



Effect of drying methods on the physical properties and microstructures of mango (Philippine ‘Carabao’ var.) powder

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ABSTRACT

Mango powders were obtained at water content below 0.05 kg water/kg dry solids using Refractance Window[®] (RW) drying, freeze drying (FD), drum drying (DD), and spray drying (SD). The spray-dried powder was produced with the aid of maltodextrin (DE = 10). The chosen drying methods provided wide variations in residence time, from seconds (in SD) to over 30 h (in FD), and in product temperatures, from 20 °C (in FD) to 105 °C (in DD). The colors of RW-dried mango powder and reconstituted mango puree were comparable to the freeze-dried products, but were significantly different from drum-dried (darker), and spray-dried (lighter) counterparts. The bulk densities of drum and RW-dried mango powders were higher than freeze-dried and spray-dried powders. There were no significant differences ($P \leq 0.05$) between RW and freeze-dried powders in terms of solubility and hygroscopicity. The glass transition temperature of RW-, freeze-, drum- and spray-dried mango powders were not significantly different ($P \leq 0.05$). The dried powders exhibited amorphous structures as evidenced by the X-ray diffractograms. The microstructure of RW-dried mango powder was smooth and flaky with uniform thickness. Particles of freeze-dried mango powder were more porous compared to the other three products. Drum-dried material exhibited irregular morphology with sharp edges, while spray-dried mango powder had a spherical shape. The study concludes that RW drying can produce mango powder with quality comparable to that obtained via freeze drying, and better than the drum and spray-dried mango powders.

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1. Introduction

Mango (*Mangifera indica* L.) is one of the most appreciated fruits in the world. The 2005 world production of mango was estimated at 28.5 million metric tons, of which 85% was produced in the following 10 countries: India (37.9%), China (12.9%), Thailand (6.3%), Mexico (5.9%), Indonesia (5.2%), Pakistan (5.9%), Brazil (3.5%), Philippines (3.5%), Nigeria (2.6%), and Egypt (1.3%) (Evans, 2008). In the Philippines, mango ranks third among fruit crops next to banana and pineapple in terms of export volume and value, with a total of metric tons harvested in 2007. The Carabao variety popularly known as “Philippine Super Mango” accounts for 73% of the country’s production (BAS, 2009). This variety is acclaimed as one of the best in the world due to its sweetness and non-fibrous flesh.

Fresh mangoes are perishable and may deteriorate in a short period of time if improperly handled, resulting in large physical damage and quality loss, ranging from 5% to 87% (Serrano, 2005).

Gonzalez-Aguilar et al. (2007) reported that 100% of untreated ripe mango fruits of the ‘Hadin’ variety showed fungal infection and severe decay damage by the end of 18 days of storage at 25 °C. In order to take advantage of the potential health benefits of mango and add value to the commodity with lesser handling and transport costs, there is a need to develop mango products in forms of mango powders that not only have desired functionality but also are stable over a longer storage time. Mango powder offers several advantages over other forms of processed mango products like puree, juice and concentrate. Besides having a much longer shelf life due to considerable reduction in water content, the transport cost is also significantly reduced. Mango powders may also offer the flexibility for innovative formulations and new markets. For example, mango powders can be used as a convenient replacement for juice concentrates or purees, and as shelf-stable ingredients for health drinks, baby foods, sauces, marinades, confections, yogurt, ice cream, nutrition bars, baked goods and cereals (Rajkumar et al., 2007). Development of high quality mango powder may match the increasing worldwide demand for more natural mango-flavored beverages either singly flavored or in multi-flavored products (FAO, 2007), and meet the great demand for natural fruit powders by the pharmaceutical and cosmetic industries.

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Several drying technologies can be viable commercial options for manufacture of mango powders, including freeze drying, drum drying, spray drying and Refractance Window® drying. Each has its own advantages and limitations. The final product obtained from these methods may differ in physicochemical or nutritional properties and microstructures. Freeze drying, also known as lyophilization, is a drying process in which the food is first frozen then dried by direct sublimation of the ice under reduced pressure (Oetjen and Haseley, 2004; Barbosa-Cánovas, 1996). To carry out a successful freeze drying operation, the pressure in the drying chamber must be maintained at an absolute pressure of at least 620 Pa (Toledo, 2007). Freeze drying is generally considered as the best method for production of high quality dried products (Ratti, 2001). But, it suffers from high production costs, high energy consumptions, and low throughputs (Ratti, 2001; Hsu et al., 2003; Caparino, 2000).

Drum drying is commonly used in production of low moisture baby foods and fruit powders (Kalogiannia et al., 2002; Moore, 2005). A drum dryer consists of two hollow cylinder drums rotating in opposite directions. The drums are heated with saturated high temperature (120–170 °C) steam inside the drums. Raw materials are spread in thin layers on the outer drum surface and dry rapidly. The product is scraped from the drum in the form of dried flakes (Kalogiannia et al., 2002; Saravacos and Kostaropoulos, 2002). A major likely drawback is undesirable cooked aromas and other severe quality losses in the final products caused by the high temperature used in the drying process (Nindo and Tang, 2007).

Spray drying is widely used in commercial production of milk powders, fruits and vegetables (Kim et al., 2009; Kha et al., 2010). This method has several advantages, including rapid drying, large throughput and continuous operation (Duffie and Marshall, 1953). During the drying process, the feed solution is sprayed in droplets in a stream of hot air (Saravacos and Kostaropoulos, 2002). The liquid droplets are dried in seconds as a result of the highly efficient heat and mass transfers (Toledo, 2007). The finished product can be made in the form of powder, granules or agglomerates (Nindo and Tang, 2007). Spray drying processes can be controlled to produce relatively free flowing and uniform spherical particles with distinct particle size distribution (Barbosa-Cánovas et al., 2005; Duffie and Marshall, 1953). However, due to the relatively high temperatures involved in spray-drying processes, this drying technique may cause losses of certain quality and sensory attributes, especially vitamin C, β -carotene, flavors and aroma (Dziezak, 1988). In addition, it is difficult to directly spray dry sugar-rich materials such as mango, because they tend to stick to the walls of the dryer (Bhandari et al., 1997a,b; Masters, 1985). Drying aids, such as maltodextrin, are widely added to the feed to increase glass transition temperature of the dried product and hence overcome the problem of stickiness during spray drying.

Refractance Window® (RW™) is a novel drying technique designed mainly to convert fruit puree into powder, flakes, or concentrates. The technology utilizes circulating hot water (95–97 °C) to transfer thermal energy to a thinly spread liquid material placed on a polyester conveyor belt that moves at a predetermined speed while in direct contact with hot water. During drying, the thermal energy from hot water is transmitted to foods through the plastic conveyor by conduction and radiation. Water vapor from foods is carried away by a flow of filtered air over the thin layer. This technology offers several benefits when applied to fruits and vegetables. For example, good retention of nutritional (vitamins), health-promoting (antioxidants) and sensory (color, aroma) attributes were reported for dried carrots, strawberries and squash (Nindo and Tang, 2007). The bright green color of pureed asparagus remained virtually unchanged when dried in the RW dryer, and was comparable to the quality of freeze-dried product (Abonyi et al., 2002). In addition,

energy efficiency of RW drying method compares favorably with other conventional dryers (Nindo and Tang, 2007).

Studies were reported that compared the influence of different drying methods on various quality attributes of fruits and vegetables, including the color of dehydrated apple, banana, carrots and potatoes (Krokida et al., 2001), β -carotene and ascorbic acid retention in carrots and strawberry (Abonyi et al., 2002), antioxidants and color of yam flours (Hsu et al., 2003), asparagus (Nindo et al., 2003), and antioxidant activities in soybean (Niamnuy et al., 2011), encapsulated β -carotene (Desobry et al., 1997), and color and antioxidant of beetroots (Figiel, 2010). However, no studies have been conducted to evaluate the effect of drying methods on mango powders in terms of color, bulk density, porosity, hygroscopicity, solubility, and microstructures. Thus, the objective of this work was to investigate the influence of four drying methods (Refractance Window® drying, freeze drying, drum drying and spray drying) on the physical properties and microstructures of resulting mango powders to provide better understanding in selecting drying techniques that can be applied toward the manufacture of high quality mango powder.

2. Materials and methods

2.1. Preparation of mango puree

Frozen mango puree (Philippine 'Carabao' var.) was acquired from Ramar Foods International (Pittsburg, CA). The puree was produced following the manufacturer's standard process that involved selection of ripened mangoes (95–100% ripeness), washing using chlorinated water, manual trimming, removal of any black portions of the peel and separation of stone/peel. The cleaned mango fruits went through a pulping machine that separated the pulp and discarded excess fibers. A buffer tank was used to standardize the puree at 14–15 °Brix. The mango puree was pasteurized, packed in 5 kg polyethylene (PE) bags, sealed and blast frozen at –35 °C. Bags of puree were placed in carton boxes and stored at –18 °C. The frozen mango puree was kept at constant temperature while in transit from the Philippines to California and finally to Washington State University (Pullman, WA). This frozen mango was stored at –35 °C until it was ready for drying. The average moisture content of the mango puree was 6.5 ± 0.1 kg water/kg dry solids determined using standard oven method (AOAC, 1998).

2.2. Drying experiment

Frozen mango puree was thawed overnight at room temperature (23 °C), and afterward blended for 5 min to a uniform consistency using a bench top blender (Oster Osterizer, Mexico) with lowest speed setting. The puree was dried to below 0.05 kg water/kg dry solids by Refractance Window® drying, freeze drying, drum drying, or spray drying. Due to difficulty in spray drying of this sugar-rich material, maltodextrin (DE = 10) (Grains Processing Corporation, Muscatine, IA) was added to mango puree before spray drying. No addition of carrier was used for the other three drying systems. Detailed procedures for each drying method are described below:

2.2.1. Refractance Window® drying

A pilot scale Refractance Window® dryer at MCD Technologies, Inc. (Tacoma, WA) was used for drying mango puree. The dryer has an effective surface drying area of 1.10 m² and length of 1.83 m in the direction of belt movement. The main components of the dryer included a conveyor belt made of "Mylar®" (polyethylene terephthalate) plastic, a water pump, a hot water tank, a heating unit, two water flumes, a hood with suction blowers and exhaust fans, a

spreader, and a scraper (Fig. 1). The drying was accomplished by spreading homogenized mango puree on the plastic conveyor belt that moves over the surface of circulating hot water. The thickness of the puree on the belt was 0.5–0.7 mm and was controlled using a spreader bar. The thermal energy from the circulating hot water (transferred to the puree through the belt) was used to remove moisture from the product (Nindo et al., 2003). Previous studies reported that the temperature of the product during drying rarely exceeded 80 °C (Abonyi et al., 2002). During drying operation, the temperature of circulating hot water was maintained between 95 and 97 °C similar to that reported by Abonyi et al. (2002) and Nindo and Tang (2007). The temperature of the circulating hot water was continuously monitored at the flume inlet and outlet section using pre-calibrated Type T thermocouple sensors. The sensors were connected to a data acquisition unit equipped with monitoring software. Water vapor removal from the samples was facilitated by forcing the suction air (22 °C) with relative humidity (50–52%) over the puree at an average air velocity of 0.7 m/s (Abonyi et al., 2002). The residence time to dry the mango puree into flakes or powder was determined by monitoring the time travelled by the thinly spread mango puree from inlet to the outlet section of the plastic conveyor belt. Measurement of the residence time was performed in triplicate.

