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Mass transport processes in orange-fleshed sweet potatoes leading to structural changes during in vitro gastric digestion

Yamile A. Mennah-Govela, Gail M. Bornhorst*

Dept. of Biological and Agricultural Engineering, 1329 Bainer Hall, University of California, Davis, 1 Shields Avenue, Davis, CA, 95616, United States

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ABSTRACT

During cooking, food undergoes structural modifications, which may impact its behavior during digestion. The objective of this study was to determine the macro- and micro-structural changes, moisture uptake, and acid uptake into sweet potatoes during simulated gastric digestion as influenced by cooking method. Sweet potatoes were cut and cooked (boiled, steamed, microwave steamed or fried), followed by in vitro gastric digestion (up to 240 min). Acidity, moisture content, and hardness were measured during the digestion period. Light microscopy was completed on cooked and digested samples to observe microstructural changes. Effective diffusivity of acid and moisture was modeled following Fick's second law in MATLAB. Acid and moisture uptake were significantly influenced by cooking method and digestion time ($p < 0.0001$). Hardness was significantly influenced by cooking method, digestion time, and their interaction ($p < 0.0001$). Microstructural changes were observed both as a result of cooking and after in vitro gastric digestion.

1. Introduction

Orange fleshed sweet potatoes (referred to sweet potatoes, *Ipomoea batatas* L.) are nutritious tubers, rich in carbohydrates and dietary fiber, vitamins, minerals, and antioxidants, such as β-carotene (Burri, 2011; Teow et al., 2007). Orange fleshed sweet potatoes can be cooked many different ways prior to consumption, such as boiled, steamed, roasted, deep fried, baked, and microwaved (Bengtsson et al., 2008; Burri, 2011). These cooking methods involve differing mechanisms of heat transfer and environmental conditions (i.e. cooking in air vs. water vs. steam), which may result in varying microstructural changes in the food matrix depending on the cooking method (Aguilera, 2005; Parada and Aguilera, 2007). These structural changes may also influence nutrient absorption, as it has been shown that structural changes induced by processing and thermal treatments influence β-carotene bioaccessibility in carrots and sweet potatoes (Bengtsson et al., 2009; Tumuhimbise et al., 2009; Tydeman et al., 2010).

During digestion, the first physical change is in the mouth; ingested food is broken down and mixed with saliva during mastication, forming a bolus. When the food particles reach a certain size they are transported through the esophagus to the stomach, where gastric digestion occurs. During gastric digestion, mechanical and chemical breakdown occur due to both stomach contractions and gastric secretions, respectively (Bornhorst and Singh, 2014). Gastric secretions contain enzymes (i.e. pepsin and lipase), electrolytes (i.e. sodium chloride), and are acidic (pH ≈ 2). These characteristics of the gastric fluid modify the food structure due to enzymatic and acid hydrolysis, resulting in softening of the food matrix. The rate of diffusion of gastric fluids into food matrices in the gastric environment may have implications in the overall gastric breakdown as well as absorption of nutrients in the small intestine. Aside from the digestion fluid composition, there are other factors that may influence the gastric acid diffusion rate, which include food composition, food properties, and processing of food, among other factors (Mennah-Govela et al., 2015).

It has been previously shown that there is a link between acid diffusion and food softening in canning, curing, and pickling processing of foods. Softening in foods occurs when the pectic material in the plant cell wall is hydrolyzed or broken down (Demain and Phaff, 1957). It has been demonstrated that pH and temperature are some of the factors that may influence cell wall hydrolysis (Krall and McFeeters, 1998; McFeeters and Fleming, 1989, 1990). Depending on the type of acid, the rate of softening may be faster or may prevent the tissue from softening. For example brine

* Corresponding author. 3056 Bainer Hall, Biological and Agricultural Engineering, University of California, Davis, Davis, CA, 95616, United States.
E-mail address: gbornhorst@ucdavis.edu (G.M. Bornhorst).

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containing gluconic acid helped retained texture in carrots (Heil and McCarthy, 1989), compared to brine containing acetic acid, which was shown to facilitate the softening of cucumbers (McFeeters et al., 1995). Additionally, previous studies have shown that the addition of salts, i.e. sodium chloride, may interact as a firming agent preventing the softening of the plant tissue (Gabaldón-Leyva et al., 2007; Heil and McCarthy, 1989; Howard et al., 1994; McFeeters and Fleming, 1991; Widjaja, 2010).

Food softening during digestion may be correlated to the food breakdown rate as well as the gastric emptying rate. These two processes are associated with transport to the small intestine, meaning that rate of food softening during gastric digestion may influence absorption of nutrients (Bornhorst et al., 2015). Previous studies have shown that in order for nutrients to be absorbed by the small intestine, they have to be released from the cell wall. The disruption of cell walls occurring as a result of processing or during gastric digestion (Failla et al., 2009; Lemmens et al., 2010; Parada and Aguilera, 2007; Van Buggenhout et al., 2010).

It was hypothesized that the cooking methods examined (boiling, steaming, frying, and microwave steaming) would induce structural changes in sweet potatoes, which would modify their uptake of acid and water as well as their propensity for additional structural changes during simulated gastric digestion.

2. Materials & methods

2.1. Raw materials

Sweet potatoes were purchased from a local supermarket (Lansing, MI, U.S.A.), and stored at 4 °C for use within 4 weeks.

