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Effect of drying and grinding characteristics of colored potato (Solanum tuberosum L.) on tribology of mashed colored potato paste

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ABSTRACT
The mouthfeel of mashed potato prepared with steamed purple flesh potato (SPFP) was investigated by measuring tribological and rheological characteristics. Mathematical models describing pre-processes such as drying and grinding associated with physical properties of mashed potato were also explored. The effect of drying temperature (60, 70, 80, and 90°C) on quality changes (moisture and anthocyanin content) of SPFP was successfully described ($R^2 > 0.9583$). The sigmoid model was suitably applied to estimate particle sizes of dried SPFP during grinding ($R^2 > 0.9864$). As the particle size of mashed SPFP increased, friction coefficient increased, and storage and loss modulus decreased. Taste, smoothness, and after-feel sensation were increased as particle sizes decreased, while appearance and odor showed no significant differences. To predict the sensory property using tribology and rheology, the specific conditions were successfully determined ($R^2 > 0.9926$).

Introduction
Potato is rich in high-quality protein, carbohydrates, vitamin B3, vitamin B6, vitamin C, and minerals (Andre et al., 2007). In addition to its high nutrition value, colored potato varieties contain significant amounts of phytoneutrients such as polyphenols. Purple-fleshed potato (PFP) has been recognized as a novel source of antioxidants and natural colorants for human health and food industries (Reyes & Cisneros-Zevallos, 2012). PFP has acylated glucosides of peonidin, pelargonidin, malvidin, petunidin, and delphinidin (Lachman et al., 2012). Antioxidant levels in PFP were about three times higher than those in yellow- or white-fleshed potatoes.

Potato starch is recognized as a useful food ingredient for the food industry. However, the unique red or purple color in colored potatoes cannot be maintained in starch because color constituents in potatoes are removed during the starch manufacturing process, in contrast to the powders attained after drying and grinding of colored potatoes could keep the unique color attributes. Due to its versatility and convenience of use, powder form of potatoes is useful for manufacturing processed food products such as dry mashed potatoes, bakery products, and noodles.

The drying process is one of the most important unit operations in manufacturing food products in powder form such as ready-to-eat dry mashed potatoes. Various studies on the drying of potato have been reported, such as fluidized bed drying far infrared radiation drying, ultrasound drying and microwave drying (Afzal & Abe, 1998; Bondaruk, Markowski, & Blaszczak, 2007; Lozano-Acevedo, Jimenez-Fernández, Ragazzo-Sánchez, Urrea-Garcia, & Luna-Solano, 2011; Ozuna, Cárce1, Garcia-Pérez, & Mulet, 2011). The hot air-drying process, a simultaneous mass and heat transfer process for removing moisture in solids, is commonly used in the food industry. Effects of drying on quality changes have been widely studied (Moon, Kim, Chung, Pan, & Yoon, 2014; Orikasa et al., 2014; Ramos, Brandão, & Silva, 2003; Telis &
Telis-Romero, 2005). Like other biological products, drying causes serious structural and physical changes to potato tissue, thus having significant effects on grinding characteristics (Ramos et al., 2003).

Classical grinding theories have provided various grinding characteristics during the grinding or crushing process of foods and agricultural products (Djantou et al., Mbefung, Scher, & Desobry, 2007; Dzik, 2007; Lee, Yoo, & Yoon, 2014; Park, Kim, Chung, Han, & Yoon, 2015; Sharma, Chakkaravarti, Singh, & Subramanian, 2008; Walde, Balaswamy, Velu, & Rao, 2002). However, these grinding theories are not suitable for estimating the amount or the size of powder at specific grinding time. These grinding theories were developed mainly based on thermodynamics. However, the generation of different sizes of particles during grinding is more like a kinetic behavior until it reaches an equilibrium size. Because the grinding time for specific particle size is an important independent variable for the grinding process, a kinetic approach is more practical to obtain suitable particle size for food applications. Grinding ability and grinding kinetics of many agricultural products have been successfully described with a sigmoid model based on the kinetic behavior of particle size reduction (Djantou et al., 2007; Lee et al., 2014; Park et al., 2015; Song, Lee, Lee, & Yoon, 2014).