2.2.2. Freeze drying

Freeze drying was carried out using a laboratory freeze dryer (Freeze Mobile 24, Virtis Company, Inc., Gardiner, NY). The thawed mango puree was poured into a stainless pan to form a layer of 15 mm. The samples were placed at –25 °C for 24 h before transferring to the freeze dryer. The vacuum pressure of the dryer was set at 20 Pa, the plate temperature was 20 °C, and the condenser was at –60 °C. The residence time needed to dry the mango puree to below 0.05 kg water/kg dry solids was determined when the vacuum pressure had dropped to 30 mTorr (4 Pa).

2.2.3. Drum drying

A laboratory atmospheric double drum dryer (Model no. ALC-5, Blaw-Knox Co., Buffalo, NY) was utilized in this experiment. The dryer has two hollow metal drums with 0.15 m external diameter and 0.19 m length. The drums were internally heated by steam at 379.2 ± 7 kPa producing a temperature of 152 ± 2 °C. Preliminary experiments were conducted at different rotational speed settings in order to obtain dried sheets of below 0.05 kg water/kg dry solids. The clearance between the two drums was fixed at 0.01 mm allowing the puree to flow (forced by rotary action) into a thin layer as it passed through the gap. The drum temperature was allowed to stabilize before feeding the puree. This prepared puree was poured

evenly over the hot pool area between the two drums. After traveling approximately three fourths of the revolution of the drums or ~15 cm distance, the dried product was scraped from the drum surface by doctor blades. The residence time for drying was recorded by taking three fourths of the time measured for one complete revolution of the drum. Due to stickiness of mango, the dried product at the exit section of the dryer tended to roll and build up while the drum was rotating forming an extruded-like product and not the expected thin flakes. Thin sheet or flakes of dried product was obtained by carefully pulling the dried product as it goes out of the exit section of the dryer. The dried product removed from the two drums was mixed together for analysis because their appearance and moisture content were generally similar.

2.2.4. Spray drying

The thawed mango puree was spray-dried in a pilot scale S-1 spray dryer (Anhydro Attleboro Falls, MA). Before starting the experiment, the dryer was conditioned for 20 min by pumping de-ionized water through the atomizer with the dryer inlet and outlet temperatures set at 180 and 80 °C, respectively (Shrestha et al., 2007). The mango puree was pumped into the spray dryer chamber at a flow rate of 50 ± 2 g/min using Masterflex pump (Cole-Parmer Instruments Co., Chicago, IL). The air temperature was maintained at 190 ± 2 °C (dryer inlet) and 90 ± 2 °C (dryer outlet) during drying. These air inlet and outlet conditions are within the recommended temperatures of 180–220 and 90–110 °C, respectively, for spray drying of heat sensitive products at atmospheric pressure (Filikova and Mujumdar, 1995; Kim et al., 2009). The outlet temperature determines the thermal exposure of the sample during spray drying. It was observed during preliminary experiments that spray drying of mango puree without any carrier was not possible due to the high content of low molecular weight sugars (e.g. fructose, glucose, sucrose), similar to what had been reported by other authors (Abonyi et al., 2002; Bhandari et al., 1997a,b). Maltodextrin (DE = 10) having a median glass transition temperature of $T_{gm} = 139.7$ °C (Jakubczyk et al., 2010) was added to produce a non-sticky and free flowing powder (Bhandari et al., 1997a,b). Preliminary experiments were carried out to obtain dried product that has better appearance and throughput. Three maltodextrin concentrations of 0.25, 0.35 and 0.45 kg/kg dried mango solids were tested for this purpose (Jaya et al., 2006; Nindo and Tang, 2007; Sablani et al., 2008). By visual examination, the color and appearance of the dried mango powder from the three treatments showed very little variation. Hence, the spray-dried mango powder with the lowest maltodextrin concentration of 0.25 kg/kg dried mango solids was selected for comparison with other dried powders. The actual residence time to obtain mango powder with

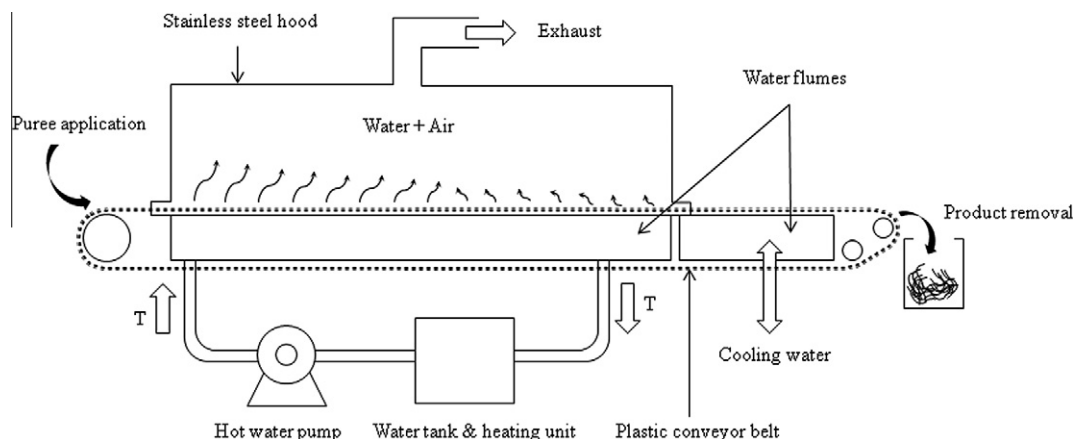


Fig. 1. Schematic layout of Refractance Window® dryer (adapted from Nindo and Tang (2007) and Abonyi et al. (2002)).

a moisture content below 0.05 kg water/kg dry solids was not measured, but the information from previous studies on spray drying of sugar-rich material was used to approximate the time.

2.3. Handling and packaging of samples

The product from each drying process had unique geometries at the exit point, so different handling procedures were employed. Rectangular cake-like dried products obtained from the freeze drying process were collected and sliced into smaller pieces using a clean stainless steel knife and packed in leak-proof Ziploc® plastic bags. The spray-dried material, which appeared like agglomerated spherical shapes, was immediately packed in the same type of plastic bags after coming out from the dryer. The dried thin sheets collected from the drum and RW drying processes were handled in a similar manner. All the samples sealed in Ziploc® bags were placed inside aluminum-coated polyethylene bags. To prevent oxidation, all the packaged samples were flushed with nitrogen gas, heat sealed and stored at -35°C until further analyses.

2.4. Grinding and sieving

One hundred grams each of dried flakes or sheets obtained from different drying processes were ground using mortar and pestle. Sieving analysis was carried out by stacking and vibrating the sieves in ascending order of mesh sizes of 35, 45, 60 and 80 (American Society for Testing and Materials, ASTM) to obtain particle sizes of 500, 350, 250 and 180 μm (International Standard for Organization, ISO), respectively (Barbosa-Canovas et al., 2005). Those with particle sizes ranging between 180–500 μm and flakes or sheets were evaluated in terms of color, bulk density and bulk porosity, while particle sizes of 180–250 μm were analyzed for solubility, hygroscopicity and microstructures.

2.5. Water content

The water content of mango puree and dried flakes/powders made from RW, freeze, drum and spray drying methods was determined using the standard oven method at 70°C and 13.3 kPa for 24 h (AOAC, 1998). The drying, cooling and weighing of samples was continued until the difference between two successive weighing was less than 1 mg.

2.6. Water activity

Water activity of the RW-, freeze-, drum-, and spray-dried mango powders was measured using water activity meter (Aqualab 3TE series, Decagon Devices, Pullman, WA). Duplicate samples were measured at $24.7 \pm 1^{\circ}\text{C}$.

2.7. Physical properties of mango powders

2.7.1. Color analysis

The dried mango in flakes or sheet forms and four different particle sizes of 500, 350, 250 and 180 μm were evaluated for color comparison. Mango powders or flakes were poured into Petri dishes, slightly shaken to form a layer of 10 mm thickness and covered with transparent film (Saran™ Wrap, SC Johnson, Racine, WI). The International Commission on Illumination (CIE) parameters L , a^* and b^* were measured with a Minolta Chroma CR-200 color meter (Minolta Co., Osaka, Japan). The colorimeter was calibrated with a standard white ceramic plate ($L = 95.97$, $a = -0.13$, $b = -0.30$) prior to reading. Corresponding L value (lightness of color from zero (black) to 100 (white); a^* value (degree of redness (0–60) or greenness (0 to –60); and b^* values (yellowness (0–60) or blueness (0 to –60) were measured for all the samples. The average L , a^* and

b^* values were obtained from six readings taken from each of five locations. The hue angle, H^* and chroma, C^* expressed as $H^* = \tan^{-1} \frac{b^*}{a^*}$ and $C^* = \sqrt{a^{*2} + b^{*2}}$, respectively were also calculated (Abo-ny et al., 2002). Hue is a color attribute by which red, yellow, green and blue are identified, while chroma distinguishes between vivid and dull colors.

For color comparison with the original mango puree, 2 g each of RW-, freeze-, drum-, and spray-dried mango powders ($\sim 250 \mu\text{m}$) with water content of 0.017 ± 0.001 , 0.023 ± 0.002 , 0.013 ± 0.001 and 0.043 ± 0.003 kg water/kg dry solids were reconstituted by adding an amount of 12.10, 12.04, 11.96 and 11.70 g of distilled water, respectively using material balance. The reconstituted mango powders produced slurries with moisture content of 6.143 kg water/kg dry solids similar as the original mango puree. The reconstitution of mango powder was carried out by mixing the powder and water at 23°C while vortexing (Fisher Scientific mini vortexer, USA) until the powder was completely dissolved. The L^* , a^* and b^* , H^* and C^* values were immediately measured and calculated following the same procedure employed for mango flakes and powders. The total change in color of the reconstituted mango powders with reference to the original puree were computed as:

$\Delta E = \sqrt{(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2}$ where, subscript “o” denotes the color of original puree (Jaya and Das, 2004; Nindo et al., 2003).

