of BF was varied at 8, 12, and 20% for the evaluation of the grinding properties and the BF powders' particle sizes, an average moisture content of 12% was used to determine the general composition of dried BFs. They contained high amounts of crude carbohydrates (69.58%) and crude proteins (6.47%). Such a high carbohydrate amount might affect the grinding kinetics at relatively high moisture contents because of the liquid bridge between the particles associated with carbohydrates.

Grinding characteristics

Mean particle sizes of balloon flower (BF) powders with various moisture contents (8, 12, 20%) were evaluated by assessing the weight fraction of powder on sieves with different mesh sizes using Eq. (1) (Fig. 1). The initial volume surface of the BFs' mean diameters was 70 mm. Particle sizes of all samples decreased as grinding times

Table 1 General compositions of fresh and dried balloon flowers

Compositions	Fresh BF* (%)	Dried BF** (%)
Moisture content	76.63 ± 0.32	12.1 ± 0.24
Carbohydrate	18.90 ± 0.27	69.58 ± 0.20
Crude protein	1.84 ± 0.05	6.47 ± 0.05
Crude fat	0.43 ± 0.03	2.08 ± 0.04
Crude ash	1.01 ± 0.07	3.55 ± 0.11
Crude fiber	1.16 ± 0.05	6.30 ± 0.05

*All values were averaged after triplication

**The general composition of dried BF were evaluated at an average moisture content (i.e., 12%) used this study

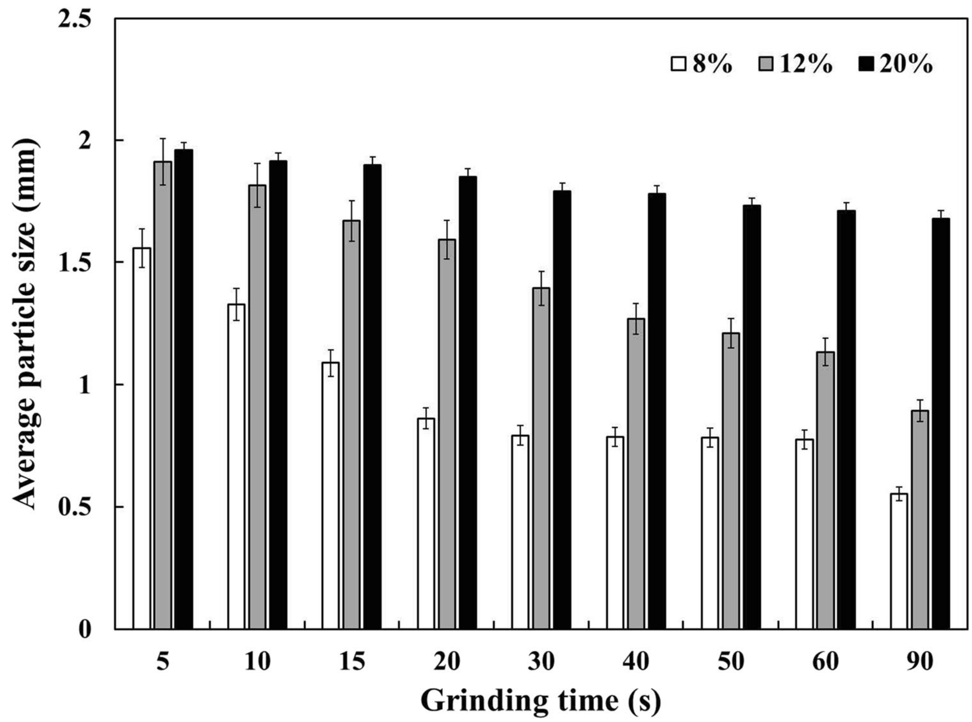

Fig. 1 Average particle size of balloon flowers by grinding time

increased. The mean particle sizes of BF powders with a higher moisture content were bigger than for those with low moisture levels. This might be associated with changes in hardness or in the brittleness of particles with different moisture contents. The brittleness of solids is generally higher when the moisture content is diminished [16]. Such an increase in the brittleness of BFs with lower moisture contents can allow easy BF grinding. BFs with lower moisture contents produced smaller particle sizes within a specific grinding time. As the moisture content increased, more time was required to grind BFs to obtain a given particle size.