Ready-to-cook and ready-to-eat products such as dry mashed potatoes are becoming increasingly popular. Textural and rheological properties have been recognized as the most important quality attributes of mashed potato since they are highly related to sensory evaluation. A traditional way to assess the mouthfeel of a paste is by measuring viscosity as a function of shear rate using a rotational viscometer (Shama & Sherman, 1973). However, the viscosity of paste food has a limitation in providing good correlation with some aspects of mouthfeel such as smoothness and creaminess (Baier et al., 2009; Kokini, 1987). Physically, much of the oral processing during paste consumption includes compression of the tongue against other oral surfaces. During such processes, the food behaves like a thin film and the food’s rheology is insufficient to determine its flow behavior and lubrication properties (Bourne, 2002; Chen & Stokes, 2012). These attributes are, instead, considered to be governed by oral lubrication or oral tribology (Kokini, Kadane, & Cussler, 1977). Lubrication property associated with the thin film could attribute to different types of mouthfeel sensory perception that is highly related to sensory results. Lubrication property is usually described by measuring friction between two surfaces (Batchelor, Venables, Marriot, & Mills, 2015; Gasson, Israelachvilli, & Yoshizawa, 1997; Huc, Michon, Bedoussac, & Bosc, 2016; Malone, Appelqvist, & Norton, 2003; Nguyen, Bhandari, & Prakash, 2016; Sonne, Buck-Stockfisch, Weiss, & Hinrichs, 2014). Especially, the after-feel sensation becomes more important for paste food because the residence time of paste food in the mouth is relatively shorter than that of other solid-type foods. Such after-feel sensation may not be clearly described by measuring the viscosity of the paste.

Tribology (also known as thin film rheology) provides important information on material properties in the form of thin film. Such properties cannot be estimated from bulk properties (Baier et al., 2009; Batchelor et al., 2015; Chen, 2009; Huc et al., 2016; Kokini, 1987; Kokini & Cussler, 1983; Nguyen et al., 2016; Selway & Stokes, 2013). Recently, tribology analysis has been recognized as a useful approach to understand mouthfeel sensation and food texture for paste type of food (Batchelor et al., 2015; Huc et al., 2016). Tribology approach to evaluate mouthfeel can be achieved by controlling the relative speed of two rubbing surfaces while holding a food material between. Lubrication properties of a food material between two surfaces can be analyzed not only in the form of bulk paste (when food enters the mouth as a bulk matter) but also in the form of layer being squeezed between oral surfaces which eventually becomes thin film residues on tongue surface and affects the after-feel sensation.

Tribological and rheological properties have been demonstrated to highly influence texture perception (Bellamy, Godinot, Mischler, Martin, & Hartmann, 2009; Van Aken, Vingerhoeds, & De Wijk, 2011) because oral processing entails a transition from rheology-dominant processes to tribology-dominant processes (Stokes, Boehm, & Baier, 2013). In addition, the size of the particle is especially crucial for mouthfeel, a major sensory attribute of paste-type food (Cayot, Schenker, Houzé, Sulmont-Rossé, & Colas, 2008; Hahn et al., 2012; Krzeminski et al., 2013; Sainani, Vyas, & Tong, 2004; Ziegler, Mongia, & Hollender, 2001). However, the information about rheological and tribological characteristics of mashed potatoes affected by the particle size still lacks in the literature. Therefore, more comprehensive understanding of the oral processing during mashed potato consumption could be obtained by investigating both rheological and tribological properties of mashed potato with different particle sizes.

The aim of this study was to investigate the tribology and the rheology of mashed potato prepared with different particle sizes of steamed purple-fleshed potato (SPFP) powders produced under different drying and grinding conditions. Specific objectives of this study were (1) to determine qualities changes such as moisture and anthocyanin content in SPFP during hot air drying at different temperatures (60, 70, 80, and 90°C), (2) to characterize grinding properties of PFP, and (3) to examine the effect of particle size on textural and sensory characteristics of mashed potato made of SPFP based on rheology and tribology.

Materials and methods

Sample preparation

PFPs (Solanum tuberosum L. cv Jayoung) were provided by the Korea Institute of Science and Technology (Gangneung, Gangwon, Korea) immediately after harvesting. These PFPs were carefully stored in a storage room maintained at 4°C with relative humidity of 80%. Samples were used for the experiment within 1 month. These potatoes were washed, peeled, and cut into regular hexahedron with a length of 10 mm. Cubes were selected from the interior of the potato; any cube containing peel was discarded. These PFP cubes were mashed for 14.6 min in a steam machine (MB-1800, Myungbo industry, Gwangju, Gyeonggi, Korea) above a pot of boiling water with the lid on. These SPFP were mashed with a hand mixer (Masha 2X, Dash, USA) for 5 min. The SPFP paste was then stuffed into stainless steel cylinders (diameter, 63 mm; height, 7 mm). These SPFP samples in disk shape were used for experiments.