2.7.2. Bulk density

The bulk density of the mango powder obtained from different drying processes and particle sizes was measured following the procedure described in previous studies with modification (Barbosa-Canovas et al., 2005; Goula and Adamopoulos, 2008). Approximately 5 g of mango powder was freely poured into a 25 ml glass graduated cylinder (readable at 1 ml) and the samples were repeatedly tapped manually by lifting and dropping the cylinder under its own weight at a vertical distance of 14 ± 2 mm high until negligible difference in volume between succeeding measurements was observed. Given the mass m and the apparent (tapped) volume V of the powder, the powder bulk density was computed as m/V (kg/m^3). The measurements were carried out at room temperature in three replicates for all samples.

2.7.3. Particle density and bulk porosity

The particle densities of mango powders obtained by different drying methods were calculated by adopting the pycnometer method. A 2.5 ± 0.04 g of each of the RW-, freeze-, drum-, and spray-dried mango powders (180–250 μm) was placed in an empty liquid pycnometer (25 ml), and filled with measured volume of toluene. Toluene was used because of its ability to penetrate the finest external pores connected to surface of the material without dissolving the material. Bulk porosity (ε_b) was calculated by determining the ratio of particle density (ρ_p) and bulk density (ρ_b) using the Eqs. (1)–(3) as (Krokida and Maroulis, 1997):

$$\rho_b = \frac{m_s}{V_t} \quad (1)$$

$$\rho_p = \frac{m_s}{V_s} \quad (2)$$

$$\varepsilon_b = 1 - \frac{\rho_b}{\rho_p} \quad (3)$$

where ρ_b is the bulk density of mango solids, ρ_p is the particle density of the solids, m_s is the mass of mango solids, V_t and V_s is the total and volume of the dry solids, respectively.

2.7.4. Solubility

Solubility of mango powder was determined using the procedure developed by Eastman and Moore (1984) as adopted by Cano-Chauca et al. (2005). One gram of the powder (dry basis) was dispersed in 100 ml distilled water by blending at high speed (~13,000 rpm) for 5 min using an Osterizer blender (Oster, Mexico). The dispersed mango powder was then centrifuged at 3000g for 5 min. A 25 ml aliquot of the supernatant was carefully pipetted and transferred to a pre-weighed aluminum dish and then oven-dried at 105 °C for 5 h. Drying was continued and weighed every hour for 2 h. The solubility of the powder (%) was determined by taking the weight difference.

2.7.5. Hygroscopicity

Ten grams each of RW-, freeze-, drum- and spray-dried mango powders with particle sizes of 180–250 µm and moisture content below 0.05 kg H₂O/kg mango solids were placed in an open glass container. Three replicate samples for each product were put separately in three sealed humidity jars containing NaCl saturated solution (75.5% humidity) and stored at 25 °C for 7 days. Samples were prepared at 20 °C. Hygroscopicity, HG (%) or 1 g of adsorbed moisture per 100 g dry solids (g/100 g) was calculated using the following equation:

$$HG = \frac{\Delta m / (M + M_i)}{1 + \Delta m / M} \quad (4)$$

where Δm (g) is the increase in weight of powder after equilibrium, M is the initial mass of powder and M_i (% wb) is the free water contents of the powder before exposing to the humid air environment (Jaya and Das, 2004; Sablani et al., 2008; Tonon et al., 2008).

2.8. Glass transition temperature

Glass transition temperature (T_g) of mango powders with water activity below 0.2 was measured using differential scanning calorimeter (DSC, Q2000, TA Instruments, New Castle, DE), following the procedure described by Syamaladevi et al. (2009). The calorimeter was calibrated for heat flow and temperature using standard indium and sapphire. Twelve to sixteen milligrams of each mango powder sample was sealed in an aluminum pan (volume of 30 µl), cooled down from 25 to –90 °C using liquid nitrogen and then equilibrated for 10 min. The samples at –90 °C were scanned to 90 °C then cooled down to 25 °C. Scanning of all samples was carried out using the same heating and cooling rate of 5 °C/min. To avoid condensation on the surface of the powder particles, a nitrogen carrier gas was purged at a flow rate of 50 ml/min. The onset- (T_{gi}), mid- (T_{gm}) and end-point (T_{ge}) values of the mango powders were determined by finding the vertical shift in the heat flow-temperature diagram. All measurements were performed in duplicate.

2.9. X-ray diffraction

X-ray diffraction (XRD) characteristics of mango powders obtained from different drying processes were investigated using a Siemens D-500 diffractometer (Bruker, Karlsruhe, Germany). The powder samples (180–250 µm) were placed and slightly pressed in an aluminum holder using a glass slide. The diffractometer was operated at a wavelength of 0.15 nm and the input energy was set at 30 mA and 35 kV. Diffractograms were taken between 5° and 50° (2θ) with a step angle of 0.02° and scan rate of 1 s per step. The XRD patterns of all the samples were plotted for comparison.

2.10. Microstructure analyses

A small quantity of mango powders (180–250 µm) from different drying systems were mounted on aluminum stubs and coated

with a fine layer of gold (15 nm) using a Sputter gold coater (Technics Hummer V, Anatech, San José, CA). All powder samples were examined by Scanning Electron Microscopy using SEM Hitachi S-570 camera (Hitachi Ltd., Tokyo, Japan) operated at an accelerating voltage of 20 kV. Micrographs were photographed at a magnification of 100×, 300× and 1000× at scale bar of 0.30 mm, 100 µm and 30 µm.

The microstructure of samples prepared for hygroscopicity experiments were also analyzed to identify possible relationships between the obtained hygroscopicity values for each mango powder sample using a Quanta 200F Environmental Scanning Electron Microscope (FEI, Field Emission Instruments, Hillsboro, Oregon, USA). The low vacuum mode (200 Pa) was used during scanning to allow measurement of samples at their native state. Observations were carried out with an accelerated voltage of 30 kV and magnification of 700× at a scale of 100 µm.

2.11. Statistical analysis

All experiments were carried out at least in duplicate, the results analyzed using the general linear model procedure of SAS (SAS Institute Inc., Cary, NC), and the means separated by Tukey-honest significant difference test with a confidence interval of 95% used to compare the means. Mean standard deviations are presented in the results.

3. Results and discussion

3.1. Residence time, water content and product temperature

The residence time during drying of mango puree from the initial moisture content of 6.52 kg water/kg mango solids to below 0.05 kg water/kg mango solids was accomplished in 180 ± 0.15 , $111,600 \pm 5100$ and 54 ± 0.2 s for RW, FD and DD, respectively, and less than 3 s with SD (Table 1). It should be noted here that the residence time used for SD was only an approximation based on the data reported by Desobry et al. (1997) and Jayasundera et al. (2011b). The actual residence time during spray drying of mango powder in our study might be higher than 3 s because of the difference in drying conditions and specifications of the spray dryer used as compared from the literature. Nevertheless, the estimated residence time for SD is definitely much smaller than for RW, freeze and drum drying. The product temperatures measured for each drying process was 74 ± 2 °C (RW), 20 ± 0.5 °C (FD), 105 ± 5 °C (DD) and 90 ± 2 °C (SD).

3.2. Physical properties of mango powder

3.2.1. Color analysis

The color of the dried product (mango flakes/sheet) or powders of different particle sizes were affected by the drying methods.

Table 1
Drying conditions for production of mango powders using different methods.

Product	Product temperature (°C)	Residence time (s)	Water content (kg water/kg dry solids)
Fresh puree	–	–	6.518 ± 0.123
RW	74 ± 2	180 ± 0.15	0.017 ± 0.001
FD	20 ± 0.5	$111,600 \pm 5091$	0.023 ± 0.002
DD	105 ± 5	54 ± 0.2	0.013 ± 0.001
SD	90 ± 2	1–3 ^a	0.043 ± 0.003

Standard deviation from the average value of at least two replicates.

^a The residence time was an approximate value, based on information given in Desobry et al. (1997) and Jayasundera et al. (2011a,b,c).

Visual examination showed that spray-dried (agglomerate powder particles) and drum-dried mango powder had the lightest and darkest color, respectively. The color difference between mango powder obtained using RW and FD was not significantly different ($P \leq 0.05$) (Fig. 2). Hunter color tristimulus values for mango powder of different particle sizes are presented in Fig. 3. Overall, the product (flakes) at exit had a significant difference in the L value (lightness) among the RW-, freeze-, drum-, and spray-dried mango flakes or powders, except for the RW and freeze-dried powder with particle size of 500 and 350 μm which showed no significant variation ($P \leq 0.05$) (Fig. 3a). The similarity in L -value for RW, FD and DD powders of the smallest particle size (180 μm) may be attributed to negligible effect on reflectance.

The mango powder produced by spray drying had the highest L value, while the drum-dried mango powder appeared to have the lowest L value (indicating darkest color). The lighter color in spray drying was due to the addition of maltodextrin carrier which was necessary to reduce the stickiness of the mango to allow the spray drying process to be effective (Abonyi et al., 2002; Jaya et al., 2006). While the outlet temperature during spray drying reached $90 \pm 2^\circ\text{C}$, the drying time was very short (1–3 s) as reported by Desobry et al. (1997). Hence the color degradation was limited. On the other hand, the darker color of the drum-dried mango powder can be attributed to high drying temperature. Such effect confirmed previous studies on strawberry puree (Abonyi et al., 2002) wherein color degradation was greatly influenced by high processing temperatures. The dark color in drum-dried mango flakes or powder can be characterized by browning reaction or Maillard reaction caused by the chemical reactions between sugars and proteins (Potter and Hotchkiss, 1995). Moreover, caramelization of sugars in mango can occur due to high temperature contributing to darkening during drying. The dominant color in mango puree is yellow and hence can be best represented by Hunter color b^* (yellowness) to distinguish the color difference of the resulting mango powders as affected by the drying process. No significant difference was observed in b^* value (yellowness) between RW and freeze-dried mango powder while there was a highly significant difference between spray and drum-dried product ($P \leq 0.05$)

(Fig. 3b). Chroma value or vividness in yellow color of 250 μm particle size RW and freeze dried mango flakes and powders showed no significant difference, but RW-dried mango powder with particle size 350–500 μm were of a more vivid yellow color than freeze dried mango powder having obtained the highest chroma value (Fig. 3c). The hue angle value in spray-dried mango powder was the highest but its chroma value is very low indicating a dull color (Fig. 3d). RW dried mango flakes or powder at all particle sizes obtained a higher hue angle compared to freeze and drum-dried mango powders suggesting that RW-dried mango powder is more vivid in its yellow color implying that it will be more attractive and appealing to consumers. The overall distinct vivid yellow color of the RW-dried mango may be indicative of high β -carotene retention. Abonyi et al. (2002) reported that β -carotene in RW and freeze-dried carrot puree was 53% and 55% higher compared to drum-dried products, respectively. Wagner and Warthesen (1995) reported that the yellow and red color of carrot slices is attributed to the presence of carotenenes. Also, the b^* (yellow) values for raw and puree sweet potato were highly correlated with β -carotene content (Ameny and Wilson, 1997). The minimal color change of product produced by RW and freeze drying suggests the appropriateness of these processes to produce high quality products. The comparable yellow color of RW and freeze-dried mango powder can also be attributed to low product temperature for RW ($74 \pm 2^\circ\text{C}$) and freeze-dried ($20 \pm 0.5^\circ\text{C}$), compared to spray-dried ($90 \pm 2^\circ\text{C}$) and drum-dried ($105 \pm 5^\circ\text{C}$) mango powder.