Drying characteristics were estimated by using the constants of Bond's, Rittinger's, and Kick's models as well as Bond's Work Index, an energy consumption index, at the various moisture levels mentioned above (8, 12, and 20%) (Table 2). The constants' values of each model increased in parallel with the BF moisture contents' elevation. The work index, defined as the amount of energy required to make a smaller particle to pass through a mesh size of 100 μm, also increased as the moisture content level heightened. When the BF samples became brittle, less energy was required for grinding. This suggests that brittle samples are less resistant to grinding. Lee et al. [16] studied the effect of seed moisture content on black soybean grinding kinetics and reported that the energy requirement for grinding to 0.2 mm is increased as the moisture content level of black soybeans heightens. Since a lower moisture content requires less energy for grinding, it generated smaller particle sizes of black soybean flour [16]. Walde et al. [5] studied microwave drying and grinding of wheat. They found that the wheat's moisture content was reduced by microwave drying and that samples with lower moisture contents required less energy to reduce the wheat particles' sizes [5]. Similar results have been reported by Dziki [17] demonstrating that wheat kernels with moisture content ranging from 10 to 20% have a high mass fraction for large particles sizes with an increasing moisture content. However, according to Pan and Tangratanavalee [18], less energy is required for a high moisture content when it is between 60 and 170% on a dry basis. It is noteworthy that the hardness of a kernel in its seed coat is low with an extremely high moisture content is extraordinarily strengthened; this requires less energy for grinding [18]. But although their finding is useful for processing wet BF, it is not applicable to making flour with dried balloon flowers. This result rather suggests that the moisture content of materials used for grinding should be controlled depending on the specific applications.

Grinding kinetics

The kinetic behavior of BF powder with different moisture contents during grinding was evaluated (Fig. 2). Kinetic model parameters were obtained using a curve-fitting method with raw data shown in Fig. 2. The values of these parameters are summarized in Table 3. The kinetic model described the grinding behavior of most samples well,

Table 2 Grinding characteristics of balloon flowers with various moisture contents (%)

Grinding time (s)	Moisture content (%)		
	8	12	20
Bond's law constant (k_b)			
5	0.052^{Aa}	0.059^{Aa}	0.060^{Aa}
10	0.096^{Ba}	0.115^{Ba}	0.118^{Ba}
15	0.128^{BCa}	0.164^{Ca}	0.177^{Ca}
20	0.149^{Ca}	0.212^{Db}	0.232^{CDb}
30	0.214^{Da}	0.295^{Eab}	0.342^{Db}
40	0.285^{DEa}	0.372^{EFb}	0.454^{DEc}
50	0.354^{Ea}	0.452^{Fab}	0.558^{Eb}
60	0.422^{EFa}	0.523^{FGab}	0.664^{Fb}
90	0.525^{Fa}	0.685^{Gab}	0.986^{Gb}
Rittinger's law constant (k_r)			
5	0.057^{Aa}	0.070^{Aa}	0.072^{Aa}
10	0.097^{ABa}	0.133^{Bab}	0.141^{Bb}
15	0.119^{Ba}	0.183^{Cb}	0.209^{Cb}
20	0.125^{BCa}	0.233^{CDb}	0.272^{CDb}
30	0.172^{Ca}	0.305^{Db}	0.394^{Dc}
40	0.227^{CDa}	0.370^{DEb}	0.522^{DEc}
50	0.283^{Da}	0.440^{Eb}	0.634^{Ec}
60	0.336^{DEa}	0.494^{EFb}	0.751^{Fc}
90	0.358^{Ea}	0.582^{Fb}	1.106^{Gc}
Kick's law constant (k_r)			
5	0.009^{Aa}	0.010^{Aa}	0.010^{Aa}
10	0.018^{Ba}	0.020^{Ba}	0.020^{Ba}
15	0.026^{Ca}	0.029^{Ca}	0.030^{Ca}
20	0.032^{CDa}	0.038^{CDa}	0.039^{CDa}
30	0.048^{Da}	0.055^{Da}	0.058^{Da}
40	0.064^{DEa}	0.071^{DEa}	0.078^{DEa}
50	0.080^{Ea}	0.088^{Ea}	0.097^{Ea}
60	0.095^{Fa}	0.104^{EFa}	0.116^{EFa}
90	0.133^{Ga}	0.147^{Fab}	0.172^{Fb}
Work index			
5	0.166^{Aa}	0.187^{Aa}	0.190^{Aa}
10	0.302^{Ba}	0.363^{Ba}	0.375^{Ba}
15	0.404^{Ca}	0.518^{Cb}	0.559^{Cb}
20	0.472^{CDa}	0.671^{Db}	0.734^{Db}
30	0.675^{Da}	0.932^{Eb}	1.080^{Eb}
40	0.896^{DEa}	1.177^{EFb}	1.435^{EFb}
50	1.119^{Ea}	1.431^{Fb}	1.763^{Fc}
60	1.334^{EFa}	1.654^{FGb}	2.101^{Gc}
90	1.660^{Fa}	2.166^{Gb}	3.117^{Hc}

