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Performance and mechanism of an innovative humidity-controlled hot-air drying method for concentrated starch gels: A case of sweet potato starch noodles

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ABSTRACT

The effects of humidity control on dried starch gels were investigated using starch noodles as a model. A two-stage innovative hot-air-drying regime was developed with the first stage humidity-controlled (70 °C, 60% RH) and the second at high temperature (100 °C). The proposed drying method is comparable to natural-air-drying in product quality and to conventional hot-air-drying (70 °C) in production efficiency. The operating humidity of the first stage predominated the swelling index and rehydration ratio of dry noodles as well as the hardness and chewiness of cooked noodles. The results from XRD, DSC, SEM, digital microscopy and low field TD ^{1}H NMR evidenced that these outcomes were largely ascribed to the higher shrinkage, lower porosity, smoother surface, lesser shape deformation and higher starch retrogradation resulting from increased humidity. The results reported herein are valuable for regulating the physicochemical properties of dried starch gels and glimpsing the underlying mechanisms of related operations.

1. Introduction

Starch granules undergo irreversible swelling, amylose leaching and total disruption upon heating in excess water above their specified temperatures, especially with the application of shear forces. This process is defined as gelatinization and results in a viscous paste consisting of a continuous phase of dispersed amylose and/or amylopectin molecules and a discontinuous phase of granular ghosts (Xie, Hu, Jin, Xu, & Chen, 2014). The resulting starch paste exists in a metastable nonequilibrium state and undergoes structural transformations upon cooling, eventually forming an interconnected three-dimensional network. This process is called gelation and intrinsically involves starch retrogradation. In the presence of a high starch concentration, the paste will form an elastic gel after cooling. Commonly, the newly prepared hot starch pastes or elastic gels thereof could be served straightaway in the forms of soup, jelly and pudding (Qasem et al., 2017). To preserve them and facilitate their distribution, the starch gel products are often dried and then rehydrated prior to consumption by soaking or cooking.

Starch noodles, or vermicelli, are definitely the most popular food in the form of dried starch gels, and they are one of the favorite traditional staple foods commonly consumed in Asia, especially in Korea, Vietnam and China (Tan, Li, & Tan, 2009). Unlike wheat flour-based noodles, starch noodles are made from isolated starch rather than flour. Traditionally, starch noodles are produced via a dropping method mainly consisting of five steps, including forming a starch dough, dropping the dough to form noodles, cooking, cooling and drying (Supplementary material 1) (Tan et al., 2009). Usually, a water content up to 50 g/100 g wb in the starch dough is necessary. In this scenario, the starch in the noodles is gelatinized upon cooking and forms concentrated elastic gels after cooling. However, the starch gel is in a metastable nonequilibrium system in the initial paste. It undergoes several structural changes during drying, such as shrinkage and crystallization. Previous studies have revealed that these structural changes heavily depend on the operating parameters of the drying process and ultimately affect the edible performance of the rehydrated products, although the products under consideration were not from isolated starches but flours (Ficco et al., 2016).

In the drying process, moisture is largely removed from the starch gel, which furthers the starch retrogradation and stabilizes the product structure (Padalino, Caliandro, Chita, & Conte, 2016). To this end, various drying approaches have been employed in the drying of starch noodles, such as natural air-drying (NAD) (Tsakama, Mwangwela, & Kosamu, 2013) and hot-air-drying (HAD) (Hoover, Li, Hynes, & Senanayake, 1997). As the most traditional method, NAD results in

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lower cost and higher product quality, but it is weather-dependent, less controlled in term of product quality and inefficient. Therefore, in the modern food industry HAD was widely adopted due to its superior production efficiency and product quality constancy compared to NAD. However, the product quality from HAD is inferior to that from NAD (Zhang, Huang, Liu, & Chen, 1998). Previous studies found that hot air drying especially high temperature had a great impact on the quality of starch noodles, although it can meet the relevant standards for water demand. In general, the improper higher temperature certainly deteriorated the quality of starch noodles, such as the generation of cracks or chaps (Ogawa & Adachi, 2017). Furthermore, the findings of Kaushal and Sharma (2013) uncovered that, compared with drying at 50 °C, 60 °C and 70 °C, the drying at 80 °C is less desirable in terms of the quality of starch noodles.

Broadly speaking, the drying of starch noodles, in effect, is an example drying process for concentrated starch gels. Despite the wide research on the drying of starch-rich foods (Zhao et al., 2017) and the gels from other hydrocolloids (Marín, Alemán, Sánchez-Faure, & Gomez-Guillen, 2018), few studies have addressed the drying of starch gels. Thus, the mechanism underlying the quality inferiority of HAD compared to NAD in the drying of starch gels has not been adequately explored and remains unknown. Combining experience and science, it is hypothesized that, besides the temperature, the humidity of hot air is crucial in determining the edible performance of dried starch gels. In detail, by controlling the relative humidity (RH) of the hot air, products from HAD could be comparable in quality to those from NAD. However, to the best of our knowledge, this hypothesis has not been proven by far. Therefore, the effects and mechanism of RH control in the HAD drying performance were investigated using sweet potato starch noodles as a model.