The reconstituted mango powder was prepared by adding water to achieve the same solid contents as the original mango puree. Visual examination of the color of the reconstituted RW-, freeze-, drum-, and spray-dried mango powders showed variations in comparison with the original mango puree (Fig. 4). Luminosity (L^*) values as presented in Table 2 showed no significant difference between reconstituted RW- and freeze-dried mango puree and both are similar in luminosity to the original puree. Reconstituted drum-dried mango puree was darker as expected because of the darker powder. The result is in agreement with the work of Abonyi et al. (2002) wherein a drum-dried carrot puree was perceived as darker in comparison with powders produced by spray, freeze

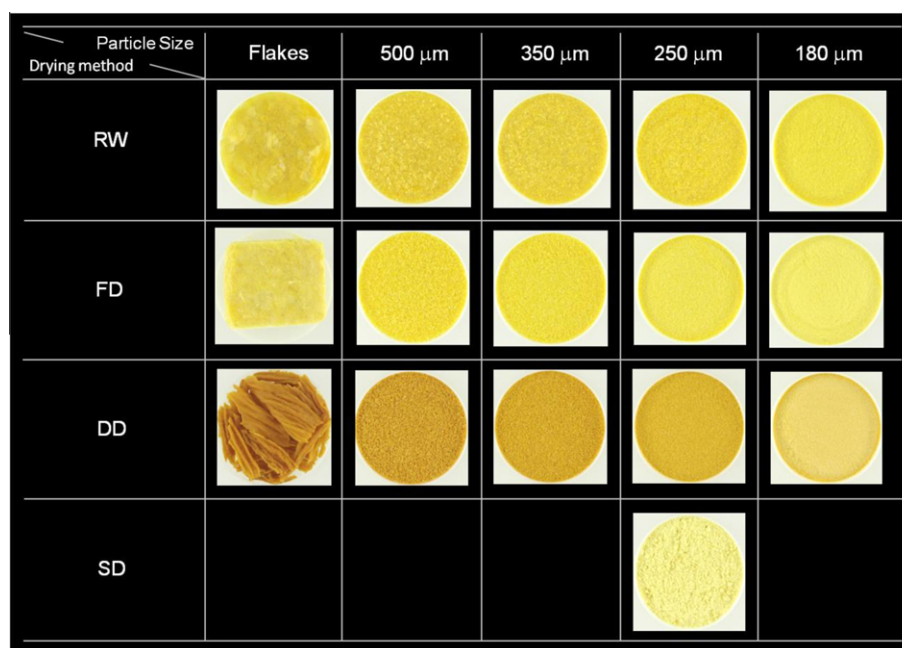


Fig. 2. Photograph of mango flakes or powders at different particle sizes obtained from Refractance Window® (RW) drying, freeze drying (FD), drum drying (DD), and spray drying (SD).

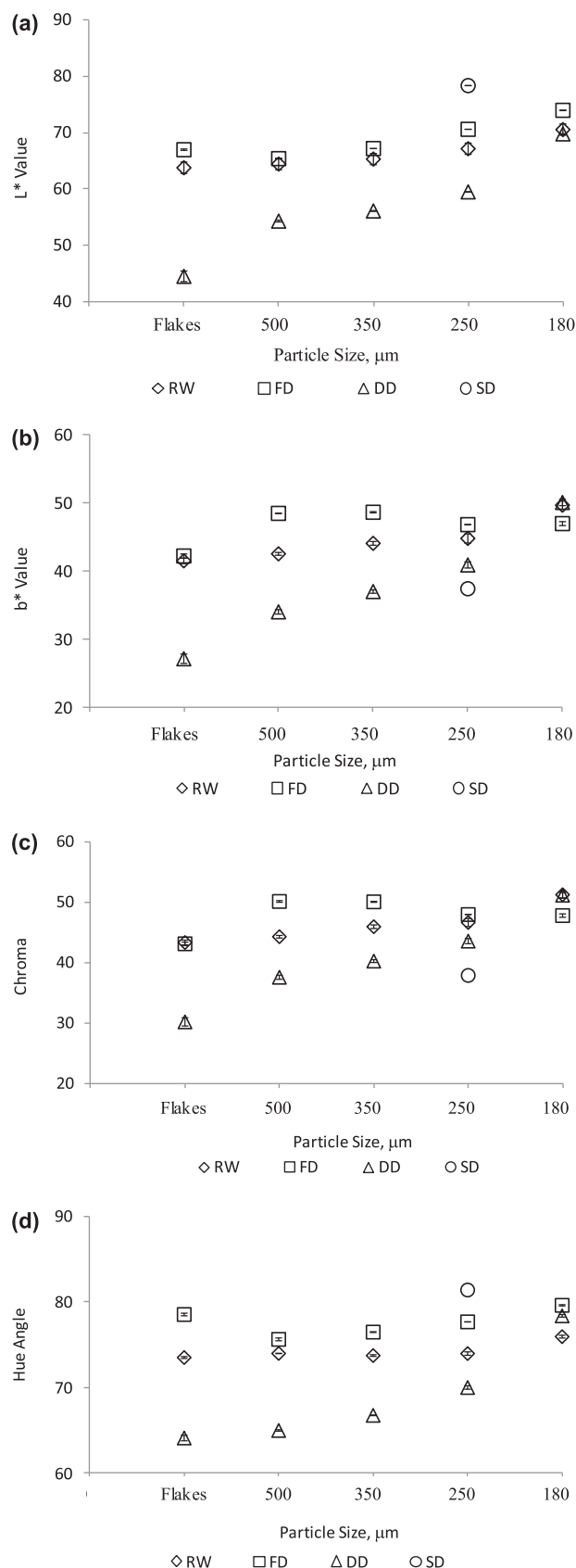


Fig. 3. Lightness (a), yellowness (b), chroma (c) and hue angle (d) of mango flakes or powders at different particle sizes obtained from Refractance Window® (RW), freeze drying (FD), drum drying (DD), and spray drying (SD).

and RW drying methods. Spray-dried mango powder was darker than RW- and freeze-dried but lighter than reconstituted drum dried mango puree. The original mango puree and reconstituted RW and freeze-dried mango powders are significantly different but comparable in terms of vividness and saturation of yellow color. On the other hand, the reconstituted drum-dried and spray-dried mango puree had lower chroma values indicating less saturation and dull yellow appearance. A comparable result was also observed for hue angle among the original puree, reconstituted RW- and freeze-dried mango puree while reconstituted drum-dried mango puree had a low hue angle value, which indicates a dull yellow color. The reconstituted spray-dried mango puree had the highest hue angle value but because of its low lightness and chroma values, it produced a grayish pale color. The reconstituted mango powder from drum drying process showed the highest deviation in color with respect to the original mango puree having a ΔE value of 9.22 ± 0.01 followed by the reconstituted spray-dried mango puree with ΔE value of 6.23 ± 0.02 (e.g. lightest). The reconstituted RW-dried mango puree had the lowest color difference with ΔE value = 1.22 ± 0.02 , a value very close to reconstituted freeze-dried mango puree with ΔE value = 1.57 ± 0.02 . The distinct superiority of RW drying process against drum and spray drying processes in producing mango powder in the present experiment is in corroboration with previous studies for asparagus (Nindo et al., 2003), and carrots and strawberry (Abonyi et al., 2002).

3.2.2. Bulk density and porosity

For all drying methods, the bulk density of mango powders increased and their porosity decreased with decreasing particle size (Figs. 5 and 6). These results may be attributed to the decrease in the inter-particle voids of smaller sized particles with larger contact surface areas per unit volume. Similar observation was reported for bulk density of ginger powder at different particle sizes (Xiaoyan, 2008). It was also consistent with the explanation by other authors that powder characteristics such as particle size may result in significant changes in bulk density and porosity (Barbosa-Canovas et al., 2005).

Freeze- and spray-dried mango powders had significantly lower bulk densities and higher porosities compared to drum- and RW-dried products ($P \leq 0.05$) (Figs 5 and 6). It is well recognized that in freeze drying of foods in the form of either puree or as a whole, the material is first frozen allowing it to maintain its structure following sublimation of ice under high vacuum (Oetjen and Haseley, 2004). Since liquid phase in the material is not present during this process, there is no transfer of liquid water to the surface, but instead the ice changes to vapor below the collapse temperature without passing the liquid state (Krokida and Maroulis, 1997). In effect the collapse and shrinkage of the product is prevented thereby resulting in a porous dried material (Karel, 1975).

The higher porosity or lower bulk density in spray-dried mango powder was due to the addition of maltodextrin (Fig. 6). Shrestha et al. (2007) demonstrated that increasing maltodextrin concentration in tomato pulps led to the decrease in bulk density. Goula and Adamopoulos (2008) also explained that maltodextrin is considered a skin-forming material and by using it as carrier can induce accumulation and trapping of air inside the particle causing it to become less dense and porous.

On the other hand, the bulk porosity and density of RW- and drum-dried mango powder were significantly lower and higher than freeze and spray dried product, respectively with drum dried product exhibited the lowest porosity ($P \leq 0.05$) (Figs. 5 and 6). During drum drying, the mango puree poured inside a pool between the two drums has vapor bubbles bursting at the free surface and spattered along side of the two drum surfaces as triggered by high temperature (above boiling). The high temperature used in

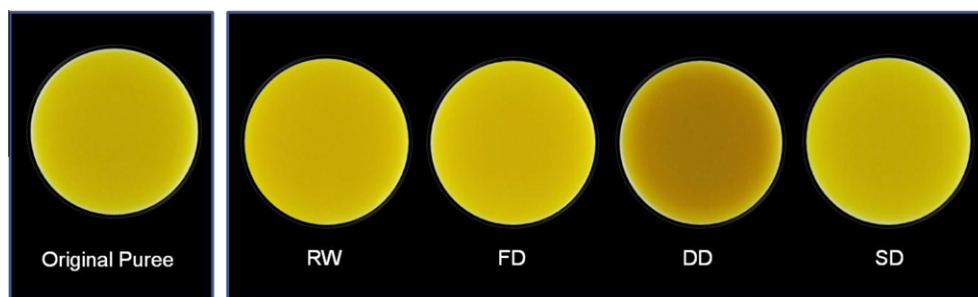


Fig. 4. Photograph of reconstituted mango powders obtained from Refractance Window® (RW), freeze drying (FD), drum drying (DD), and spray drying (SD).