Different capital letters indicated significant differences ($P < 0.05$) among different grinding time. Different lower-case letters indicated significant differences ($P < 0.05$) among different moisture content

except for those with a high moisture content or small particle sizes, specifically in case of less than 0.25 mm along with 20% of moisture content. The coefficient of determination was low ($R^2 = 0.20$). Such a deviation from the grinding kinetic model might be associated with an agglomeration of particles at high moisture contents. This kinetic model hypothesizes that each particle does not have any force for particle aggregation during grinding. Agglomeration at a high moisture content does not conform to this hypothesis. It was also difficult to accurately separate agglomerated particles on sieves. The pattern observed in the kinetic curve shown in Fig. 2 can be explained by the results displayed in Tables 2 and 3. In the kinetic model, the coefficient BF_{max} indicates the amount of ground BF separated by passing through a sieve with a diameter i, while a and b denote the grinding ability and grinding time to obtain 50% of BFs, respectively. As BF moisture content in decreased, the BF_{max} increased which illustrates that a low moisture content produced smaller particles (< 0.25 mm). Both a and b decreased as the moisture content diminished, except for BFs at a 20% moisture content level (Table 3). It should be noted that changes in b values due to the moisture content were greater than those in the a values. This implies that the moisture dependence of time required to obtain a specific BF particle size is more sensitive than the grinding ability depending on the slope of grinding time to the amount of particles. Overall, the moisture dependence of a and b values demonstrated that grinding of BF was more effective at a lower moisture content. According to Figs. 1 and 2, the grinding efficiency depended highly on the dried BFs' moisture content and the best grinding conditions to obtain particles with an average size of less than 1 mm could be found when the time was 75 s for 12% of moisture content and 17 s for 8%.

Properties of BF powder

The ground BFs' moisture content with different particle sizes was measured because the powders' flow properties were dependent on both the moisture content and particle sizes (Table 4). The particle sizes listed in Table 4 were determined with standard sieves and their different sizes did not differ at a statistically significant level. Thus, flow properties such as the flow index and the bulk density of BFs were solely dependent on particle sizes which has already been demonstrated in many previous studies on powder flows originating from biological matter such as food. For example, Fitzpatrick et al. [11] reported that the flow properties of salt powder show the size dependence of fine powder having a low flow index. Teunou et al. [10] also demonstrated that the flowability of milk powder is dependent on particle sizes. They compared the flow properties of whey powders and skim milk powders and found that particle sizes can significantly influence the flow index. The size dependence of fine-grained solids' flow

Fig. 2 Grinding kinetics of balloon flower powders with different moisture content during grinding: (**A**) 8%, (**B**) 12% and (**C**) 20%