Drying studies

Hot air-drying experiments were carried out in a horizontal tray dryer (NB-901M, N-BIOTEK, Bucheon, Gyeonggi, Korea) at temperatures of 60, 70, 80, and 90°C. The size of the chamber of the tray dryer was 550 × 520 × 600 mm³. The drying temperature in the dryer was controlled within ±1°C from the target temperature for the experiment. Air velocity
was set at 3 m s⁻¹. Changes in moisture content during drying were manually measured every 30 min using an analytical balance (HS410A; Hansung, Seoul, Korea) with an accuracy of 0.01 g. All moisture contents were determined on a dry basis (d.b.).

**Determination of anthocyanin content**

Spectrophotometer method was used to measure anthocyanin content of SPFP (SpectraMax® i3; Molecular Devices, Sunnyvale, CA, USA). To measure anthocyanin content, sampling was performed every 60 min during drying. Whole sample (diameter of 63 mm and height of 7 mm before drying) was cut into small pieces (a cube with 10 mm in length on one side). Then, 10 g of these small pieces was homogenized with 100 mL distilled water for 15 min on ice. The mixture was then filtered through four layers of cheesecloth. To quantify anthocyanin content in the sample, pH differential method (Lee, Durst, & Wrolstad, 2005) was used. The maximum wavelength (Amax) values observed for SPFP were 530 and 510 nm.

Total anthocyanins (mg L⁻¹) = \( A \times MW \times DF \times \frac{1000}{\epsilon \times l} \)  
(1)

where \( A = (A_{\lambda_{max}} - A_{700})_{\text{ph} 1.0} - (A_{\lambda_{max}} - A_{700})_{\text{ph} 4.5} \); \( MW \) (molecular weight) = 486.5 g mol⁻¹ for pelargonidin-3-glucoside and 718.5 g mol⁻¹ for malvidin-3-glucoside and DF is the dilution factor as final volume per initial volume; \( \epsilon \) (molar extinction coefficient) = 30,200 L mol⁻¹ cm⁻¹ for malvidin-3-glucoside and 27,300 L mol⁻¹ cm⁻¹ for pelargonidin-3-glucoside; \( l \) = path length of the 96-well plate and 1000 = conversion factor from g to mg. Twice-distilled water was used as a control for absorbance reading.

**Determination of kinetic parameters**

Changes in most quality parameters of potatoes during thermal processing have been suitably described by the first-order reaction kinetics in many previous studies (Reyes & Cisneros-Zevallos, 2007; Troncoso & Pedreschi, 2007). However, the kinetics of anthocyanin degradation in colored potatoes during drying is still lacking in the literature. In our study, several kinetic models, including zero model (Equation (2)), modified zero model (Equation (3)), the first-order kinetics model (Equation (4)), and the modified first-order kinetics (Equation (5)), were used to determine reaction kinetic parameters. These kinetic types are expressed by the following equations:

\[ C = C_0 \pm k \times t \]  
(2)

\[ C = A \pm k \times t \]  
(3)

\[ C = C_0 \times \exp(\pm k \times t) \]  
(4)

\[ C = C_0 - (C_0 - A) \times \exp(\pm k \times t) \]  
(5)

where \( t \) is time (min); \( k \) is rate constant (min⁻¹); \( C_0 \), \( C \), and \( A \) are quality parameter at time 0, time \( t \), and transition time, respectively.

In addition, the reduction in anthocyanins level during hot air drying was estimated using decimal reduction time (\( D \) value) defined as the time required for a 10-fold reduction of the initial concentration at a given temperature. \( D \) value is related to \( k \) values by the following equation:

\[ D \text{ value} = \frac{\ln(10)}{k} \]  
(6)

Half-life (\( t_{1/2} \)), the time needed for 50% degradation, was calculated by the following equation:

\[ t_{1/2} = \frac{\ln(2)}{k} \]  
(7)

Arrhenius equation was used to evaluate temperature dependence of rate constant by plotting ln \( k \) against 1/T:

\[ \ln k = \ln k_0 - \frac{E_a}{RT} \]  
(8)

where \( k_0 \) is frequency factor of the Arrhenius equation (min⁻¹), \( E_a \) is activation energy (kJ mol⁻¹), \( R \) is universal gas constant (8.314 J mol⁻¹ K⁻¹), and \( T \) is absolute temperature (K).

