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The effect of vacuum frying on starch gelatinization and its *in vitro* digestibility in starch–gluten matrices

Ingrid Contardo [a], Javier Parada [b], Angel Leiva [c], Pedro Bouchon [a,*]

[a] Department of Chemical and Bioprocess Engineering, Pontificia Universidad Católica de Chile, P.O. Box 306, Santiago 6904411, Chile
[b] Institute of Food Science and Technology, Universidad Austral de Chile, P.O. Box 47, Valdivia, Chile
[c] Department of Physical Chemistry, Pontificia Universidad Católica de Chile, P.O. 360, Santiago 6904411, Chile

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ABSTRACT

Starch digestibility in a food matrix depends on processing conditions that may affect its physical state and microstructure. Starch gelatinization is one critical change that takes place during frying which could be affected during low-pressure processing. This study assessed the effect of vacuum frying on starch gelatinization and its *in vitro* digestibility. Laminated dough was made of a reconstituted blend of wheat starch (88% d.b.) and gluten (12% d.b.). Samples were fried under vacuum (6.5 kPa, $T_{water\text{-}boiling\text{-}point}$ = 38 °C) or atmospheric conditions up to bubble-end point, maintaining a thermal driving force of 70 °C ($T_{oil} - T_{water\text{-}boiling\text{-}point}$ = 70 °C). Vacuum fried samples showed less starch gelatinization (28%), less *rapidly available glucose* (27%), and more *unavailable glucose* (70%) than their atmospheric counterparts (which presented 99% starch gelatinization, 40% *rapidly available glucose*, and 46% *unavailable glucose*), and the values were close to those of raw dough. These results show how vacuum processing may be used to control the degree of starch gelatinization and related digestibility.

1. Introduction

Starch is the main carbohydrate in human nutrition. It is mostly found in corn, potatoes, wheat, cassava, and rice, and it is used in foods as a thickening, gelling, and structure-forming agent (Bertolini, 2010). Most of these properties are triggered when starch is heated in the presence of liquid water (Biliaderis, 1991). Under these circumstances, starch granules swell and lose their crystallinity and molecular organization in a process known as gelatinization (Wang & Copeland, 2013).

The temperature range for gelatinization and the energy required for that process depend on the botanical source, and they are often characterized through differential scanning calorimetry (DSC) (Gonera & Cornillon, 2002). The amount of water available is also a critical factor (Baks, Ngene, van Soest, Janssen, & Boom, 2007). In fact, at intermediate concentrations of water (30–70% w/w), the gelatinization temperature range may be extended (Biliaderis, 2009; Parker & Ring, 2001). Furthermore, the addition of sugars such as sucrose, glucose, and fructose to solutions containing starch may delay the process due to water accessibility limitations (Molina, Leiva, & Bouchon, 2015; Mason, 2009; Sopade, Halley, & Junming, 2004). An increase in the heating rate may increase the onset gelatinization temperature (Ovalle, Cortés, & Bouchon, 2013), whereas freezing prior to heating may delay it (Molina et al., 2015).

When starch granules are gelatinized, the disruption of their structure increases their susceptibility to enzymatic degradation and related digestibility (Holm, Lundquist, Björck, Eliasson, & Asp, 1988). Also, when starch granules are trapped within a matrix (as is the case in dough) differences in starch digestibility may be associated with the changes in the physical state of the granule itself as well as the type of microstructure developed during processing. This may hinder the accessibility of hydrolytic enzymes during digestion (Lee, Kim, Choi, & Moon, 2012; Parada & Aguilera, 2011a; Singh, Dartois, & Kaur, 2010). Thus, structural changes which occur during thermal food processing may change the postprandial response (Bravo, Siddhuraju, & Saura-Calixto, 1998; Englyst, Englyst, Hudson, Cole, & Cummings, 1999; Kawai, Matsusaki, Hando, & Hagura, 2013; Lee et al., 2012; Parada & Aguilera, 2011a,b). In order to account for such differences, Englyst et al. (1999) developed an *in vitro* enzymatic method of classifying starch based on its digestibility. The approach involves measuring the amount of glucose released from a food during timed incubation under standardized conditions. Rapidly available glucose (RAG) was defined as the fraction that was obtained after 20 min of hydrolysis. Slowly available glucose (SAG) was said to

* Corresponding author at: 4860 Vicuña Mackenna Ave. P.O. Box 306, Santiago 6904411, Chile.
E-mail address: pbouchon@ing.puc.cl (P. Bouchon).

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be the fraction obtained between 20 and 120 min of hydrolysis. These amounts of glucose are likely to be available for rapid and slow absorption, respectively, in the human small intestine. Finally, unavailable glucose (UG) was defined as the fraction that could not be released after 120 min of hydrolysis.