Table 2

Hunter color measurements of reconstituted mango powders obtained from different drying processes.

Drying method	L^*	a^*	b^*	C^*	Hue angle	b^*/a^*	ΔE
Original puree	45.12 ± 0.02 ^a	4.65 ± 0.01 ^c	41.52 ± 0.03 ^a	41.78 ± 0.03 ^c	83.61 ± 0.01 ^a	8.93 ± 0.01 ^c	–
RW	43.95 ± 0.02 ^b	4.40 ± 0.01 ^d	41.79 ± 0.03 ^a	42.02 ± 0.03 ^b	83.99 ± 0.01 ^a	9.50 ± 0.02 ^b	1.22 ± 0.02 ^d
FD	43.74 ± 0.06 ^c	4.69 ± 0.01 ^b	40.99 ± 0.23 ^b	41.26 ± 0.23 ^d	83.47 ± 0.04 ^b	8.73 ± 0.06 ^d	1.57 ± 0.03 ^c
DD	37.73 ± 0.01 ^d	6.92 ± 0.02 ^a	36.48 ± 0.02 ^c	37.13 ± 0.02 ^e	79.27 ± 0.03 ^c	5.28 ± 0.03 ^e	9.22 ± 0.01 ^a
SD	41.59 ± 0.07 ^e	3.05 ± 0.01 ^e	36.64 ± 0.02 ^c	36.77 ± 0.03 ^a	85.24 ± 0.02 ^d	12.00 ± 0.05 ^a	6.23 ± 0.02 ^b

ΔE is calculated using the original mango puree as reference.

^{a–e} Means with the same superscript letters within a column indicate no significant differences ($P \leq 0.05$).

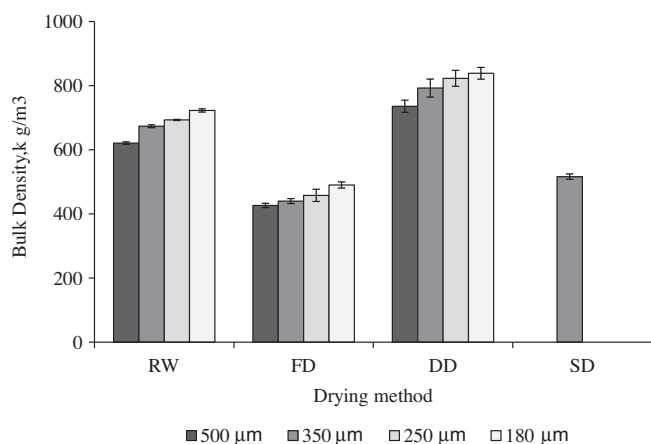


Fig. 5. Bulk density of mango powders obtained from Refractance Window® (RW) drying, freeze drying (FD), drum drying (DD), and spray drying (SD).

drum drying may have caused collapse which resulted in more compact and rigid product. These characteristics resulted in lower porosity when compared to freeze- or spray-dried mango powder. RW-dried mango powder exhibited low porosity compared to freeze- and spray-dried mango powder but significantly higher than drum-dried powder ($P \leq 0.05$) (Figs. 5 and 6). RW is categorized as a direct drying technique similar to drum-drying (Nindo and Tang, 2007), except that the energy is indirectly transferred via plastic film instead of steel as in drum drying. Apparently, both drying processes seem to produce a similar form of end product.

3.2.3. Solubility

Solubility is the most reliable criterion to evaluate the behavior of powder in aqueous solution. This parameter is attained after the powder undergoes dissolution steps of sinkability, dispersability and wettability (Chen and Patel, 2008). There was no significant difference in the solubility between spray and drum-dried mango powder, while both were significantly higher compared to RW and freeze-dried product ($P \leq 0.05$) (Table 3). The high solubility of spray-dried mango powder can be attributed to the addition of

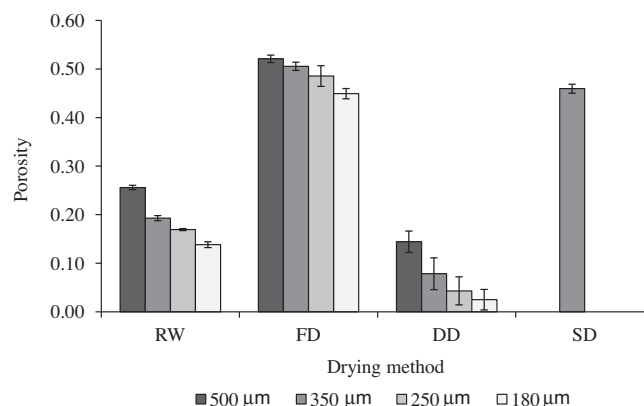


Fig. 6. Porosity of mango powders obtained from Refractance Window® (RW) drying, freeze drying (FD), drum drying (DD), and spray drying (SD).

maltodextrin (DE = 10). This result was in agreement with the study reported by Cano-Chauca et al. (2005) where they concluded that solubility of mango powders increased when maltodextrin was added during spray-drying. Maltodextrin is a material that serves as coating agent as the particle crust is developed during spray drying resulting in a product that is highly soluble (Desai and Park, 2004). Cai and Corke (2000) also confirmed that maltodextrin as a carrier and coating agent increased the solubility of spray-dried betacyanins. The atomization of mango puree during spray drying may also contribute to solubility of spray-dried product. Fibers present in mango might have been broken into tiny pieces as a result of high atomization of the material resulting in increased solubility. From the above observations, maltodextrin was proven effective in increasing solubility of spray-dried mango powder. However, spray drying of mango puree containing 25 kg/kg dried mango solids significantly altered the total color change of the resulting mango powder as earlier discussed. Likewise, the cyclone recovery of mango powder at this maltodextrin concentration was only $37.8 \pm 1.8\%$ (data not shown), far below the $>50\%$ benchmark cyclone recovery for a marginally successful spray drying process of sugar-rich material (Bhandari et al.,

Table 3Solubility and hygroscopicity of RW-, freeze-, drum-, and spray-dried mango powders with particle size 180–250 μm .

Drying methods	Particle size (μm)	Moisture content (kg water/kg mango solids)	Solubility ^A (%)	Hygroscopicity ^B (%)
RW	180–250	0.017 \pm 0.001	90.79 \pm (0.394) ^a	18.0 \pm 0.36 ^a
FD	180–250	0.023 \pm 0.002	89.70 \pm 0.631 ^a	18.0 \pm 0.19 ^a
DD	180–250	0.013 \pm 0.001	94.38 \pm 0.431 ^b	20.1 \pm 0.88 ^b
SD	180–250	0.043 \pm 0.003	95.31 \pm 0.112 ^b	16.5 \pm 0.06 ^c

^a Standard deviation from the average value.^{a,b} Means with the same superscript letters within a column indicate no significant differences ($P \leq 0.05$).^A Measurement was done at 23 °C.^B Samples were exposed to 75 \pm 1% RH at 25 °C for 7 days.

1997a,b; Jayasundera et al., 2011a,b). The application of alternative drying aids such as proteins and low molecular surfactants may improve the recovery and quality of spray-dried mango powders and help in maintaining higher solubility (Jayasundera et al., 2011a,b,c; Adhikari et al., 2009a,b). Recently, a type of protein called “Protein X” developed at the University of Sydney, was found to increase the recovery of sugar-rich material of up to 80% by just adding a small amount (<5%) to the sticky fruit juice or puree (Wang et al., 2011).

Drum dried mango powder also had a high solubility value that was not significantly different from spray-dried mango powder. The higher solubility of drum-dried samples could be attributed to a higher degree of macromolecular disorganization of the material as affected by drying process and condition. However, its inferior dark color may restrict consumer acceptance even though its solubility is high.

The solubilities of freeze- and RW-dried mango powders were similar and significantly lower than that of spray- and drum-dried mango powders. Both drying methods are gentle in terms of product temperature (Table 1). One possible reason for the lower solubility of those samples is that the cell structure of mango puree was not disrupted and smaller amounts of solids were dissolved to become part of the supernatant.

3.2.4. Hygroscopicity

A demarcation or cut-off values for hygroscopicity (HG) of mango powder ranging from 5.13% to 9.38% were considered as the basis for comparing the results in our study. These figures were based on the average range of hygroscopicity values of instant coffee (lower HG) and tomato soup powder (higher HG) as calculated by Jaya and Das (2004). Table 3 shows the hygroscopicity of mango powders made from Refractance Window, freeze, drum and spray drying. The drum-dried mango powder exhibited the highest hygroscopicity (20.1 \pm 0.88%), 74% higher than the higher limit cut-off HG, indicating its strong capacity to attract water molecules when in contact with the surrounding air. Mujumdar (2007) explained that drum drying of sugar-rich fruits requires high temperature and usually a dry to very low moisture thin sheet product. This drying condition usually causes the product to be very hygroscopic and often other quality attributes are degraded. The lower hygroscopicity value obtained for spray drying (16.5 \pm 0.06) or 68.91% higher than the benchmark HG can be attributed to the addition of maltodextrin in the mango puree before drying. Tonon et al. (2008) demonstrated that the hygroscopicity of spray-dried acai powder gets lower as the concentration of maltodextrin was increased. Similar observation was confirmed during spray drying of cactus pear juice (Rodríguez-Hernández et al., 2005), sweet potato powder (Ahmed et al., 2009) and betacyanin pigments (Cai and Corke, 2000), suggesting that maltodextrin is an efficient carrier agent in lowering hygroscopicity of dried material. Consequently, when this carrier is added, other quality attributes of the mango powder such as color and β -carotene (data not shown) were found inferior. There was no significant difference in the

hygroscopicity between RW- (18.0 \pm 0.36%) and freeze-dried (18.0 \pm 0.19%) mango powder ($P \leq 0.05$) obtaining a similar increase of 71.50% based on the higher limit cut-off HG, suggesting the superiority of RW over drum and spray-dried mango powder.

The small variation of moisture content of the different samples may have direct relationship with the hygroscopicity as shown in Table 3. Tonon et al. (2008) expound that the low moisture spray-dried acai has the greater capacity to absorb water from the surrounding air and hence is more hygroscopic. However, his findings on the moisture–hygroscopicity relationship cannot be generalized for all commodities. Ahmed et al. (2009) reported that hygroscopicity of spray-dried sweet potato was greatly affected by carrier agents with no direct relationship to varying moisture content. The present study was in agreement with his findings wherein maltodextrin greatly influenced the hygroscopicity of the spray-dried mango powder.