**Grinding studies**

SPFP samples dried at 60°C for 600 min were used for grinding studies. The grinding process for 100 g of sample was conducted for 90 s using a 650-W dry grinder (HMF-3260S, Hanil electric, Seoul, Korea). A mechanical shaker attached with sieves of different mesh sizes (CG-211-8, Chunggye, Seoul, Korea) was used to separate particles by sizes. Mesh sizes applied for the separation were as follows: 0.15, 0.25, 0.43, 0.60, 1.00, 1.18, 1.40, 1.79, and 2.00 mm. To separate particles, 15 min of shaking time was constantly maintained for all treatments.

**Kinetic model for calculating grinding time**

A sigmoidal curve was used to prototypically represent the yield of various sizes of particles during grinding. The kinetic behavior of a certain amount of particles with certain sizes at a given time is described as follows (Park et al., 2015):

\[ S_i(t) = \frac{S_{\text{max}}}{1 + e^{-(t/\alpha-b)}} \]  
(9)

where \( S_{\text{max}} \) is the maximum quantity of a mesh with size \( i \). Coefficients \( \alpha \) and \( b \) are grinding ability constant and the time (s) needed to grind 50% of the SPFP, respectively. The model parameter representing the grinding time to obtain certain amount of particles with a given size was evaluated by the sigmoid model. It was used to develop the grinding kinetic model for SPFP as described previously (Lee et al., 2014).

**Evaluation of the quality of mashed SPFP**

SPFP powders with different particle sizes (<0.43, <0.25, and <0.15 mm) were used to make mashed potatoes. Potato mixture powder consisted of 91.12% of SPFP powder, 4.85% of skimmed milk powder, and 4.04% of dextrin powder. To make mashed potato, 50 g of potato mixture powder was mixed with 75 g of water for 5 min at room temperature in a mechanical mixer (SKSSS, KitchenAid, St. Joseph, MI, USA).

**Scanning electron microscopy**

The microstructure of mashed SPFP samples with different particle sizes (<0.43, <0.25, and <0.15 mm) was examined using a HITACHI S-4300 FESEM (Hitachi Science Systems Ltd., Tokyo, Japan). The accelerating voltage applied for the mashed SPFP was 15 kV.
Rheological measurements
Rheological characteristics of mashed SPFP were evaluated after equilibrating the sample at 35°C for 1 min to imitate oral processing condition using a Discovery Hybrid Rheometer (TA Instruments, New Castle, DE, USA) with a 40-mm cone plate. To investigate the linear viscoelastic properties, amplitude sweeps were performed, and a strain of 0.03% was chosen. Frequency sweep tests were conducted with a fixed gap of 1 mm and frequency (\(\omega\)) ranged from 0.1 to 100 rad s\(^{-1}\). All measurements were performed in triplicates.

Tribological apparatus and measurement procedure
Tribological characteristics were evaluated using a Discovery Hybrid Rheometer with a steel ring-on-plate tribo-rheometry on a rough plastic surface of 3 M Transpose Surgical Tape 1527-2 (3M Health Care, St. Paul, MN, USA) based on the method described by Nguyen et al. (2016) and the TRIOS Manual (2013). The surface of human tongue with hydrophobic properties was modeled using 3 M Transpose Surgical Tape 1527-2. A square shape of the tape was prepared and attached firmly onto the top of the lower plate of the tribo-rheometry. After each evaluation, the tape was replaced by a new tape and the tribo-rheometry was cleaned with deionized water and dried with laboratory wipes.

Tribology evaluations were conducted after equilibrating the sample at 35°C for 1 min to imitate oral processing conditions. The force used for chewing food in the mouth has been reported to be between 0.01 and 10 N (Miller & Watkin, 1996). Therefore, 1 N was used in this study to represent moderate normal force applied to paste-type food during oral processing. Before tribology evaluation, mashed potato samples were pre-sheared at 1.5 mm s\(^{-1}\) for 1 min and equilibrated at rest for 2 min. Measurements were recorded while entrainment speeds were applied ranging from 1.5 to 2287.5 mm s\(^{-1}\) (20 points per decade). All measurements were performed in friction stress (\(\sigma_F\)), friction force (\(F_F\)), and friction coefficient (\(\mu\)) between rheometry and solid substrate that were calculated using the following equations:

\[
\text{Normal stress } \sigma_N = \frac{F_N}{\pi(n_1^2 - n_2^2)} \quad (10)
\]

\[
\text{Friction stress } \sigma_F = \frac{\tau(r_2 + r_1)}{\pi(n_1^2 - n_2^2)} \quad (11)
\]

\[
\text{Friction force } F_F = \frac{(r_2 + r_1)}{(r_2^2 + r_1^2)} \tau \quad (12)
\]

\[
\text{Friction coefficient } \mu = \frac{\sigma_F}{\sigma_N} = \frac{\tau(r_2 + r_1)}{F_N(n_1^2 + r_1^2)} \quad (13)
\]

where \(F_N\) is normal force (N); \(\tau\) is torque (N m); \(r_1\) and \(r_2\) are ring inner and outer radius (\(r_1 = 29 \text{ mm}\) and \(r_2 = 32 \text{ mm}\), respectively; and \(n_s\) is active ring section (\(n_s = 1\) for full ring, \(n_s = 0.5\) for half ring geometry).

Sensory analysis
Sensory properties of mashed SPFP with different particle sizes were evaluated by 50 panelists. These panelists were trained to be familiar with scoring for the following six attributes: appearance, taste, odor, smoothness (the degree of smoothness to swallow the bulk of the sample), after-feel sensation (the absence of a powdery texture that clings to the mouth), and overall acceptance. The attributes related to oral friction (smoothness and after-feel sensation) were defined according to the sensory analysis of paste-type food (Laiho, Williams, Poelman, Appelqvist, & Logan, 2017). These attributes are common in the assessment of mashed potato (Alvarez, Canet, & Fernández, 2005; Canet, Dolores, Fernandez, & Tortosa, 2005). Each attribute was scored on a scale of 1–9. All samples were served within 1 h after preparation and kept at room temperature (25°C). Samples were presented blind and in a random order to these panelists. All samples were evaluated in triplicates. Average scores from sensory analysis were analyzed by analysis of variance. Statistical significance was considered at \(P < 0.05\).

Results and discussion
Quality changes during hot air drying of SPFP

Drying characteristics of SPFP
The initial moisture content of SPFP was approximately 446 ± 22% on d.b. Results of temperature dependence of moisture changes in SPFP during hot air drying are shown in Figure 1a). As expected, the drying rate of colored potatoes was affected by drying temperature. Drying time required to reach target moisture content (20%, d.b.) was reduced as drying temperature was increased. Drying time required to

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**Figure 1.** Changes in (a) moisture and (b) anthocyanin content of SPFP during hot air drying and predicted data.

**Figura 1.** Cambios en (A) humedad y (B) cantidad de antocianina contenida en la PPMV durante el secado con aire caliente y datos pronosticados.
The degradation kinetic parameters of SPFP for anthocyanin content.

| Temperature (°C) | $k_a \times 10^3$ (min$^{-1}$) | $k_0$ (min$^{-1}$) | $E_a$ (kJ mol$^{-1}$) |
|-----------------|-------------------------------|-------------------|----------------------|
| 60              | 5.46 (0.9995)                 | 1.95              | 16.17 (0.9583)       |
| 70              | 7.15 (0.9990)                 | 1.95              | 16.17 (0.9583)       |
| 80              | 7.91 (0.9987)                 | 1.95              | 16.17 (0.9583)       |
| 90              | 9.04 (0.9983)                 | 1.95              | 16.17 (0.9583)       |

Numbers in parentheses are the coefficient of determination ($R^2$).

The kinetic parameters of SPFP for moisture content.

| Temperature (°C) | $k_a \times 10^3$ (min$^{-1}$) | $k_0$ (min$^{-1}$) | $E_a$ (kJ mol$^{-1}$) |
|-----------------|-------------------------------|-------------------|----------------------|
| 70              | 7.91 (0.9987)                 | 1.95              | 16.17 (0.9583)       |
| 80              | 9.04 (0.9983)                 | 1.95              | 16.17 (0.9583)       |
| 90              | 10.16 (0.9983)                | 1.95              | 16.17 (0.9583)       |

Numbers in parentheses are the coefficient of determination ($R^2$).