Deep-fat frying involves immersing foods in edible oils and fats at elevated temperatures in order to induce rapid dehydration and related microstructural changes (Moreno, Brown, & Bouchon, 2010). In starchy matrices, starch gelatinization is one of these critical changes. Excess consumption of fat, a main component of fried food, and the formation of toxic compounds within the food (e.g. acrylamide) have led the food industry to develop new alternatives such as vacuum frying (Dueik & Bouchon, 2011). This process is carried out under pressures well below atmospheric levels, reducing the boiling point of water, which makes it possible to substantially reduce the frying temperature (Garayo & Moreira, 2002). These processing conditions allow for better preservation of nutrients, minimize oil degradation, and may reduce oil absorption while maintaining the organoleptic properties of fried fruits and vegetables (Da Silva & Moreira, 2008; Dueik, Robert, & Bouchon, 2010; Fan, Zhang, Xiao, Sun, & Tao, 2005). Interestingly, starch gelatinization may be impaired under vacuum conditions, as determined by Ovalle et al. (2013) using *in situ* vacuum hot-stage microscopy. Similar results were recently reported by Oginni, Sobukola, Henshaw, Afolabi, and Munoz (2015) when vacuum frying a cassava gluten-based snack. These processing conditions may in turn affect starch digestibility.

The objective of this study was to assess the effect of vacuum conditions on starch gelatinization and *in vitro* digestibility when a restructured matrix made with native wheat gluten and starch was fried. In accordance, this research aims to understand how starch digestibility can be modulated when processing under vacuum conditions in order to illustrate how processing may help tune nutritional properties.

2. Materials and methods

2.1. Materials

Starch-gluten matrices (laminated dough) were prepared using native wheat starch (Comercial Venser S.A., Santiago, Chile), vital wheat gluten (Asitec S.A., Santiago, Chile), and distilled water. High oleic sunflower oil (Camilo Ferrón Chile S.A., Santiago, Chile) was used as the frying medium in all experiments.

Pepsin-P7000, amyloglucosidase-A7095, pancreatin-7545 (Sigma–Aldrich, St Louis, MO, USA), and invertase-390203D (VWR International Ltd., Poole, UK) were used in *in vitro* digestibility essays.

2.2. Sample preparation

Dough was prepared following the procedure described by Moreno et al. (2010) with a few modifications. Formulations were prepared using native wheat starch (88% d.b.) and wheat gluten (12% d.b.) and steps were taken to ensure that all of the dough had the same final moisture content (40% w.b.). The amount of water added to the dry ingredients was a function of the initial water content of the dry ingredients and was adjusted in order to ensure that all samples contained the specified amount. Table 1 shows the initial moisture content of the dry ingredients and the dough.

Table 1
Initial moisture content of the dry ingredients and the laminated dough (unprocessed matrix). Data are means ± standard deviation ($n = 6$).

	Moisture content (g water/100 g dry solids)
Wheat starch	12.43 ± 0.92
Gluten	5.73 ± 0.26
Dough	61.12 ± 0.41

To form the dough, the dry ingredients were first mixed for 3 min using a 5K5SS mixer (Kitchen Aid, St. Joseph, MI, USA) equipped with a K5AB flat beater at 40 rpm. Half of the water was added at 15 °C while mixing for 2 min. The remaining amount was added at 85 °C while mixing for 2 min. The dough was then allowed to rest for 40 min inside of a plastic film. Next, the dough was sheeted using a LSB516 dough sheeter (Doyon, Saint-Côme-Linière, Quebec, Canada), obtaining a final thickness of 2 mm. The sheeted dough was cut into squares (3.8×3.8 cm^2) with constant weight (3.56 ± 0.10 g). The samples were stored in plastic film to prevent dehydration.

2.3. Frying experiments under vacuum or atmospheric conditions

Frying experiments were performed using an electrically heated 10 l stainless steel fryer that could be hermetically covered with a stainless steel lid. The fryer was filled with 3.5 l high-oleic sunflower oil. The container was thermostatically controlled to maintain the set frying temperature (±2 °C), as described by Dueik et al. (2010). The fryer basket rod was connected to a rotor that was used to stir the oil at 40 rpm before frying in order to minimize temperature gradients. An equivalent thermal driving force of 70 °C was used to compare vacuum and atmospheric frying. The thermal driving force was defined by Mariscal and Bouchon (2008) as the difference between the oil temperature and the boiling temperature of water at the working pressure. Those temperatures are 100 °C under atmospheric conditions and 38 °C under the vacuum conditions used in this study (6.5 kPa). This yielded frying temperatures of 170 and 108 °C, respectively. The fryer was covered during both sets of experiments. Once the oil reached the required frying temperature, 8 slices (~28 g) of dough were placed in the frying basket in order to minimize the drop in temperature. The slices were covered with a grid in order to prevent them from floating. In vacuum frying, the slices were loaded and the vessel was depressurized (in ≈20 s). Once the vessel reached the target pressure, the basket was dipped into the frying oil for the required period of time.

Two frying times were used at each pressure: the time required to reach bubble-end point (≈2.5% moisture), which is defined as t_{ep}, and half this time ($t_{hp} = t_{ep}/2$). During atmospheric frying, t_{ep} and t_{hp} were 180 and 90 s. During vacuum frying, the frying times were 120 and 60 s, respectively. The samples were then removed from the fryer and stored in a desiccator for further analyses. Vacuum fried samples were removed from the oil before the vessel was pressurized. In addition, some batches were centrifuged at 400 rpm for 150 s just after frying. In vacuum frying, samples were centrifuged after they were removed from the oil but before the vessel was pressurized.

2.4. Analytical methods

2.4.1. Oil content

Total oil content of grounded samples was determined gravimetrically by Soxhlet extraction using petroleum ether (official method 920.39; AOAC, 1995).

2.4.2. Moisture content

The oil-free samples were dried in a forced oven at 105 °C to constant weight (official method 945.15; AOAC, 1995). Moisture content was determined gravimetrically by weight difference.