3.3. Glass transition temperature

The glass transition temperatures of RW-, freeze-, drum- and spray-dried mango powders were determined in the water activity range from 0.169 to 0.177 and water content below 0.05 kg water/kg mango solids (Table 4). The onset of T_g (T_{gi}) values of mango powders were slightly lower than the room temperature (25 °C) normally used for long-term storage of food powders. Adhikari et al. (2009a) reported that water activity below 0.2 is the value commonly applied for processing of spray-dried powders in a commercial scale. The T_{gi} values of mango powders ranged from 18.7 \pm 0.2 to 26.1 \pm 0.8 with RW-dried mango powder displaying the lowest T_{gi} and being significantly different from spray-dried product having the highest T_{gi} value ($P < 0.05$). The higher T_g value of spray-dried product may be attributed to the addition of higher T_g maltodextrin before spray drying. Maltodextrin has high molecular weight and adding this amorphous material to low molecular weight sugar-rich material such as mango will cause it to increase the glass transition temperature of the product (Jaya and Das, 2004). The glass transition temperature of RW- freeze- and drum-dried mango powder produced without the drying aids showed no significant differences among each other ($P < 0.05$). It can also be seen from the data that the glass transition

Table 4

Glass transition temperatures and water activity of RW-, freeze-, drum-, and spray-dried mango powders.

Drying methods	Glass transition temperatures			Water activity
	T_{gi}	T_{gm}	T_{ge}	
RW	18.7 \pm 0.2 ^b	23.1 \pm 0.7 ^a	24.6 \pm 0.5 ^a	0.177 \pm 0.001 ^a
FD	20.1 \pm 0.8 ^{ab}	25.8 \pm 2.7 ^a	27.6 \pm 1.8 ^{ab}	0.174 \pm 0.001 ^a
DD	22.4 \pm 1.1 ^{ab}	27.6 \pm 1.3 ^a	30.3 \pm 1.1 ^{ab}	0.169 \pm 0.002 ^a
SD	24.4 \pm 0.8 ^a	28.8 \pm 4.3 ^a	31.5 \pm 0.7 ^a	0.173 \pm 0.006 ^a

Means with the same superscript letters within a column indicate no significant differences ($P < 0.05$). T_{gi} , T_{gm} and T_{ge} represent the onset, mid- and end-point glass transition temperatures of mango powders (180–250 μm).

temperature of mango powder with water activity <0.2 was not affected by the drying process and condition.

3.4. X-ray diffraction

X-ray diffraction is a common technique used to confirm the crystalline–amorphous state of dried products in a powder form. In general, crystalline material shows a series of sharp peaks, while amorphous product produces a broad background pattern. The X-ray diffraction patterns of RW-, freeze-, drum- and spray-dried mango powders at $a_w < 0.2$ clearly exhibited amorphous characteristics and showed no crystalline peak formation (Fig. 7). The rapid drying of low molecular weight sugars present in mango (sucrose, fructose and glucose) and organic acids that happened under RW, drum and spray drying processes tend to produce amorphous metastable state dried products because of insufficient time to crystallize (Jayasundera et al., 2011a,b). The diffractogram of freeze-dried mango powder obtained in this study was similar to the one reported by Harnkarnsujarit and Charoenrein (2011) and Haque and Roos (2005).

The X-ray patterns and shapes for all the mango powders tested were similar to spray-dried sucrose indicating the dominance of sucrose sugars present in mango (Adhikari et al. (2009a). However, it is interesting to note that the intensity count for drum-dried mango powder as shown in the diffractograms was significantly lower compared to the other three powder products. This could be due to puree gelatinization that occurred before the actual drum drying, resulting in the disorganization of intra- and intermolecular hydrogen bonding between water and starch molecules (Gavrilidou et al., 2002). Anastasiades et al. (2002) confirmed that gelatinization process causes irreversible changes in the physical structure of starch, which is present in mango resulting in degradation of molecular structure and loss of crystallinity. The absence of crystalline peaks confirmed that no substantial changes occurred on the hygroscopicity of RW-, freeze-, drum- and spray-dried mango powders as earlier discussed.

3.5. Microstructure

Scanning electron micrographic studies of mango powders (180–250 μm) obtained by different drying processes are shown in Figs. 8–10. The microstructure of RW-dried mango powder

was smooth, and flaky with uniform thickness (Fig. 8a and b). The uniformity of the flake thickness was the result of a controlled feeding of mango puree using a spreader bar at the inlet section of the RW dryer. During drying, the thinly spread mango puree on the surface of the plastic film conveyor is undisturbed, except for removal of moisture, as it moves toward the other end of the dryer, hence producing a continuous sheet with thickness nearly equal. Crushing the RW-dried mango flakes into powder form produced irregularly shaped particles while maintaining its thickness. The two sides of a single particle were smooth indicating more flowability and less susceptibility to oxidation because of lesser surface area. Freeze-dried mango powder (Fig. 8c and d), showed a skeletal-like structure and was more porous than the other mango powders. This result happens because the ice in the material during freeze drying helps prevent shrinkage and collapse of the structure and shape resulting in an insignificant change in volume (Ratti, 2001). The microstructure of drum-dried mango powder (Fig. 8e and f) was compact and exhibited irregular particles with sharp edges and considerable indentation as a result of crushing into powder. Caric and Kalab (1987) reported similar structure for drum-dried milk powder. They explained that the compactness of drum-dried milk powder was due to deaeration of raw milk during drum drying. It is also evident that the drum dried sheets are smooth on one side that is in direct contact with the drum surface, while visible corrugation and crinkle was observed on the other side. These observations are in agreement with the microstructure of drum-dried pre-gelatinized maize starches as described by Anastasiades et al. (2002). Spray-dried mango powder (Fig. 8g and h) has spherical or oval shape and smooth surface particles due to effect of spray-drying condition, which was maintained at inlet temperature of $190 \pm 2^\circ\text{C}$ during drying. Nijdam and Langrish (2005) demonstrated that milk powders spray-dried at inlet temperature of 200°C have spherical, smooth and larger particles, while particles were smaller and shriveled when the inlet temperature was reduced to 120°C . The smooth spherical-shaped mango powder contributed to its high porosity compared to the other three drying methods.

Individual particles of mango powders obtained from different drying processes were further examined (Fig. 9). The RW-dried mango powder clearly showed a composite sheet with distinguishable internal pores within the particle indicating that some emptied space during evaporation is not replaced as the mango puree

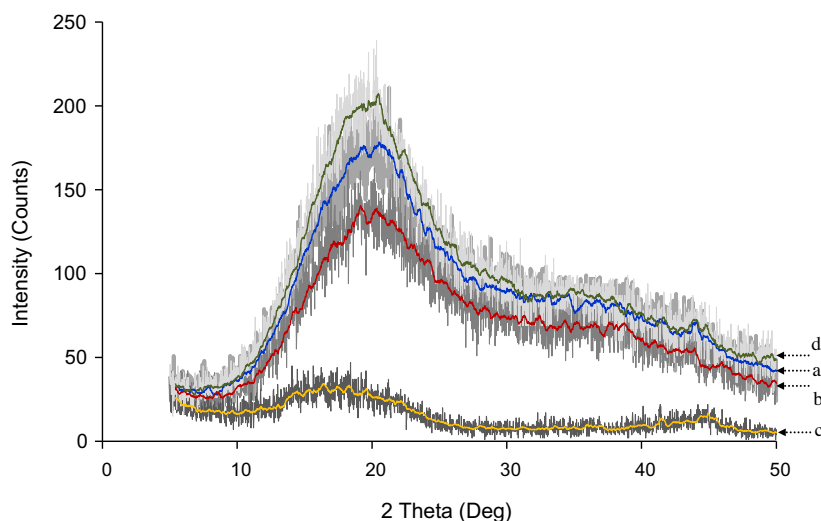


Fig. 7. X-ray diffraction patterns of Refractance Window®-dried (a), freeze-dried (b), drum-dried (c) and spray-dried (d) mango powders with particle size 180–250 μm and $a_w < 0.2$.

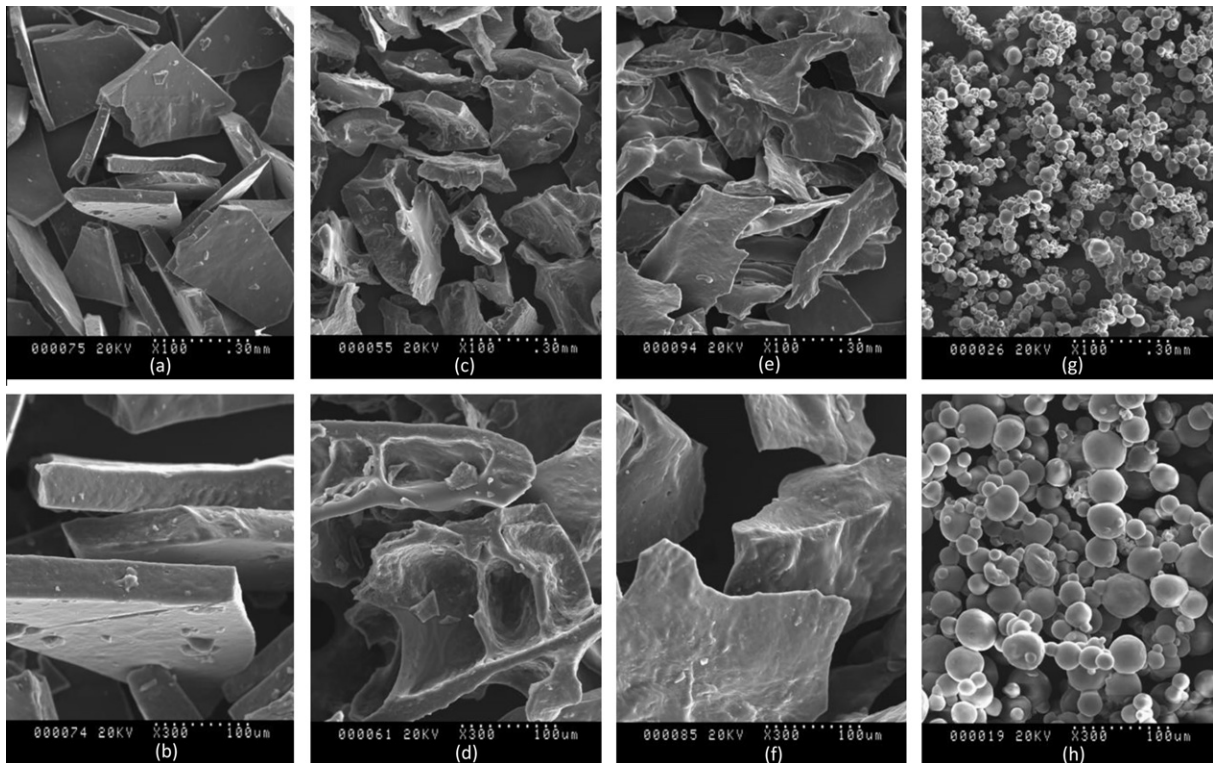


Fig. 8. Scanning electron micrographs (SEM) of mango powders (180–250 μm) dried using Refractance Window[®] drying (a and b), freeze drying (c and d), drum drying (e and f) and spray drying (g and h) (magnification of 100 \times (a, c, e and g) and 300 \times (b, d, f and h), 20 kV).