Degradation kinetics of anthocyanins

Results of degradation kinetics of anthocyanins in SPFP during hot air drying as a function of drying time are shown in Figure 1(b). Initially, anthocyanin content of SPFP was about 675.11 ± 20.72 mg kg$^{-1}$. Anthocyanin content of SPFP was decreased as the drying time was increased. The degradation rate of anthocyanin in PFP during hot air drying was about 39.3–70.2%. It has been reported that the degradation level of anthocyanin in PFP without steaming during hot air drying (60–80°C) is approximately 80–90% (Moon, Pan, & Yoon, 2015). The SPFP used in this study was found to be more stable during hot air drying. This might be due to the fact that cooking or steaming induces the release of phenolic compounds and provides a favorable state for their extraction (Burgos et al., 2013). In addition, cooking might have enabled the extractability of polyphenols by changing their matrix, resulting in better recoveries. Moreover, cooking might have inactivated some enzymes that can oxidize these polyphenol compounds (Navarre, Shaka, Holden, & Kumar, 2010). Many studies have shown various degrees of anthocyanin degradation during thermal treatments. For example, Nayak, Berrios, Powers, Tang, and Ji (2011) have reported that total anthocyanin content of PFP flakes is lost 45%, 41%, and 23% after freeze drying, drum drying, and refractive window drying, respectively. In addition, many methods have been used to investigate the stability of anthocyanins. Reyes and Cisneros-Zevallos (2007) have reported that anthocyanins extracted from colored potato at different pH values have thermal degradation following the first-order model. The degree of anthocyanin degradation has also been used to evaluate the stability of PFP during drying. Anthocyanin content in PFP has been reported to be significantly decreased (50–80%) after frying (Kita, Bakowska-Barczak, Hamouz, Kulakowska, & Lisirska, 2013). The wide range of degradation was interpreted that pelargonidin derivatives were more stable during frying than petunidin and malvidin derivatives. It suggests that the changes in anthocyanin levels in colored potatoes are dependent on the type of thermal processing. These reports suggest that changes in anthocyanin levels in colored potatoes might be dependent on the type of thermal processing. It has been reported that anthocyanin content in colored potatoes is increased 3.3 times and 4.2 times after baking and cooking in boiled water, respectively (Lachman et al., 2012). Because anthocyanin degradation level of SPFP (39.3–70.2%) in this study during drying was lower than that of uncooked colored potato (80–90%) (Moon et al., 2015), dried SPFP was used to prepare mashed potato in this study after applying the grinding process.

Degradation kinetic parameters of anthocyanin including activation energy ($E_a$), half-life ($t_{1/2}$), degradation kinetic constant ($k_a$), and $D$ value were evaluated at each drying temperature. Results are summarized in Table 2. All coefficients of determination ($R^2$) of the first-order kinetics showed higher values than those of zero-order kinetics. As expected, drying temperature significantly affected $k_a$ values of samples. Higher $k_a$ values were observed at higher temperatures. Values of $t_{1/2}$ for anthocyanin degradation in SPFP samples ranged from 5.61 to 15.25 h. $D$ and $t_{1/2}$ values were decreased with increase in drying temperature. This might be due to faster reactions accompanying higher $k_a$ values at higher temperature. Karaaslan et al. (2014) have reported that $t_{1/2}$ values for anthocyanin degradation in pomegranate arils during vacuum drying at 75, 65, and 55°C are 1.83, 2.36, and 5.50 h, respectively. Compared to pomegranate aril anthocyanins, anthocyanins in SPFP were less susceptible to high temperatures. This might be due to the difference in anthocyanin composition between pomegranate arils and SPFP. The calculated $E_a$ value for anthocyanin degradation in SPFP was 32.91 kJ mol$^{-1}$. Reyes and Cisneros-Zevallos (2007) have determined thermal degradation kinetics of anthocyanins in aqueous extracts of PFP and reported an $E_a$ value of 72.49 kJ mol$^{-1}$ in the range of 25–98°C. Karaaslan et al. (2014) have studied degradation of anthocyanins in pomegranate arils in the range of 55–75°C and reported an $E_a$ value of 52.39 kJ mol$^{-1}$. Based on these studies, $E_a$ values for the degradation of anthocyanins might vary depending on processes of heat treatment as well as different agricultural products containing anthocyanins.

Grinding characteristics

Sigmoidal curves were observed in the grinding kinetics of SPFP powder (Figure 2). Raw data were fit with the grinding kinetic

| Temperature (°C) | $k_a \times 10^3$ (min$^{-1}$) | $k_0$ (min$^{-1}$) | $E_a$ (kJ mol$^{-1}$) |
|-----------------|-------------------------------|-------------------|----------------------|
| 60              | 0.76 (0.9936)                 | 1.95              | 16.17 (0.9583)       |
| 70              | 1.29 (0.9941)                 | 1.95              | 16.17 (0.9583)       |
| 80              | 1.66 (0.9938)                 | 1.95              | 16.17 (0.9583)       |
| 90              | 2.06 (0.9958)                 | 1.95              | 16.17 (0.9583)       |

Numbers in parentheses are the coefficient of determination ($R^2$).

