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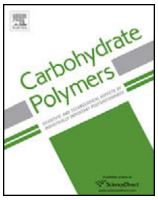

Digestibility prediction of cooked plantain flour as a function of water content and temperature

A. Giraldo Toro[a,b], O. Gibert[a], J. Ricci[a], D. Dufour[a,c,d], C. Mestres[a], P. Bohuon[b,*]

[a] *Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR QualiSud, Food Process Engineering Research Unit, 34398 Montpellier, France*

[b] *Montpellier SupAgro, UMR QualiSud, Food Process Engineering Research Unit, 1101 avenue Agropolis, CS 24501, 34093 Montpellier cedex 5, France*

[c] *International Center for Tropical Agriculture (CIAT), Km 17 Recta Cali-Palmira, AA 6713 Cali, Colombia*

[d] *Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), UMR QUALISUD, Food Process Engineering Research Unit, AA 6713 Cali, Colombia*

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ABSTRACT

The effect of temperature (T = 55–120 °C) and water content (X_1 = 1.4–2.0 kg kg^{-1} dry basis) on the gelatinization and digestibility of plantain flour (Dominico Harton genotype) were investigated. The degree of plantain starch gelatinization (α) was measured by DSC and modelled as a function of T and X_1, using the Weibull model. Rapidly digestible starch (*RDS*) and resistant starch (*RS*) fractions were evaluated for different α values. An appropriate dimensionless variable was introduced to the analyzed and modelled *RDS* and *RS* as a function of α. Starch gelatinization begins at a temperature above 59.6 ± 0.5 °C and α is strongly dependent on T in non-limiting water conditions. The combined effects of T and X_1 on the *RDS* and *RS* can be explained by α. We demonstrate that various heat treatments and water contents lead to the same α, with the same *RDS* and *RS* values.

1. Introduction

Banana (*Musa* sp.) is a staple food for millions of people worldwide, particularly in sub-tropical countries, with global production estimated at 139.1 MT in 2012 (FaoStat, 2013). The Cavendish dessert banana is by far the most widely produced cultivar (49%). It is predominantly grown in Asia. Cooking bananas (22% of world production) are largely grown in Asia and Africa, while other dessert banana cultivars (14.6%) are cultivated in Asia and Latin America. The plantain group (14.4%), is most common in Africa and Latin America (Lescot, 2013). Most cooking banana varieties require cooking (boiling, roasting or frying) before they can be eaten.

Banana is a major source of macro-elements and contains resistant starch, dietary fibre, rapidly digestible starch, and slowly digestible starch. Native banana starch is also known for its high level of resistant starch, which remains unhydrolyzed after 120 min by α-amylase with a procedure similar to the *in vivo* digestion (Bello-Perez, Agama-Acevedo, Gibert, & Dufour, 2012; Englyst, Kingman, & Cummings, 1992; Zhang & Hamaker, 2012). Englyst and Cummings (1986) reported that a fraction of starch resists α-amylase in green banana and plantain: 53.6% and 66.7%, respectively. Menezes et al. (2010) thus highlighted the potential of unripe banana flours and starches as functional ingredients that present high *in vitro* fermentability. This is due to the high content of unavailable carbohydrates (resistant starch and/or dietary fibre), which, in turn, do not produce a high increase in the postprandial glycaemic response in healthy volunteers (Miao, Zhang, Mu, & Jiang, 2010). Faisant et al. (1995) observed intact starch granules in ileal samples of healthy individuals after ingestion of unripe bananas. The resistant starch fraction of banana flour seems to be higher at the green ripe stage of maturity (Tribess et al., 2009).

Starch susceptibility to enzyme digestion varies depending on the original plant source of the starch. In addition, it is affected by processing, especially starch thermo-hydric history and storage conditions in comparison with raw, unprocessed flour. The physical state of the starch ingested has a major impact on its digestibility, which is closely linked to the processing techniques (thermal processing, such as extrusion cooking, autoclaving, puffing, roasting, baking, frying) (Singh, Dartois, & Kaur, 2010).

Bahado-Singh, Wheatley, Ahmad, Morrison, and Asemota (2006) studied the Glycaemic Index (GI) values for fourteen common Caribbean foods that were carbohydrate-rich and processed

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* Corresponding author at: Montpellier SupAgro, UMR QualiSud, 1101 av. Agropolis, B.P. 5098, 34093 Montpellier cedex 5, France. Tel.: +33 4678740 81; fax: +33 4676144 44.

E-mail address: philippe.bohuon@supagro.inra.fr (P. Bohuon).

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Abbreviations

a_α	Constant parameter for scale parameter of the Weibull distribution (Eq. (3))
a_Y	Constant parameter for Y response (Eq. (6))
DSC	Differential scanning calorimetry
ΔH_e	Whole variation of enthalpy (kJ kg^{-1} db starch)
ΔH_r	Specific residual variations of enthalpy (kJ kg^{-1} db starch)
G	First endotherm of gelatinization
G_{20}	Glucose hydrolysis at 20 min
G_{120}	Glucose hydrolysis at 120 min
GI	Glycaemic index
M1	Starch fusion peak
RDS	Rapidly digestible starch (kg per 100 kg of dry starch)
RDS^*	Dimensionless rapidly digestible starch
RDS_α	Rapidly digestible starch for α value (kg per 100 kg of dry starch)
RS	Resistant starch (kg per 100 kg of dry starch)
RS^*	Dimensionless resistant starch
RS_α	Resistant starch for α value (kg per 100 kg of dry starch)
T	Temperature (°C)
T_g	Effective glass transition temperature (°C)
TEG	Terminal extent of starch gelatinization
TS	Total starch content (kg per 100 kg of dry starch)
u_δ	Uncertainty of identified parameter δ (at a 95% confidence interval)
v_1	Water volume fraction (m^3 m^{-3})
X_1	Water content (kg kg^{-1} dry basis db flour)
Y^*	Dimensionless fraction of RDS^* or RS^* (Eq. (6))

