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Title

A kinetic approach to textural changes of different banana genotypes (*Musa* sp.) cooked in boiling water in relation to starch gelatinization.

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Nomenclature

α	fraction of gelatinized starch (%) of Eq. (7)
ΔH	enthalpy ($J.kg^{-1}$) of Eq. (7)
d	displacement (m)
D	time for decimal reduction of the texture (min) of Eq. (5)
f	fractional conversion of Eq. (2) to (3)
F	firmness (N)
k	rate constant (min^{-1}) of Eq. (1) to (2) and (5)
n	population of experimental data of Eq. (6)
q	number of variables in the model of Eq. (6)
TP	texture property of Eq. (1) and (3) to (4) as firmness (N), area (N.mm) or linear distance
y	experimental value of texture property TP of Eq. (6)
$\hat{y}$	predicted value of texture property TP of Eq. (6)

Subscripts

0	initial time
t	any time
∞	infinite time

ABSTRACT

A standardized textural test was developed for characterizing the banana pulp softening process during boiling. While a correlation was established between initial dry matter content and firmness, we observed large differences in cooking behavior between varieties and genotypes, with various softening rates and equilibrium retainable firmnesses. After 33 minutes' cooking, some genotypes exhibited firmnesses 7 times higher than the softest. The biggest firmness losses relative to initial textures found after cooking were: FHIA 20 (20-fold) and FHIA 18 genotypes (40-fold) after 2 hours, and Guineo (100-fold) after 98 minutes. The extent of starch gelatinization was investigated by Differential Scanning Calorimetry and correlated to the amylographic maximum slope using Rapid Visco Analyzer. Regardless of water uptake, the first 15 minutes' cooking demonstrated a strong contribution by the gelatinization process to thermal softening. The firmness losses of 15 Colombian cultivated dessert and cooking banana varieties were evaluated using fractional conversion, and were best fitted by a first-order reaction ($R^2 \geq 0.98$). Multiple regression was shown to be suitable for preliminary cooking time prediction using Musaceae flour amylographic properties. At 30 minutes' cooking, firmness evaluation was shown to be sufficient for identifying genotypic behavior, and therefore for predicting consumer preferences.

Keywords: Banana; plantain; Cooking; Firmness; Gelatinization; kinetics.

1. Introduction

The banana (*Musa* sp.) is one of the most important staple foods in the intertropical countries. Including the subgroup of plantains, cooking bananas are mostly cooked for consumption at different stages of maturity, whereas dessert bananas are eaten raw at a fully ripe stage. Banana cultivars are consumed in several forms, and consumers often prefer one variety over the others, depending on cooking mode and consumption pattern (Ngalani and Tchango Tchango, 1997), or in relation to their composition (Gibert et al., 2009). Texture remains the first sensorial criterion for quality appraisal by consumers (Qi et al., 2000).

Most of the studies on banana textural characteristics in the literature are focused on the influence of ripeness stage (Bugaud et al., 2006; Chauhan et al., 2006; Kojima et al., 1992). There is very little information available on the texture of cooked fully green and mature bananas (Eggleston et al., 1991; Ngalani et al., 1997; Qi et al., 2000). Cano et al. (1997) and Ferris et al. (1999) establish a positive relationship between textural traits and dry matter content. The latter authors also report a higher texture value for plantains than cooking bananas, plantain hybrids and dessert bananas. The literature lacks information on the textural behavior during Musa thermal processing, and also on hot textural characteristics linked to consumer perception of texture. Even after being cooked or fried, the overall pulp mechanical strength is noted to be lower in bananas than in plantains and to be related to their starch content (Peleg, 1979; Qi et al., 2000). The mean starch content in bananas and plantains is reported to be 81.9 and 86.5 %, respectively (Gibert et al., 2009). The influence of a boiling process on banana texture has been studied by few authors (Ngalani et al., 1997; Qi et al., 2000). The authors highlight some significant differences between tested varieties (2 and 7 varieties, respectively belonging to few consumption subgroups). Qi et al. (2000) suggest that the banana cooking process results in pectin solubilization and middle lamella dissolution leading to cell wall separation at constant pulp starch content, whereas Ngalani et al. (1997) note a good cooking quality of plantain landrace, probably related to its high dry matter content. Verlinden et al. (1995) conclude that gelatinization could only contribute to a limited extent to the texture of potatoes depending on variety, while taking into account both kinetics of texture softening and starch gelatinization. However, hydro-thermal treatment is also considered to be linked to hydration, swelling and gelatinization in other starchy vegetables (Andersson et al., 1994), providing unique textural characteristics.