Grinding characteristics

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| 80              | 1.66 (0.9938)                 | 1.95              | 16.17 (0.9583)       |
| 90              | 2.06 (0.9958)                 | 1.95              | 16.17 (0.9583)       |

Numbers in parentheses are the coefficient of determination ($R^2$).
model (Equation (9)). Results of modeling are summarized in Table 3. All samples fitted the kinetic model suitably ($R^2 > 0.9864$). Similar pattern of grinding kinetics has been found in soybeans, rice, and black soy beans (Lee & Yoon, 2015; Lee et al., 2014; Song et al., 2014). In studies of Djantou et al. (2007) on grinding characteristics of mango, caking phenomena have been observed with an increase in grinding time due to high sugar content in mango. In this study, no caking phenomenon was observed during a grinding period of 90 s. The grinding kinetics model is practically useful for controlling the grinding time to obtain suitable sized particles of SPFP powders.

**Effect of the particle size on tribology and rheology of mashed SPFP**

Frequency sweep results for storage ($G'$) and loss modulus ($G''$) are shown in Figure 3. Regardless of the particle size, all samples showed higher values for the storage modulus compared to the loss modulus, which indicates an elastic-dominant behavior. Storage modulus values increased as the particle size increased. In contrast to the results of storage modulus, loss modulus values were fairly similar among samples at low-frequency levels (0.25–2.51 Hz). These results indicate that the elastic behavior was more affected by the particle size than viscous behavior. As the particle size decrease, mashed SPFP could have a greater potential to increase interface area. The increase of interface area might

![Figure 2. Grinding kinetics of SPFP during grinding.](image)

**Figure 2.** Cinética de trituración de PPMV durante la trituración.

| Particle size (mm) | $A_{\text{max}}$ (g) | $a$ (s) | $b$ (s) | $R^2$ |
|-------------------|----------------------|---------|---------|-------|
| <2.00             | 98.66                | 5.40    | 6.46    | 0.9916|
| <1.70             | 98.11                | 6.15    | 7.59    | 0.9892|
| <1.40             | 97.71                | 7.38    | 9.82    | 0.9895|
| <1.18             | 96.95                | 8.13    | 11.58   | 0.9896|
| <1.00             | 96.20                | 8.91    | 13.33   | 0.9903|
| <0.60             | 89.86                | 11.37   | 20.21   | 0.9899|
| <0.43             | 80.12                | 13.41   | 25.57   | 0.9900|
| <0.25             | 53.80                | 15.62   | 31.71   | 0.9920|
| <0.15             | 30.46                | 15.41   | 34.23   | 0.9864|

$A_{\text{max}}$: The maximum quantity of a mesh with size $i$; $a$ and $b$: the grinding ability constant.

$A_{\text{max}}$: Cantidad máxima de una malla con tamaño $i$; $a$ y $b$, constante de la capacidad para triturar.

![Figure 3.](image)

**Figure 3.** (a) Storage and (b) loss modulus for mashed potato of SPFP at different particle sizes.

**Tabla 3.** Constante para el ajuste del modelo cinético de trituración.
increase the interfacial adhesion, and this interaction could lead to the increase of storage modulus. The result is in line with the study reported for the relationship between interface area and storage modulus in mayonnaise (Maruyama, Sakashita, Hagura, & Suzuki, 2007).

Tribological behavior of mashed potato samples was evaluated by measuring friction coefficient of sample between the tribo-rheometer and 3 M surgical plastic tape surface. Tribological data were screened based on studies of Joyner, Pernell, and Daubert (2014). When normal force error was greater than 5% of set values, data were removed from analysis. Average friction curves for mashed potato samples with different particle sizes (0.15, 0.25, and 0.43 mm) are shown in Figure 4.