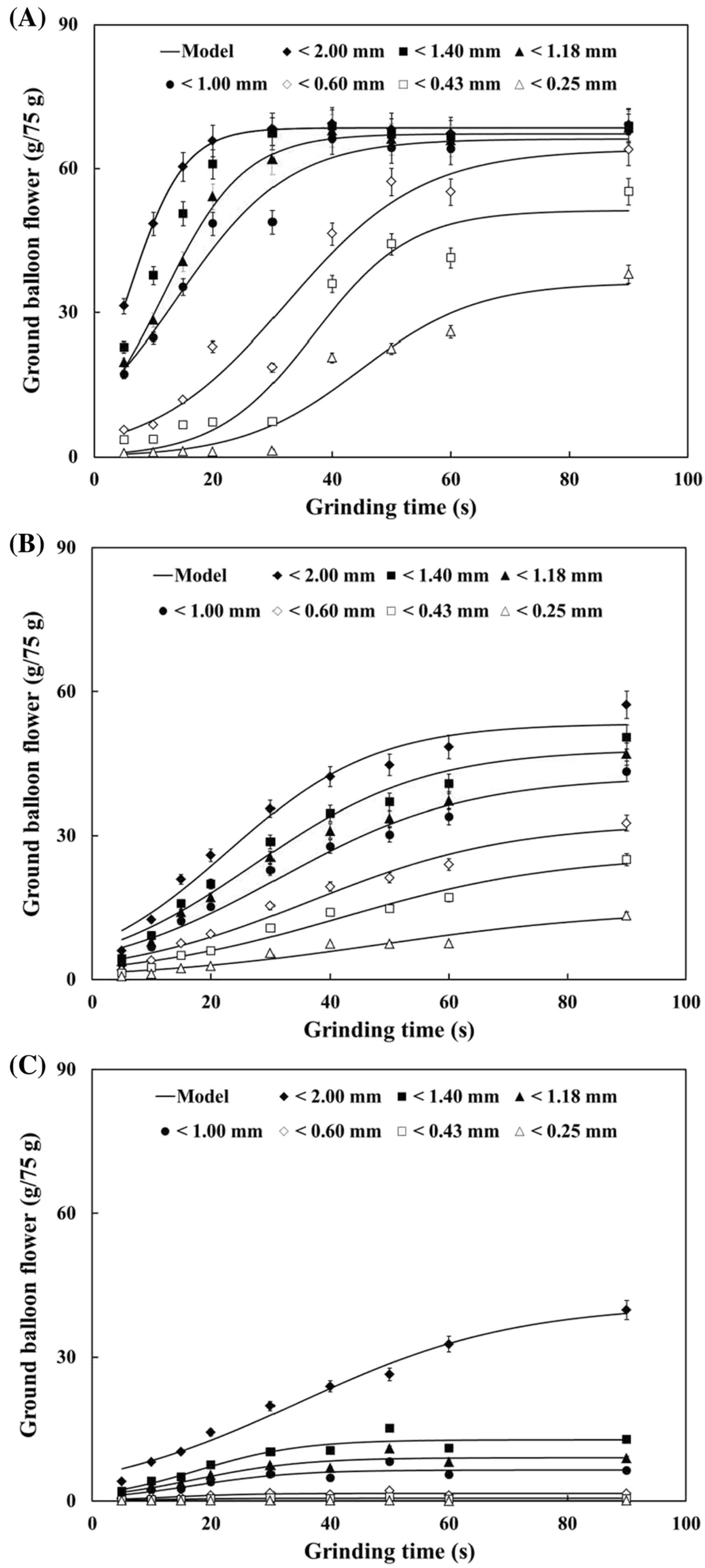

Table 3 Grinding kinetic model fitting constant depending on moisture content (%)

Moisture content (%)	Particle size (mm)	BF_{max} (g/75 g)	a (s)	b (s)	R^2
8	< 2.00	68.52	4.61	5.84	0.9979
	< 1.40	68.10	5.49	8.83	0.9992
	< 1.18	67.26	6.79	11.64	0.9938
	< 1.00	66.19	9.35	14.01	0.9641
	< 0.60	64.02	11.28	32.35	0.9550
	< 0.43	51.31	8.15	36.98	0.9290
	< 0.25	36.22	9.87	44.66	0.9403
12	< 2.00	53.31	12.37	22.81	0.9722
	< 1.40	47.93	14.27	27.26	0.9596
	< 1.18	45.27	15.18	29.62	0.9615
	< 1.00	42.24	15.75	31.38	0.9614
	< 0.60	32.57	16.81	36.55	0.9616
	< 0.43	25.89	18.32	41.94	0.9551
	< 0.25	14.55	20.80	48.28	0.9101
20	< 2.00	40.99	18.20	34.68	0.9771
	< 1.40	12.76	8.68	17.76	0.8886
	< 1.18	9.02	9.04	17.41	0.8586
	< 1.00	6.45	8.62	17.12	0.8442
	< 0.60	1.57	6.91	12.76	0.7309
	< 0.43	0.57	6.84	10.41	0.4936
	< 0.25	0.08	4.33	4.69	0.2001