Objective measurement of the relative firmness can be correlated to the degree of cooking of vegetables. It helps varieties to be graded for ease of cooking (Sajeev et al., 2008). The degree of gelatinization can be estimated by means of various techniques (Spigno and De Faveri, 2004), including differential scanning calorimetry (DSC). The thermal softening of vegetable tissue generally follows first-order kinetics of textural degradation (Loh and Breene, 1981), or two simultaneous first-order degradation mechanisms when considering a longer processing time (Huang and Bourne, 1983). In addition, a modified first-order fractional conversion model is suggested where the second softening mechanism could be characterized by the equilibrium or maximum retainable texture property, when considering the experimental error encountered with textural property measurements (Rizvi and Tong, 1997). Zanoni et al. (1995) assumes that starch gelatinization in excess water follows pseudo first-order kinetics in a complex food system. Conversely, Lund and Wirakartakusumah (1984) found that gelatinization follows first-order kinetics only beyond a certain degree of gelatinization, corresponding to the initial gelatinization of amorphous starch regions.

Thus, the conclusions regarding the contributions of composition and other factors to the evolution of texture during the cooking process are restricted due to the literature's shortcomings regarding softening kinetics of green bananas. Hence, the main objectives of this research were (i) to evaluate and compare the hot textural properties and thermal softening pattern of 15 cultivated varieties of Colombian bananas at a fully green stage of maturity (different genotypes) boiled in excess water for a fixed time period (120 min), (ii) to establish a kinetic model to fit the banana textural data and identify apparent rate constants, and (iii) to determine the extent to which quality attributes can be used to predict the cooking and textural properties of cultivated cooked bananas.

2. Materials and methods

2.1. Samples

Fifteen edible Musa L. section Eumusa varieties cultivated by inter-cropping with cocoa on smallholdings, including 3 dessert bananas (“Cavendish”, Cav; “Rollizo”, Ro; “Tafetan Morado”, TM), 2 banana FHIA hybrids (“FHIA 1”, F1; “FHIA 18”, F18), 6 plantain landraces (“Africa” or “Mbouroukou”, Af; “Dominico Harton”, DH; “Dominico from Cauca”, Do; “Dominico from Quindío”, Do Q; “Harton”, Ha; “Maqueño”, Ma), 1 cooking FHIA hybrid (“FHIA 20”, F20) and 3 cooking banana landraces (“Cachaco”, Ca; “Guayabo”, Gua; “Guineo”, Gui) were collected at their optimal green stage of maturity from non-intensive farming systems in the states of Cauca, Valle del Cauca and Quindío in Colombia (Gibert et al., 2009).

Peeled bananas from the second hands of the varieties were sliced into 45 mm long cylinders at their widest diameters (in the approximate range 3.10^{-2} to 9.10^{-2} m between varieties, according to girths reported by Gibert et al., 2009). At random, some banana cylinders were milled (Foss Tecator AB, Höganäs, Sweden) and dried at 40°C for subsequent flour thermal and functional analysis. Five grams of flour were dried in triplicate in a ventilated oven at 104°C ± 1°C for water content determination for each variety. Triplicate samples from 10 varieties were similarly dried for water content determination and flour-milled after thermal processing.

2.2. Cooking processes

Cooking was carried out in a boiling water pan at 96.5°C (1040 m above sea level in Cali, Colombia). After sampling, all the cylinders of the varieties were immediately immersed into the hot water bath with a 6:1 drilling water to banana ratio. Duplicate samples from the 15 varieties were removed from the water bath at various time intervals up to 120 min, except for the Guineo variety which was removed at 98 min to avoid complete disintegration.

Some peeled samples derived from 4 varieties (Cav, DH, F1 and Gui) were also tightly packed and vacuum sealed into triple-layer heat resistant pouches (23/12/100μm PET/Aluminum foil/low density PET) prior to undergoing similar cooking in the boiling water pan. The packed cylinders remained submerged throughout the cooking process to prevent mass transfer (water uptake, leaching of solutes) while limiting as possible thermal inertia on heat transfer.

2.3. Texture analysis

Immediately after cooking and without being cooled, the cylinders were removed from the water bath to avoid cooling and starch retrogradation, and were immediately transferred onto a TAxT2 texture analyzer platform (Stable Micro Systems, Ltd., Surrey, UK) with a 25 kg load cell capacity. Among other probes, including cylindrical borers (5 and 50 mm), a craft knife and a 40° edge angle plastic conical probe were attached to the load cell. Uncooked freshly peeled and sliced samples were similarly and centrally placed with parallel cut cross-sections respectively facing the platform and the probe. The evolution of the temperature and the texture of the cylinders were not evaluated during cooling since it does not reflect the conditions hot cooked pulps are appreciated and consumed. Both cross-sections were submitted to a 15 mm puncture test at the central point of the cylinders as follows: Pre-speed, 2 mm, cross-head speed 0.5 mm.s^{-1}, post-speed 10 mm.s^{-1}, with a 500 points.s^{-1} (pps) data acquisition rate and a using a 0.049 N trigger force. Analyses were performed on samples in duplicate or more, depending on availability at each cooking time. Texture Expert Exceed software was used to record the textural property TP on a force vs. displacement curve: maximum peak force as firmness F (N), area under the curve as the compression work (N.mm), and linear distance as the perimeter of the force vs. displacement curve.