The friction curves showed a Stribeck curve only in the boundary and mix regimes (Figure 4). The effect of the particle size on the tribological behavior was more clearly observed at low-to-intermediate entrainment speeds. Especially, as the particle size in the paste increased, the increase of the friction coefficient at low-to-intermediate entrainment speeds was more obvious. This might be due to the fact that the grittiness of mashed potato with bigger size particles is anticipated to have higher friction coefficients at lower speeds due to their lack of lubrication between rubbing surfaces (Batchelor et al., 2015). Thus, the particle size significantly affected the rheological and tribological characteristics of mashed SPFP. During oral processing, the physicochemical and mechanical properties of paste-type food continually change in response to enzymatic breakdown and hydration by saliva (Chen, 2009). The after-feel perception is determined by the tribological characteristics of food residuals and their interaction with saliva (Prakash, Tan, & Chen, 2013). The decrease of particle size might increase the effect of saliva as the interface area increased.

Figure 4. Friction curves of mashed potato of SPFP at different particle sizes.

Figure 5. Results of sensory attributes of mashed SPFP. Bars with different letters are significantly different ($P < 0.05$).

Figure 5. Atributos sensoriales del puré de papa preparado con PPMV. Las barras con letras distintas son significativamente diferentes ($P < 0.05$).
Correlation between sensory data and instrumental data

Results of sensory analysis of SPFP samples with different particle sizes are shown in Figure 5. Appearance and odor for differing particle sizes showed no significant differences ($P < 0.05$). Interestingly, taste, smoothness, after-feel sensation, and overall acceptance showed similar pattern, i.e. the score was increased as particle size was decreased. As expected, the size of particles of mashed SPFP significantly influenced attributes related to oral friction (smoothness and after-feel sensation). However, appearance and odor showed no significant differences. This is in agreement with results of Sato and Cunha (2009) showing that particle size of jaboticaba pulp can significantly influence its rheological properties.

The scanning electron microscopy (SEM) micrographs of the mashed SPFP were produced to figure out the relationship between microstructure and sensory property (Figure 6). Obviously, it can be observed that mashed SPFP made with bigger particles showed rougher surface, which might influence attributes related to oral friction. The result of the morphological analysis is in agreement with the result of the sensory analysis in that the attributes related to oral friction (smoothness and after-feel sensation) were decreased as the particle size increased.

Tribological and rheological data were produced by varying the entrainment speeds and frequencies, respectively. Thus, a specific entrainment speed and frequency may need to be selected to determine the correlation between the sensory result (i.e. smoothness), and the tribological and rheological result. The following four different speeds and frequencies were chosen: 2, 10, 50, and 100 mm s$^{-1}$, and 0.1, 1, 10, and 100 Hz, respectively. Results of the correlation between sensory attributes and friction coefficients, $G'$ and $G''$, are shown in Figure 7. The highest correlations were expected at 10 mm s$^{-1}$ for the friction coefficient, 100 Hz for $G'$, and 10 Hz for $G''$. For mashed SPFP at different particle sizes, a negative correlation for tribology and a positive correlation for rheology were found between particle size and the smoothness of mashed SPFP, i.e. an increase in friction and a decrease in $G'$ and $G''$ were correlated with a decrease in smoothness (Figure 7). Thus, the friction coefficient, $G'$ or $G''$, measured at a specific condition might be a useful parameter to correlate smoothness of mashed SPFP which may represent an important ‘mouthfeel’ perception for paste-type food.
time required for certain amounts of SPFP powders with the required average particle size. The increase in particle size of mashed potato increased the friction coefficient, especially at low-to-intermediate entrainment speeds. Storage modulus values increase as particle size increased while loss modulus values were fairly similar among samples at low frequencies. Sensory results showed that the taste, smoothness, and afterfeel sensation of mashed potato prepared with different particle sizes were significantly increased as particle size decreased. This study investigated that the correlation between sensory characteristics and physical properties of mashed SPFP, such as tribological and rheological properties, and microstructure observed by SEM. Results of this study could be applied to determine optimum drying and grinding conditions to achieve acceptable sensory results of mashed potato while maintaining a certain level of anthocyanin in the product. Tribology and rheology of mashed colored-potato were useful tools to understand the oral processes related to the mouthfeel.

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Disclosure statement

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**Conclusions**

SPFP slices were dried in hot air at 60, 70, 80, and 90°C and their quality changes (moisture and anthocyanin content) were measured and modeled for analysis. Our results demonstrated that fast drying rate at a higher temperature caused more degradation of anthocyanin. Therefore, the optimum drying temperature should be determined based on the degradation rate of anthocyanin as well as the drying rate of products. The sigmoid model was successfully applied in this study to estimate particle sizes of SPFP during the grinding process. This model could be used to estimate the grinding
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