Table 4 Moisture content, flow index, and ratio of change bulk density of ground balloon flower

(mm)	Moisture content (%)	Flow index	Ratio of change bulk density (%)
1.70	8.13 ± 0.14^{ab}	11.20 ± 0.88^{b}	6.96 ± 0.54^{a}
1.40	8.23 ± 0.47^{ab}	10.80 ± 0.49^{b}	6.21 ± 0.41^{a}
1.18	9.01 ± 0.48^{b}	9.05 ± 0.65^{ab}	6.78 ± 0.98^{a}
1.00	8.45 ± 0.43^{ab}	8.85 ± 0.87^{ab}	8.61 ± 0.81^{ab}
0.60	8.84 ± 0.13^{b}	8.12 ± 0.37^{a}	11.03 ± 1.10^{b}
0.43	7.95 ± 0.10^{a}	8.01 ± 0.45^{a}	10.41 ± 0.91^{b}
0.25	8.34 ± 0.11^{ab}	6.87 ± 0.74^{a}	18.25 ± 0.64^{c}

Different lower-case letters indicated significant differences ($P < 0.05$) among different particle size of grinded balloon flower

properties is associated with bulk-density-related consolidation stress. Incompressible easy-flowing is usually observed for large coarse materials (e.g., wheat grains) [19]. This could provide a useful operational index for many biologically oriented particles.

Flow properties of BF powder

Flow properties of BF powder samples at different particle sizes (0.25, 0.43, 0.60, 1.00, 1.18, 1.40, and 1.70 mm) were evaluated by applying a variety of major principal consolidating stresses. Easy flowing characters followed by free flowing were observed as the BF particle sizes increased. Easy flowing was observed for particle sizes at 0.25, 0.43, 0.60, 1.00, and 1.18 mm while free flowing was evidenced for 1.40 and 1.70 mm. The flow index diminished as particle sizes decreased (Table 4). Generally, flow characteristics will move from an easy-flow region to a difficult one as the powder flow function's slope increases. The flow function of BF powder also follows a prototypical flow pattern where the flow function moves in a clockwise direction as the particle size increases [Fig. 3(A)]. The flowing difficulty is usually higher for smaller particles than for bigger ones, mainly because a particle's surface area per unit mass increases as the particle size shrinks. An enlarged surface area causes surface cohesive force, leading to more cohesive flow [11]. In general, when particle sizes are bigger than 200 μm, the powder shows a free-flowing characteristic, although with enhanced cohesion properties, flowing difficulties may ensue [10]. In this