Greek symbols

α	Degree of plantain starch gelatinization
β	Shape parameter of the Weibull distribution
γ	Scale parameter of the Weibull distribution (°C)
θ	Location parameter of the Weibull distribution (°C)

using ten healthy subjects. Green banana and green plantain were found to have the lowest GI, reducing the incidence of postprandial spikes in blood glucose levels. Foods processed by boiling and frying were found to have the lowest GI. The greatest increase in the digestibility of plantain flour was observed with autoclaving at 121 °C for 60 min (Niba, 2003).

During cooking with water, the starch undergoes glass transition followed by gelatinization and/or melting transition, depending on the water content (Donovan, 1979; Lelièvre & Liu, 1994; Slade & Levine, 1988). These transitions in turn induce the swelling of granules, leaching of molecular components from the granules, and eventually disruption of the granules. A consequence of crystalline structure loss is an increase in starch digestion (Miao et al., 2010). The starch gelatinization can be estimated by various techniques, such as microscopy, X-ray diffractometry, Differential Scanning Calorimetry (DSC), and many chemical techniques. DSC in particular makes it possible to detect heat flow changes associated to both first-order (gelatinization and melting) and second-order (effective glass transition) transitions (Biliaderis, Maurice, & Vose, 1980; Donovan, 1979; Slade & Levine, 1988). A state diagram model of starch–water mixtures can be established to predict the extent of starch gelatinization/melting. For instance, few starch state diagrams have been established using either the Flory–Huggins equation (van der Sman & Meinders, 2011), or the empirical equation (Briffaz, Mestres, Matencio, Pons, & Dornier, 2013; Kaletunç & Breslauer, 1996). This model could be used as a monitoring tool to control and optimize the cooking process (Briffaz, Bohuon, Méot, Dornier, & Mestres, 2014a) with different targets in terms of texture (Briffaz et al., 2014b) and digestibility. Due to a limited water content (Briffaz et al., 2013) or an insufficient heating temperature (Parada & Aguilera, 2009), a fraction of starch can remain ungelatinized, which leads to significant changes in the starch's functional quality, *e.g.* nutritional (Holm, Lundquist, Björck, Eliasson, & Asp, 1988), An incomplete swelling of starch granule will induce a partial increase in starch susceptibility to enzyme breakdown. Thus, the extent of disruption caused by heat and moisture will directly impact the ease and extent of enzymatic hydrolysis of cooked starch as earlier reviewed (Wang & Copeland, 2013). For raw cooking banana with a water content that ranges between 1.1 and 2.0 kg kg^{-1} db (dry basis) (Gibert et al., 2009), water content is not limiting (Gibert et al., 2010).

Given the potential health benefits of cooked banana products, linked to cooking conditions, this study set out to generate a quantitative relationship between the degree of starch gelatinization (α) measured by DSC and digestibility using an *in vitro* technique. A state diagram of plantain flour could be a powerful tool for developing food processing methods that modify starch resistance to digestion in order to optimize its nutritional quality and enhance its physiological benefits.

2. Materials and methods

2.1. Material

One bunch of Dominico Harton plantain cooking bananas (AAB *Musa* sp.), grown in a non-extensive farming system, was harvested at optimal green stage of maturity on a farm in Puerto Tejada (state of Cauca, Colombia). The second hand of the bunch was always selected to minimize variability. The cooking bananas from the second hand of the bunch were peeled and the pulp was cut into thin slices, oven dried at 40 °C overnight, ground into a fine powder using a laboratory grinder with a 100 μm opening screen grid, prior to flour storage at 4 °C in an airtight plastic bag for further analysis. For starch preparation, freshly cut pieces of pulp, randomly sampled from the second hand of the bunch, were suspended in distilled water and crushed in a 4 L capacity Waring blender (New Hartford, CT). The slurry was filtered through a 100 mesh sieve, washed three times and decanted. After removal of the dark top layer, the starch was centrifuged three times (17,700 × g per 10 min). The isolated starch was oven-dried at 40 °C for 48 h, carefully ground in a mortar, and stored at 4 °C in airtight plastic bags for further analysis.

2.2. Methods

2.2.1. Total starch content and free glucose

Total starch content (*TS*) was estimated after hydrolysis by incubation with Termamyl 120 L heat-thermostable α-amylase enzyme (Novo Nordisk, Copenhagen, Denmark) and then with amyloglucosidase (Sigma, St. Louis, MO, USA). The total released glucose was measured by enzymatic colorimetry at 510 nm after reaction with glucose oxidase (GOD, Sigma, St. Louis, MO, USA) and peroxidase (POD, Sigma, St. Louis, MO, USA) enzymes (Holm, Björck, Drews, & Asp, 1986). Free glucose was estimated separately after the extraction of plantain flour using sulphuric acid (5 mM) and the GOD-POD enzymatic system.

2.2.2. Amylose content

The amylose content of plantain starch as a percentage (kg of amylose per 100 kg db starch) was determined in duplicate by Differential Scanning Calorimetry (DSC) using a Perkin Elmer DSC 7