Food Research International 88 (2016) 247–255

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Acid and moisture uptake in steamed and boiled sweet potatoes and associated structural changes during in vitro gastric digestion

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ARTICLE INFO

Article history:
Received 1 August 2015
Received in revised form 5 December 2015
Accepted 10 December 2015
Available online 11 December 2015

Keywords:
Sweet potatoes
Effective diffusivity
Texture
Microstructure
Gastric digestion
In vitro

ABSTRACT

Orange-fleshed sweet potatoes are a good source of phytochemicals. For these nutrients to be absorbed, they must be released from the food matrix as a result of physical and chemical breakdown. A key factor in food breakdown is gastric acid diffusion into the matrix, and its influence on structural changes. Cooking treatment may influence mass transport properties and structural changes of foods during digestion. The objective of this study was to determine the acid and moisture uptake into sweet potatoes and its influence on macro- and microstructures during in vitro gastric digestion as a result of varying cooking treatments. Sweet potatoes were cut into cubes and cooked (boiled or steamed) for different times. In vitro oral and gastric digestions were simulated in a shaking water bath at 37 °C. Acidity, moisture content, and solid loss were measured after 9 digestion times (15 to 240 min). Hardness of individual cubes and microstructure (light microscopy) were completed before and after digestion. Effective diffusivity of acid and moisture into the cubes was estimated using MATLAB. Cooking method, cooking severity, and digestion time significantly influenced moisture uptake ($p < 0.0001$). Acid uptake was significantly influenced by digestion time ($p < 0.0001$). The change of softening after digestion was influenced by cooking method and severity ($p < 0.05$). Effective diffusivity of acid ranged from 0.03×10^{-10} (mild steamed) to 11.40×10^{-10} m^2/s (severely boiled). Percent texture decrease after digestion from the initial hardness ranged from 16% (severely steamed) to 34% (mild boiled). Textural changes were related to cell wall breakdown and starch degradation. In general, mass transport properties and macro- and microstructural changes were influenced by cooking treatment and gastric digestion. The link between food cooking and behavior during digestion is crucial in determining optimal food processing and cooking methods for specific food functional properties.

1. Introduction

Orange-fleshed sweet potatoes (referred to sweet potatoes, *Ipomoea batatas* L.) are a good source of dietary fiber, vitamins, and antioxidants, specifically β-carotene (Teow et al., 2007). Prior to consumption, sweet potatoes can be prepared in a variety of ways, including steaming, boiling, roasting, frying, or microwaving. It has been shown that carotenoids in sweet potatoes are well retained after thermal treatment (Burri, 2011). However, their bioaccessibility may vary depending on the food matrix, thermal process, and extent of gastric breakdown (Bengtsson, Brackmann, Enejder, Alminger, & Svanberg, 2010; Lemmens et al., 2014; Tumuhimbise, Namutebi, & Muyonga, 2009; Tydeman et al., 2010). The extent of gastric breakdown may be related to the release of carotenoids from the food matrix during gastric digestion, allowing them to be degraded. As such, a thorough understanding of the influence of processing and digestion conditions on cell wall degradation is crucial to understand carotenoid bioaccessibility and bioavailability in sweet potatoes and other similar food matrices.

Previous studies with sweet potatoes and carrots have shown that cooking or processing treatment (type of heating, heating temperature, heating time) influences the behavior of plant food matrices during digestion, affecting the release and absorption of nutrients (Bengtsson et al., 2010; Castenmiller, West, Linssen, van het Hof, & Voragen, 1999; Lemmens et al., 2014; Lemmens, Van Buggenhout, Van Loey, & Hendrickx, 2010; Tumuhimbise et al., 2009; Tydeman et al., 2010; Van Buggenhout et al., 2010). These studies have hypothesized that the food processing (thermal and mechanical) increases the nutritional value of the food due to cellular breakdown, since plant cell rupture is required for the carotene release and absorption. Quantification of cell wall breakage or damage in plant matrices, especially those saturated with liquid (i.e. gastrointestinal secretions), is not straightforward. Aside from microstructural imaging, it has also been shown that certain textural characteristics may be related to microstructural changes in white potatoes (Bordoloi, Kaur, & Singh, 2012).

A clear relationship between food processing/cooking method and severity (i.e. length of heat treatment) to food breakdown and nutrient

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http://dx.doi.org/10.1016/j.foodres.2015.12.012
0963-9969/

release during digestion has not been established. Several previous studies (Lemmens et al., 2010, 2014; Svelander, Lopez-Sanchez, Pudney, Schumm, & Alminger, 2011) suggested that breakdown of cellular structure is crucial for further nutrient release. The breakdown of the food cellular structure will be catalyzed by both physical forces (during mastication and gastric digestion), as well as uptake of acid and enzymes from gastrointestinal fluids (Parada & Aguilera, 2007). As such, it is crucial to understand how the cooking treatment influences the food properties, microstructure, and their evolution during gastric digestion.

The rate of both acid and moisture diffusion into the sweet potato bolus may have implications on the overall breakdown of the food (Mennah-Govela, Bornhorst, & Singh, 2015). The effective diffusivity of gastric acid into the food bolus might be an important parameter to help describe the gastric breakdown and behavior of the food during gastric digestion, and it has not been previously estimated in sweet potatoes. The cooking treatment may have an effect on the effective diffusivity of gastric acid, which may be due to the microstructural changes during both cooking and in vitro gastric digestion. The objectives of this study were to estimate the effective diffusivity of acid and water into boiled and steamed sweet potatoes with varying cooking severity and to determine the influence of these mass transport processes on macro- and micro-structural changes during in vitro gastric digestion.