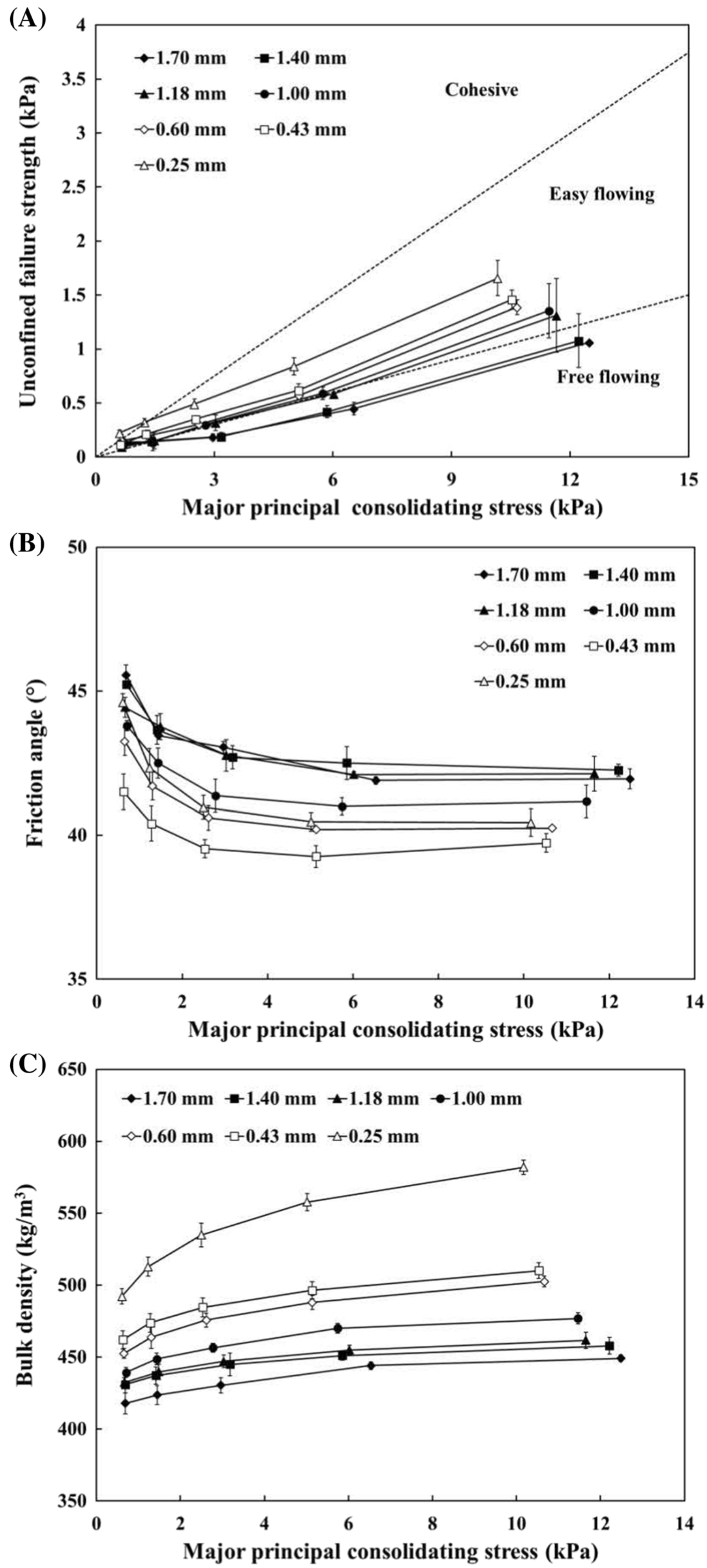

Fig. 3 Flowability properties of balloon flower powders by particle size: (**A**) flow function, (**B**) angle of internal friction and (**C**) bulk density

study, BF powder with sizes bigger than 200 μm demonstrated easy or free flow as well [Fig. 3(A)]. According to Teunou et al. [10], tea powders with a size < 25 μm exhibited poor flowability (flow index = 4.22) whereas the flowability of milk powder with a size > 200 μm was adequate (flow index = 11.04). Salt powders also showed similar particle size dependencies [11]: At a constant moisture level, the poor flow ability was poor (flow index = 1.3) when particle sizes were smaller than 5.8 μm [11]. And although the particle size was one of the most significant determinants that influenced the flowability of BF powders, other factors such as the surface-force interaction may also affect the physical properties of particles. Additional important constituents can affect the flowability of food powders [11]. For example, the particle shape of BFs can be irregular although the averaged size of BF powders is grouped uniformly by sieving. Such irregular shapes of BF powder might also influence its flowability.

Internal friction angles and bulk density

The internal friction angle and bulk density of BF powders were measured [Fig. 3(B), (C)]. The former was defined as the angle between the tangent and the yield locus. The normal stress axis indicates the amount of friction between particles and a low friction angle is associated with less resistance to flow. Generally, the internal friction angle (or the angle of depose) is increased as particle sizes decrease because the adhesion force between particles is enhanced when their sizes are small [8]. However, the interacting force of particles is also affected by their shapes. Although the internal friction angle of BF powders with different particle sizes [Fig. 3(B)] was expected to display a similar pattern as that of the flow function shown in Fig. 3(A), the size dependence of the internal friction angle was inconsistent with that of the flow function. Such a difference may be due to non-homogenous particle shapes of BF powders. The uneven structure of biological matters could produce irregular shapes of particles during grinding. For example, even sugar is established in various forms (spangle, angular, and spherical) of particles [8].