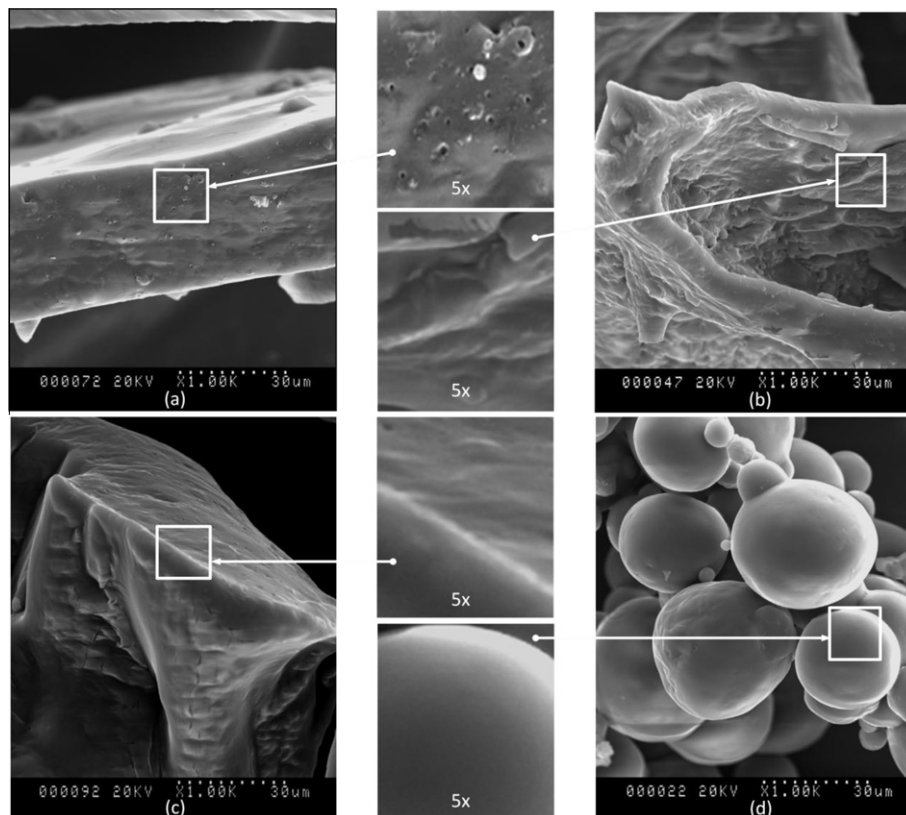


Fig. 9. Scanning electron micrographs (SEM) of individual mango powder particles (180–250 μm) dried using Refractance Window[®] drying (a), freeze drying (b), drum drying (c) and spray drying (d) (magnification of 1000 \times , 20 kV).

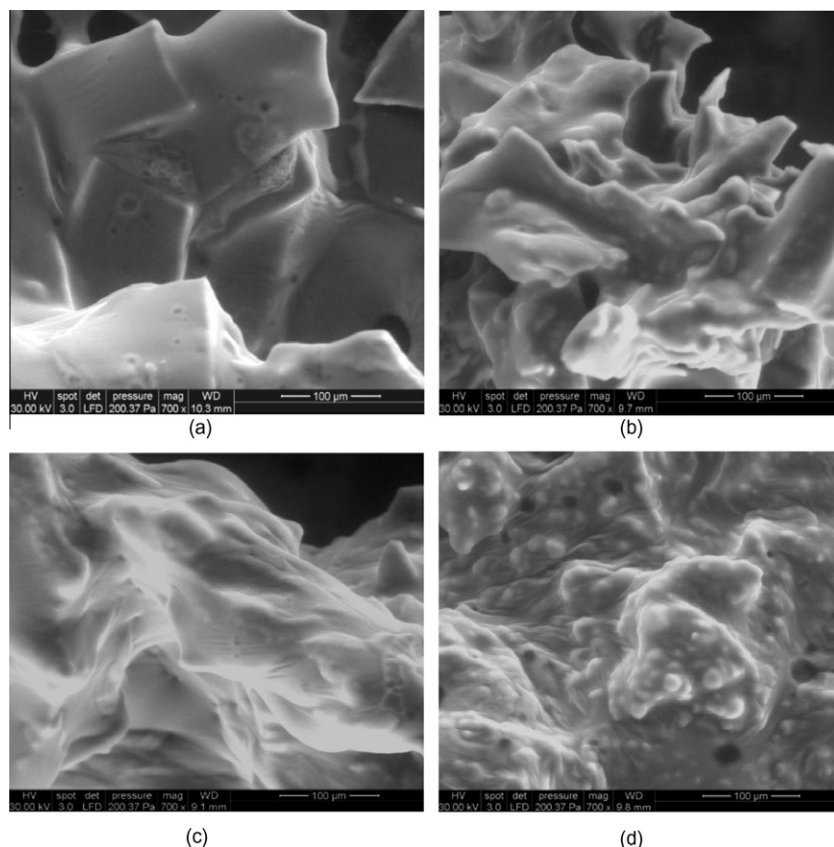


Fig. 10. Field emission scanning electron micrographs (FESEM) of Refractance Window[®]-dried (a), freeze-dried (b), drum-dried (c) and spray-dried (d) mango powders (180–250 µm) stored for 7 days at 25 °C with RH = 75.5% (magnification of 300×, 30 kV).

is dried. These pores might have contributed to the higher porosity of RW-dried compared to drum-dried mango powder. Drum-dried mango powder developed a fine particle surface allowing it to be more compact and rigid. Spray-dried mango powder particle showed a very fine and smooth surface, but it may not be indicative of being rigid and compact as it contains vacuoles forming a hollow spherical shape (Cai and Corke, 2000). Apparently, external pores were developed within the internal pores of a single particle freeze-dried mango powder. This further explains why the porosity of freeze-dried materials always is higher in comparison with other drying methods.

The microstructures of mango powders (180–25 µm) exposed at 23 °C for 7 days at high relative humidity (75.5%) showed different water adsorption behavior (Fig. 10). The particle surfaces and edges of RW- and freeze-, and spray-dried mango powders were still visible indicating that the materials adsorbed less when compared to drum-dried mango powder wherein its particles were nearly dissolved with water. This result confirmed the higher hygroscopicity value obtained for drum-dried mango powder compared to the other three powder products.

4. Conclusions

The physical properties and microstructures of mango powders were significantly affected by drying methods applied. Drying of mango puree to below 0.05 kg/kg dry mango solids was accomplished in 180 ± 0.15 , $111,600 \pm 5100$ and 54 ± 0.2 s for RW, FD and SD, respectively, and less than 3 s with SD. The color of drum-dried mango powder was severely degraded because of high processing temperature, while the spray-dried powder became lighter due to the addition of maltodextrin. On the other hand, the color of RW- and freeze-dried mango powder was comparable

at different particle sizes. The reconstituted RW-dried mango puree showed a slight deviation in comparison with the original puree and was very close to reconstituted freeze-dried mango puree. Reconstituted drum- and spray-dried mango puree suffered discoloration and were respectively darker and lighter than the original puree. Both the drum- and RW-dried mango powders were significantly denser compared to freeze- and spray-dried. Regardless of the particle size and shape, freeze-dried mango powder had the highest bulk porosity compared to the other three drying methods. Drum-dried mango powder was the most hygroscopic while spray-dried was the least hygroscopic. There was no significant difference in hygroscopicity and solubility between RW and freeze-dried material. The glass transition temperatures of RW-, freeze-, drum- and spray-dried powders were not significantly different at water activity just below 0.2. The X-ray diffraction patterns of RW-, freeze-, drum- and spray-dried mango powders ($a_w < 0.2$) clearly exhibited amorphous characteristics and showed no crystalline peak formation. The microstructure analysis verified the variations in bulk density, porosity, solubility and hygroscopicity of mango powders. Also, the microstructures of individual particles played an important role in analyzing the physical properties of mango powders. Overall, our study concludes that the RW drying method can produce superior quality mango powder compared to drum and spray drying, while it is highly comparable to freeze drying. The study provides an opportunity to the powder processing industry in selecting a better drying technique that can be utilized for the manufacture of high quality mango powder.