2. Materials & methods

2.1. Raw materials

Sweet potatoes were acquired from a local grocery store (Lansing, MI, U.S.A.), and were stored at 4 °C for a maximum of 4 weeks.

2.2. Sweet potato cooking procedure

Sweet potatoes were cut into strips using a potato cutter, followed by cutting the strips into cubes (approximately 0.012 × 0.012 × 0.012 m) using a knife. Cubes were selected from the interior of the sweet potato; any strips containing peel were discarded. Even though the size selected is larger than what would typically be swallowed, it was chosen due to a lesser variation in acidity compared with smaller sized samples. As the objective of this study was to model and describe mass transport processes and their influence on structure, large enough samples were needed to be used to remain in a usable form (e.g. not completely broken down) during the 4 h digestion period. Additionally, the mechanisms described here will remain the same regardless of the cube size.

Sweet potatoes were either boiled or steamed for different times, resulting in a mild and severe heat treatment for each cooking method. The cooking times for the mild and severe heat treatment were based on previous trials to maintain similar hardness after cooking within the mild or severe heat treatments, regardless of cooking method (initial data not shown). For boiled sweet potatoes, cubes were cooked in boiling water (100 °C) for 6 or 20 min (mild and severe, respectively). For steamed sweet potatoes, cubes were placed in a metal steamer above a pot of boiling water and kept with the lid on for 8 or 30 min (mild and severe, respectively).

2.3. Volume change after cooking

Volume of sweet potato cubes was measured using an electronic digital caliper (Mitutoyo, Aurora, IL, U.S.A.), by measuring the length of three sides of the cube before and after cooking. Measurements were completed on ten cubes for each cooking method.

2.4. In vitro digestion

2.4.1. Simulated saliva and gastric fluid formulations

Oral and gastric digestion fluids were prepared following the procedure of Bornhorst and Singh (2013). Briefly, simulated saliva was made by mixing 1 g/L of mucin (Sigma-Aldrich, MO, U.S.A.), 1.8 g/L of α-amylase (from *Bacillus subtilis*, MP Biomedicals, catalog number 100447, activity of 160,000 BAU/g, Santa Ana, CA, U.S.A.), 0.117 g/L of NaCl (Avantor Performance Materials, PA, U.S.A.), 0.149 g/L of KCl (Fisher Science Education, IL, U.S.A.), and 2.10 g/L of $NaHCO_3$ (Fisher Science Education) with deionized water. The solution was adjusted to pH 7 using 0.01 N NaOH. Similarly, simulated gastric juice was made by mixing 1.5 g/L of mucin (Sigma-Aldrich, MO, U.S.A.), 8.78 g/L of NaCl (Avantor Performance Materials), and 1.0 g/L of pepsin from porcine pancreas (Sigma-Aldrich) with deionized water. The pH of the gastric juice solution was adjusted to 1.8 using 1 N HCl (Bornhorst & Singh, 2013).

2.4.2. Oral and gastric digestion conditions

To simulate both oral and gastric digestions, ten cooked sweet potato cubes were weighed (approx. 20 g), placed in a 250 mL beaker, and mixed for 30 s with simulated saliva (0.2 mL saliva/g sample) by gentle agitation. Immediately after mixing, 100 mL of gastric juice (previously heated to 37 °C) was added to the beaker, the beaker was covered, and it was placed in a shaking water bath (37 °C, 100 rpm) for up to 240 min. Samples were removed and analyzed for solid loss, acidity, and moisture content at eight time points (15, 30, 45, 60, 90, 120, 180, and 240 min). Texture and microstructural analyses were performed before (0 min) and after 240 min of gastric digestion. After each digestion time, sweet potato cubes were separated from the gastric juice using a sieve, weighed, and immediately processed for further analysis. Digestions were completed in triplicate for each cooking treatment.

2.5. Sweet potato behavior during in vitro gastric digestion

2.5.1. Acidity and moisture content

After digestion, 3 cubes (approx. 6 g) were weighed and mixed with 20 mL of deionized water. The mixture was homogenized at 14,000 rpm for 60 s (IKA T18 Ultra Turrax, Wilmington, NC, U.S.A.) The initial pH of the homogenized sample was measured using a HI 99161 portable pH meter (HANNA instruments, Woonsocket, RI, U.S.A.). Potentiometric titrations were performed to measure sample acidity, by adding sodium hydroxide (0.01 N NaOH) until the sample reached a pH of 8.2 ± 0.05. Moisture content was measured gravimetrically after drying for 16 h at 100 °C.

2.5.2. Solid loss

Solid loss was determined using a mass balance. The solid loss (g) for each digestion was estimated by mass difference using the initial mass, initial moisture content, mass after digestion, and moisture content after digestion. The initial mass and moisture content values were measured prior to the addition of saliva and gastric juice. To account for differences in the initial mass of samples, solid loss was expressed as a percent of the initial sample mass.

2.5.3. Texture analysis

Hardness of individual sweet potato cubes was measured before and after 240 min of in vitro gastric digestion. Hardness was measured as the maximum force during compression following the method reported by Kaur, Singh, Sodhi, and Gujral (2002) with minor modifications. Briefly, samples were compressed using a 50 mm diameter cylinder probe with a test speed of 2 mm/s to 6 mm. Hardness was quantified as the maximum force during the compression measurement (N). Measurements were done using a TA.HD *Plus* Texture Analyzer (Texture Technologies Corp., Hamilton, MA, U.S.A.). Eight samples were measured for each replicate of each