2. Materials and methods

2.1. Materials

Sweet potato starch was provided by Chongqing Jintian Agricultural Group Co. Ltd. (Chongqing, China) with a proximate composition of moisture (13.0 g/100 g), total starch (92.7 g/100 g db), amylose (26.6 g/100 g db), amylopectin (66.1 g/100 g db), protein (0.2 g/100 g db), crude fat (1.0 g/100 g db) and ash (0.5 g/100 g db).

2.2. Starch noodles preparation

Starch noodles were prepared according to the method described by Tan, Gu, Zhou, Wu, and Xie (2006) with some modifications. In brief, an aliquot of starch (10 g, db) was mixed with 85 g of warm water (approximately 30 °C) in a stainless-steel cup and then heated in a boiling water bath with continuous manual stirring for 90 s to produce a starch paste. The resultant paste was transferred into the steel bowl of an HM740 dough mixer (Qingdaohanshang, Shangdong, China) containing 190 g (db) starch. The dough mixer was operated at 150 r/min, and the stirring was continued for 15 min. In the first 5 min of stirring, warm water (75 g) was added gradually. Then, the obtained dough was transferred into a steel gourd (i.d. 2.5 cm) with holes in its bottom, which was installed above a boiling water bath at a height of 35 cm. With a palm flap, the dough was evenly and continuously flowed through the gourd holes to form starch noodles which were vertically dropped into the boiling water. After a cooking time of 20 s, the starch noodles were pulled from the boiling water bath and immediately immersed into tap water to be cooled for at least 5 min. The cooled noodle strips with moisture contents approximately 68 g/100 g db were harvested, the surface water was drained, and the noodles were hung on a steel bar with both ends descending along the two sides of the bar. After storage at 4 °C for 24 h, the noodles with moisture contents approximately 63 g/100 g db were subjected to drying to achieve a final moisture content approximately 12 g/100 g db. An oven equipped with a GH-816 ultrasonic humidifier (Zhongshan, China) was used for drying. For HAD, the humidifier was shut off, while, for humidity controlled hot air drying (HHAD), the relative humidity (± 5% RH) was controlled by adjusting the fog supply form the humidifier. The RH of the room atmosphere was determined to be 73%. The final moisture content of the starch noodles was determined by drying them in an oven at 105 °C until a constant weight was achieved (AACC, 2010).

2.3. Evaluation of the edible performance of starch noodles

2.3.1. Determination of cooking performance

The cooking performance, in terms of cooking loss, swelling index and rehydration ratio, of the starch noodles was evaluated by following a previously described procedure with minor modifications (Wang et al., 2014). Starch noodles (M_0, 3.0 g db) were cooked in 200 mL of boiling water for 15 min with slight agitation. The cooked starch noodles were harvested with chopsticks, drained with filter paper to remove surface water and weighed (M_1, g) immediately. Then, the cooked noodles were dried at 105 °C to a constant weight (M_2, g). The cooking loss (%), swelling index (%) and rehydration ratio (%) were calculated by $(M_0 - M_2)/M_0 \times 100$, $M_1/M_2 \times 100$ and $(M_1 - M_0)/M_0 \times 100$, respectively.

2.3.2. Determination of chewing performance

To determine the chewing performance, the cooked starch noodles were subjected to further testing. Starch noodles were cooked in boiling water for 15 min, cooled in running water for 1 min, drained with filter paper to remove surface water, and immediately subjected to texture analysis using a CT3 texture analyzer (Brookfield, USA). The test was conducted according to the method by Zhou et al. (2013) with some modifications. Noodles with a length of 10 cm were used and, for each sample, three strands were placed in parallel on a flat metal plate with 1 cm of space between neighboring strands. They were compressed twice to 45% of their original height using a TA4/1000 probe at a speed of 1 mm/s. The trigger force was set as 4.0 g and the textural parameters of hardness, elasticity and chewiness were reported as the mean of seven determinations for each sample.

2.4. Instrumental characterization of starch noodles

2.4.1. X-ray diffraction (XRD)

X-ray diffractograms of the starch noodles were recorded using an X'Pert3 Powder10300 X-ray diffractometer (PANalytical, Holland). The samples were ground and passed through a 200-mesh sieve. The diffractometer was operated at 40 kV and 40 mA, and the sample was scanned from 4° to 40° at a speed of 2°/min. The relative crystallinity (%) was defined as the percentage of the crystalline area relative to the total diffraction area (Wang et al., 2007).

2.4.2. Differential scanning calorimeter (DSC)

DSC thermograms of the starch noodles were recorded using a Q2000 differential scanning calorimeter (TA Instruments, Norwalk, USA). Starch noodles were ground and passed through a 100-mesh sieve. An aliquot of the resultant powder (4.0 mg, db) was accurately weighed into an aluminum pan, and distilled water (8.0 μL) was added with the aid of a micro-syringe. Then, the pan was tightly sealed and kept at room temperature for 24 h to achieve a complete equilibrium. With an empty pan as a reference, the sample was scanned across the temperature range of 30 °C–105 °C with a heating rate of 10 °C/min. The gelatinization temperatures of the retrograded starch in the starch noodles were reported as the onset temperature (T_o), peak temperature (T_p) and conclusion temperature (T_c). The gelatinization enthalpy (ΔH) was estimated by integrating the area between the thermogram and the baseline under the peak and expressed in J/g.