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References

- Abonyi, B.I., Feng, B.I., Edwards, C.G., Tang, J., 2002. Quality retention in strawberry and carrot purees dried with Refractance Window system. *Journal of Food Science* 67, 1051–1056.
- Adhikari, B., Howes, T., Bhandari, B., Langrish, T.G., 2009a. Effect of addition of proteins on the production of amorphous sucrose powder through spray drying. *Journal of Food Engineering* 94 (2), 144–153.
- Adhikari, B., Howes, T., Wood, B.J., Bhandari, B.R., 2009b. The effect of low molecular weight surfactants and proteins on surface stickiness of sucrose during powder formation through spray drying. *Journal of Food Engineering* 94, 135–143.
- Ahmed, M., Akter, M.S., Eun, J.-B., 2010. Impact of alpha-amylase and maltodextrin on physicochemical, functional and antioxidant capacity of spray-dried purple sweet potato flour. *Journal of Food Agriculture* 90, 494–502.
- Ameny, M.A., Wilson, P.W., 1997. Relationship between hunter color values and β -carotene contents in white-fleshed African sweet potatoes (*Ipomoea batatas* Lam.). *Journal of the Science of Food and Agriculture* 73, 301–306.
- Anastasiades, A., Thanou, S., Loulis, D., Staporis, A., Karapantsios, T.D., 2002. Rheological and physical characterization of pregelatinized maize starches. *Journal of Food Engineering* 52, 57–66.
- AOAC, 1998. Official Methods of Analysis. Association of Official Analytical Chemists, Washington, DC, USA.
- Barbosa-Cánovas, G.V., 1996. Dehydration of Foods. Chapman and Hall, New York.
- Barbosa-Cánovas, G.V., Ortega-Rivas, E., Juliano, P., Yan, H., 2005. Food Powders: Physical Properties, Processing, and Functionality. Kluwer Academic/Plenum Publishers, New York.
- BAS, 2009. Situation Report on Selected Fruit Crops. Retrieved March 1, 2011, from <<http://www.bas.gov.ph>>.
- Bhandari, B.R., Datta, N., Howes, T., 1997a. Problems associated with spray drying of sugar-rich foods. *Drying Technology* 15 (2), 671–684.
- Bhandari, B.R., Datta, N., Crooks, R., Howes, T., Rigby, S., 1997b. A semi-empirical approach to optimize the quantity of drying aids required to spray dry sugar-rich foods. *Drying Technology* 15 (10), 2509–2525.
- Cai, Y.Z., Corke, H., 2000. Production and properties of spray-dried amaranthus betacyanin pigments. *Journal of Food Science* 65 (6), 1248–1252.
- Cano-Chauca, M., Stringheta, P.C., Ramos, A.M., Cal-Vidal, C., 2005. Effect of the carriers on the microstructure of mango powder obtained by spray drying and its functional characterization. *Innovative Food Science and Emerging Technologies* 6, 420–428.
- Caparino, O.A., 2000. Characteristics and quality of freeze-dried mango powder pre-frozen at different temperatures. *Philippine Agricultural Scientist Journal* 83 (4), 338–343.
- Caric, M., Kalab, M., 1987. Effects of drying techniques on milk powder quality and microstructure: a review. *Food Microstructure* 6, 171–180.
- Chen, X.D., Patel, K.C., 2008. Manufacturing better quality food powders from spray drying and subsequent treatments. *Drying Technology* 26, 1313–1318.
- Desai, K.G., Park, H.J., 2004. Solubility studies of valdecoxib in the presence of carriers, co-solvent and surfactants. *Drug Development Research* 62, 41–48.
- Desobry, S.A., Netto, F.M., Labuza, T.P., 1997. Comparison of spray-drying, drum-drying and freeze-drying for β -carotene encapsulation and preservation. *Journal of Food Science* 62 (6), 1158–1162.
- Duffie, J., Marshall, W., 1953. Factors influencing the properties of spray-dried materials. *Chemical Engineering and Processing* 49, 417–423.
- Dziezak, 1988. Microencapsulation and encapsulated ingredients. *Food Technology* 42, 136–148.
- Eastman, J.E., Moore, C.O., 1984. Cold Water Soluble Granular Starch for Gelled Food Composition. U.S. Patent 4465702.
- Evans, E.A., 2008. Recent Trends in World and US Mango Production Trade, and Consumption. University of Florida. Food and Resource Economics Department, Gainesville, Florida.
- FAO, 2007. FAOSTAT Database Collections, Agricultural Data, Food and Agriculture Organization of the United Nations. Retrieved 10.03.11, from <<http://www.faostat.org>>.
- Figiel, A., 2010. Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. *Journal of Food Engineering* 98, 461–470.
- Filkova, I., Mujumdar, A.S., 1995. Industrial spray drying systems. In: Mujumdar, A.S. (Ed.), *Handbook of Industrial Drying*. Marcel Dekker, New York, pp. 263–307.
- Gavrielidou, M.A., Vallous, N.A., Karapantsios, T.D., Raphaelides, S.N., 2002. Heat transport to a starch slurry gelatinizing between the drums of a double drum dryer. *Journal of Food Engineering* 54, 45–58.
- Gonzalez-Aguilar, G.A., Zavaleta-Gatica, R., Tiznado-Hernandez, M., 2007. Improving postharvest quality of mango 'Haden' by UV-C treatment. *Postharvest Biology and Technology* 45, 108–116.
- Goula, A.M., Adamopoulos, K.G., 2008. Effect of maltodextrin addition during spray drying of tomato pulp in dehumidified air: II. Powder properties. *Drying Journal* 26, 726–737.
- Haque, M., Roos, Y., 2005. Crystallization and X-ray diffraction of spray-dried and freeze-dried amorphous lactose. *Carbohydrate Research* 340, 293–301.
- Harnkarnsujarit, N., Charoenrein, S., 2011. Effect of water activity on sugar crystallization and beta-carotene stability of freeze-dried mango powder. *Journal of Food Engineering* 105, 592–598.
- Hsu, C.L., Chen, W., Weng, Y.M., Tseng, C.Y., 2003. Chemical composition, physical properties, and antioxidant activities of yam flours as affected by different drying methods. *Food Chemistry* 83, 85–92.
- Jakubczyk, E., Ostrowska-Ligeza, E., Gonde, E., 2010. Moisture sorption characteristics and glass transition temperature apple puree powder. *International Journal of Food Science and Technology* 45, 2515–2523.
- Jaya, S., Das, H., 2004. Effect of maltodextrin, glycerol monostearate and tricalcium phosphate on vacuum dried mango powder properties. *Journal of Food Engineering* 63, 125–134.
- Jaya, S., Das, H., Mani, S., 2006. Optimization of maltodextrin and tricalcium phosphate for producing vacuum dried mango powder. *International Journal of Food Properties* 9, 13–24.
- Jayasundera, M., Adhikari, B., Adhikari, R., Aldred, P., 2011a. The effect of protein types and low molecular weight surfactants on spray drying of sugar-rich foods. *Food Hydrocolloids* 25 (3), 459–469.
- Jayasundera, M., Adhikari, B., Adhikari, R., Aldred, P., 2011b. The effects of proteins and low molecular weight surfactants on spray drying of model sugar-rich foods: powder production and characterisation. *Journal of Food Engineering* 104 (2), 259–271.
- Jayasundera, M., Adhikari, B., Howes, T., Aldred, P., 2011c. Surface protein coverage and its implications on spray-drying of model sugar-rich foods: solubility, powder production and characterisation. *Food Chemistry* 128 (4), 003–1016.
- Kalogiannia, E.P., Xynogalos, V.A., Karapantsios, T.D., Kostoglou, M., 2002. Effect of Feed Concentration on the Production of Pregelatinized Starch in a Double Drum Dryer. Elsevier Science Ltd.
- Karel, M., 1975. Freeze dehydration of foods. In: Karel, M., Fennema, O.R., Lund, D.B. (Eds.), *Principles of Food Science*. Marcel Dekker, Inc., New York, pp. 359–395.
- Kha, T.C., Nguyen, M.H., Roach, P.D., 2010. Effects of spray drying conditions on the physicochemical and antioxidant properties of the Gac (*Momordica cochinchinensis*) fruit aril powder. *Journal of Food Engineering* 98, 385–392.
- Kim, E.H.-J., Chen, X.D., Pearce, D., 2009. Surface composition of industrial spray-dried milk powders. 2. Effects of spray drying conditions on the surface composition. *Journal of Food Engineering* 94, 169–181.
- Krokida, M.K., Maroulis, Z.B., 1997. Effect of drying method on shrinkage and porosity. *Drying Technology* 15 (10), 2441–2458.
- Krokida, M.K., Maroulis, Z.B., Saravacos, G.D., 2001. The effect of the method of drying on the color of dehydrated products. *International Journal of Food Science and Technology* 36, 53–59.
- Masters, K., 1985. *Spray Drying Handbook*, fourth ed. Godwin, London.
- Moore, J.G., 2005. Drum dryers. In: Mujumdar, A.S. (Ed.), *Handbook of Industrial Drying*, vol. 1, second ed., Marcel Dekker, New York, pp. 249–262.
- Mujumdar, A.S., 2007. *Handbook of Industrial Drying*, third ed. Taylor and Francis Group, CRC Press, Florida.
- Niamnuy, C., Nachaisin, M., Laohavanich, J., Devahastin, S., 2011. Evaluation of bioactive compounds and bioactivities of soybean dried by different methods and conditions. *Food Chemistry*, 899–906.
- Nijdam, J.J., Langrish, T.A., 2005. An investigation of milk powders produced by a laboratory-scale spray dryer. *Drying Technology* 23 (5), 1049–1056.
- Nindo, C.I., Tang, J., 2007. Refractance Window dehydration technology: a novel contact drying method. *Drying Technology* 25, 37–48.
- Nindo, C.I., Sun, T., Wang, S.W., Tang, J., Powers, J.R., 2003. Evaluation of drying technologies for retention of physical and chemical quality of green asparagus (*Asparagus officinalis*, L.). *Food Sci. Technol. (LWT)* 36 (5), 507–516.
- Oetjen, G.W., Haseley, P., 2004. *Freeze-drying*, second ed. Wiley-VCH GmbH & Co. KGaA, Germany.
- Potter, N.N., Hotchkiss, J.H., 1995. *Food Science*, fifth ed. Springer, New York.
- Rajkumar, P., Kailappan, R., Viswanathan, R., Raghavan, G.S., Ratti, C., 2007. Foam mat drying of Alfonso mango pulp. *Drying Technology* 25, 357–365.
- Ratti, C., 2001. Hot air and freeze-drying of high-value foods – a review. *Journal of Food Engineering* 49, 311–319.
- Rodríguez-Hernández, G.R., Gonzalez-Garcia, R., Grajales-Lagunes, A., Ruiz-Cabrera, M.A., 2005. Spray-drying of cactus pear juice (*Opuntia streptacantha*): effect on the physicochemical properties of powder and reconstituted product. *Drying Technology* 4, 955–973.
- Sablani, S.S., Shrestha, A.K., Bhandari, B.R., 2008. A new method of producing date powder granules: physicochemical characteristics of powder. *Journal of Food Engineering* 87 (3), 416–421.
- Saravacos, G.D., Kostaropoulos, A.E., 2002. *Handbook of Food Processing Equipment*. Kluwer Academic/Plenum Publishers, New York.
- Serrano, E.P., 2005. Postharvest management of fruit and vegetables in the Asia-Pacific region: Philippines country report. Asian Productivity Organization

- (APO); Food and Agriculture Organization of the United Nations (FAO). APO and FAO, Japan, Rome, pp. 216–226.
- Shrestha, A.K., Ua-arak, T., Adhikari, B.R., Howes, T., Bhandari, B.R., 2007. Glass transition behavior of spray-dried orange juice powder measures by differential scanning calorimetry (DSC) and thermal mechanical compression test (TMCT). *International Journal of Food Properties* 10, 661–673.
- Syamaladevi, R.M., Sablani, S.S., Tang, J., Powers, J., Swanson, B.G., 2009. State diagram and water adsorption isotherm of raspberry (*Rubus idaeus*). *Journal of Food Engineering*, 460–467.
- Toledo, R., 2007. *Fundamentals of Food Process Engineering*, 3rd ed. Aspen Publishers, Inc., Athens, GA, USA.
- Tonon, V.R., Brabet, C., Hubinger, M.D., 2008. Influence of process conditions on the physicochemical properties of acai (*Euterpe oleraceae* Mart.) powder produced by spray drying. *Journal of Food Engineering* 88, 411–418.
- Wagner, L.A., Warthesen, J.J., 1995. Stability of spray-dried encapsulated carrot carotenes. *Journal of Food Science* 60, 1048–1053.
- Wang, S., Konkol, E., Langrish, T.G., 2011. Spray drying of fruit juice using proteins as additives. *Drying Technology* 29 (16), 1868–1875.
- Xiaoyan, Z.Y., 2008. Effect of superfine grinding on properties of ginger powder. *Journal of Food Engineering* 91 (2), 217–222.