2.2. Sweet potato cooking procedure

Sweet potatoes were cut into cubes (approx. 0.012 × 0.012 × 0.012 m) by first using a potato cutter to obtain long strips and followed by manually cutting each strip into cubes of uniform size. Samples were taken only from the interior of the sweet potatoes, and any pieces containing peel were discarded.

The cooking methods selected were boiling, steaming, microwave steaming, and frying. The total cooking time for each method was selected based on preliminary trials to ensure similar hardness after cooking (data not shown). For all cooking methods, 20 cubes were cooked together in one batch to ensure comparable sample heating conditions for each experiment. For boiled sweet potatoes, cubes were immersed in boiling water (100 °C) for 15 min. For steamed sweet potatoes, cubes were put in a metal steamer that was placed above a pot of with boiling water. Cubes were heated with the lid on the pot for 20 min. For microwave steamed sweet potatoes, cubes were placed in the top compartment of a microwave steamer and were cooked for 8 min and kept covered for an additional 2 min. For fried sweet potatoes, cubes were fried in soybean oil (Meijer Inc., Grand Rapids, MI, U.S.A.) at 180 °C for 5 min. In all cooking methods, with the exception of microwave steamed, a thermocouple was kept inside one cube during cooking to record the temperature profile (data not shown) over time to ensure similar cooking conditions for each batch.

2.3. Volume change after cooking

Sweet potato volume was measured using a 5000S electronic digital caliper (Chicago Brand, Medford, OR, U.S.A.). Three sides of the cubes were measured before and after cooking times to estimate the volume. Ten cubes were measured before and after cooking for each cooking method.

2.4. Simulated digestion

2.4.1. Simulated saliva formulation

Saliva was prepared following Bornhorst and Singh (2013). All components were mixed in deionized water: mucin (1 g/L, Sigma-Aldrich, MO, U.S.A.), α-amylase (from *Bacillus subtilis*, 1.18 g/L, MP Biomedicals, Catalog Number 100447, activity of 160,000 BAU/g, Santa Ana, CA, U.S.A.), NaCl (0.117 g/L, Avantor Performance Materials, PA, U.S.A.), KCl (0.149 g/L, Fisher Science Education, IL, U.S.A.), and $NaHCO_3$ (0.21 g/L, Fisher Science Education, IL, U.S.A.). After addition of all ingredients, the pH was adjusted to 7 with 0.01 N NaOH (Bornhorst and Singh, 2013).

2.4.2. Gastric juice formulation

Gastric juice was prepared by mixing the following ingredients in deionized water: mucin (1.5 g/L, Sigma-Aldrich, MO, U.S.A.), NaCl (8.78 g/L, Avantor Performance Materials, PA, U.S.A.), and pepsin from porcine pancreas (1.0 g/L, Sigma-Aldrich, MO, U.S.A.). After addition of all ingredients, the pH was adjusted to 1.8 using 0.1 N HCl (Bornhorst and Singh, 2013).

2.4.3. Oral and gastric digestion conditions

Oral and gastric digestion conditions were performed following Mennah-Govela and Bornhorst (in press) digestion model in a shaking water bath; which was slightly modified from previous studies (Bornhorst and Singh, 2013; Hedren et al., 2002; Mennah-Govela et al., 2015; Minekus et al., 2014). Ten sweet potato cubes (initial mass of 12–20 g, depending on the cooking method) were weighed, placed in a 250 mL glass bottle, and hand-mixed with 0.2 mL/g of saliva for 30 s. One bottle was used for each replicate of each digestion time. Immediately after mixing, 100 mL of preheated gastric juice at 37 °C was added to the bottle, and the bottles were placed inside a shaking water bath (37 °C, 100 rpm). Samples were taken after oral digestion (0.5 min) and after 15, 30, 45, 60, 90, 120, 180, and 240 min of gastric digestion. Sampling was conducted by removing an individual bottle from the shaking water bath and the 10 cubes were analyzed from that digestion time. After the samples were removed, the sweet potato cubes were separated from the gastric juice with a sieve. The cubes were weighed and both the sweet potato cubes and gastric juice were retained for further analysis. From the 10 sweet potato cubes in one digestion, 6 cubes were used for duplicate measurements of acidity (3 cubes per replicate) and 4 cubes were used for duplicate measurements of moisture content (2 cubes per replicate). Separate digestions were completed for both texture and fat content measurements. Simulated digestions were performed in triplicate for each cooking method and digestion time point.

2.5. Sweet potato behavior during simulated gastric digestion

2.5.1. Acidity and pH measurement

Briefly, from the 6 cubes of the glass bottle, acidity measurements were done in duplicates, where 3 cubes (approx. 6 g) were weighed and homogenized with 20 mL of deionized water using a Polytron model PT 10/35 homogenizer (Brinkmann Instruments Co., Switzerland) for 30 s. The initial pH was measured using a HI 99161 portable pH meter (HANNA instruments, Woonsocket, RI, U.S.A.). Acidity measurements where completed via potentiometric titrations. Sodium hydroxide (0.01 N NaOH) was added to each sample until the pH reached a value of 8.2 ± 0.05.

2.5.2. Moisture content

The 4 cubes left in the glass bottle were used to determine duplicate measurements of moisture content. Moisture was determined gravimetrically by drying in a convection oven for