The bulk density is an index for the degree of powders' compactness [20]. It is high in BF powders as the maximum consolidating stress level is elevated. In this study, the bulk density change ratio was decreased with diminished particle sizes was since the interaction between particles increases for small-sized particles (Table 4). Interactions between particles are mainly due to capillary forces or van der Waals forces [11]. The capillary force in powders is highly associated with the liquid bridge which can become a significant feature when the moisture content of powder varies. In this study, the cohesive interaction force might not have been due to capillary force between particles since the moisture content was constantly maintained during measurement. Therefore, the major factor that contributed to changes in the bulk density of BFs was the particle size. Generally, as the fraction of smaller particles increases, the bulk density also intensifies. However, beyond a specific proportion, the bulk density can decrease again due to an expanded fraction of voids between particles [21]. The BF samples' bulk density demonstrated a pattern similar to one that changed most abruptly at the smallest particle size (0.25 mm). The dependence of bulk density of BFs on particle sizes was in agreement with that of the flow function [Fig. 3(A), (C)]. The flow function of BF powder with smaller particle sizes was located in the easy-flowing region with decreased flowability. Similarly, the bulk density of powders with smaller particle sizes was dramatically changed with decreased flowability.

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References

1. Tada A, Kaneiwa Y, Shoji J, Shibata S. Studies on the saponins of the root of *Platycodon grandiflorum* A. De Candolle. I. Isolation and the structure of platycodin-D. Chem. Pharm. Bull. 23: 2965–2972 (1975)
2. Indira TN, Bhattacharya S. Grinding characteristics of some legumes. J. Food Eng. 76: 113–118 (2006)
3. McCabe WL, Smith JC, Harriott P. Unit Operations of Chemical Engineering, Fifth ed. McGraw-Hill Inc., Singapore, pp. 963–964 (1993)
4. Dziki D. The crushing of wheat kernels and its consequence on the grinding process. Powder Technol. 185: 181–186 (2008)
5. Walde SG, Balaswamy K, Velu V, Rao DG. Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). J. Food Eng. 55: 271–276 (2002)
6. Velu V, Nagender A, Rao PGP, Rao DG. Dry milling characteristics of microwave dried maize grains (*Zea mays* L.). J. Food Eng. 74: 30–36 (2006)
7. Lee YJ, Lee MG, Yoon WB. Effect of seed moisture content on the grinding kinetics, yield and quality of soybean oil. J. Food Eng. 119: 758–764 (2013)
8. Barbosa-Ćanovas GV, Ortega-Rivas E, Juliano P, Yan H. Food Powders: Physical Properties, Processing, and Functionality. Kluwer Academic, New York (2005)
9. Fu X, Huck D, Makein L, Armstrong B, Willen U, Freeman T. Effect of particle shape and size on flow properties of lactose powders. Particuology 10: 203–208 (2012)
10. Teunou E, Fitzpatrick JJ, Synnott EC. Characterisation of food powder flowability. J. Food Eng. 39: 31–37 (1999)
11. Fitzpatrick JJ, Barringer SA, Iqbal T. Flow property measurement of food powders and sensitivity of Jenike's hopper design methodology to the measured values. J. Food Eng. 61: 399–405 (2004)
12. Rhodes M. Introduction to Particle Technology, second ed. Wiley, England (2008)
13. AOAC. Official methods of analysis. 16th ed. Association of Official Analysis Chemists, Washington DC, USA, pp. P777–P784 (2005)

14. Djantou EB, Mbofung CM, Scher J, Desobry S. A modelling approach to determine the effect of pre-treatment on the grinding ability of dried mangoes for powder production (*Mangifera indica var Kent*). J. Food Eng. 80: 668–677 (2007)
15. Jenike AW. Storage and flow of solids. Bulletin 123. Engineering Experiment Station, University of Utah (1964)
16. Lee YJ, Yoo JS, Yoon WB. Grinding characteristics of black soybeans (Glycine max) at varied moisture contents: particle size, energy consumption, and grinding kinetics. Int. J. Food Eng. 10: 347–356 (2014)
17. Dziki D. Effect of preliminary grinding of the wheat grain on the pulverizing process. J. Food Eng. 104: 585–591 (2011)
18. Pan Z, Tangratanavalee W. Characteristics of soybeans as affected by soaking conditions. LWT Food Sci. Tech. 36: 143–151 (2003)
19. Schulze D. Powders and Bulk Solids: Behavior, Characterization, Storage and Flow. Springer, Heidelberg (2008)
20. Teunou E, Fitzpatrick JJ. Effect of storage time and consolidation on food powder flowability. J. Food Eng. 43: 97–101 (2000)
21. Pai DA, Okos MR. Predicting the density and tensile strength of viscoelastic soy powder compacts. J. Food Eng. 116: 184–194 (2013)