2.4. Kinetic calculations

Assuming a simple first-order texture softening kinetics, the quantitative textural property was described in terms of irreversible degradation kinetics as Eq. (1), where 'TP_t' is the quantitative textural property read at time t, 'k' the rate constant (s^{-1}) for texture softening:

$$\ln \frac{TP_t}{TP_0} = -k \cdot t \qquad (1)$$

or complementarily Eq. (2):

$$\ln(1 - f) = -k \cdot t \qquad (2)$$

with

$$f = \left(\frac{TP_0 - TP_t}{TP_0 - TP_\infty} \right) \qquad (3)$$

the fractional conversion of the reaction, or the fraction of reactant that has been converted. TP_0 to TP_∞ are usually identified by means of various replicates of the experimental data. The selection of equation (1) or (2) for rate constant identification depends on the texture ratio of TP_0 to TP_∞, namely without or with fractional conversion (Rizvi and Tong, 1997). Those authors stressed that the texture property can be predicted on the basis of identifying the rate constant if the linear relationship exists between ln (1−*f*) vs. time from Eq. (2).

In addition, the ratio of initial textural criterion of raw samples over textural criterion of cooked samples in Eq. (4) was as follows:

$$F_{RT} = \left(\frac{TP_0}{TP_\infty} \right) \quad (4)$$

where F_{RT} is the factor of reduction of texture (Beleia et al., 2004). The F_{RT} could either be computed on the basis of textural property at time t instead of infinite time. In addition, the time *D* for the decimal reduction of the texture measured in Eq. (5) was as follows:

$$D = \left(\frac{\ln(10)}{k} \right) \quad (5)$$

by combination of Eq. (1) and (5), *D* was computed from the constant rate *k*, by analogy to the time necessary for killing 90% of the microorganisms of a population at a given temperature T, as suggested by Rizvi and Tong (1997). Hence, *D* becomes the time taken to lose 90% of the initial texture for a given variety. *D* was considered at an estimated temperature of 90°C, as the time needed to measure two cylinder firmnesses on both cross-sections, as soon as they had been removed from the boiling water bath at 96.5°C. If *D* could be considered as redundant with the constant rate, it gives an explicit quantification of the textural loss with technological significance with regard to the cooking behavior of bananas described in the Colombian food consumption survey (Quintero et al., cited by Gibert et al, 2009).

After collecting all data for the 15 varieties, some statistical tests were carried out, to validate the use of both cross-sections' textural data, to select the *TP* trait and at which displacement *d* (mm) of the cone into the cylinder the data has to be collected, and subsequently to try to differentiate varieties and genetic subgroups with the optimal textural trait highlighted. ANOVA and Least Square Difference test (LSD post-hoc) at $p \leq 0.05$ and $p \leq 0.01$, using the Statistica V.6.1 software package (StatSoft Inc., Tulsa, Oklahoma, US) were carried out. Complementary curve fits were applied using TableCurve 2D v5.01, Systat Software Inc., Chicago, IL, USA). In order to estimate the quality of the model predictions, the goodness of fit was evaluated by the determination coefficient and root mean square error (RMSE) between experimental y_i data in ($1-f$) form and predicted $\hat{y}_i$ data of *TP* at a confidence level of 95% in Eq. (6) as follows:

$$RMSE = \sqrt{\frac{1}{(n-q)}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (6)$$

where 'n' is the number of data and 'q' the number of parameters (here, q=3 for a first-order model).

2.5. Cooking degree estimation

The onset, peak and end temperatures, and variation of enthalpy (ΔH) were determined on DSC Perkin-Elmer DSC 7 device (Perkin-Elmer, Norwalk, VA, USA) using sealed stainless steel pans. The sample pan was filled with the flour, and the moisture content was adjusted to 80% on wet basis (10 to 11 mg of flour with 40 μL of pure water). Both the sample pan and empty reference pan were heated from 25 to 140°C at 10°C.min^{-1}, held at 140°C for 2 min, and then cooled to 60°C at 10°C.min^{-1}. The fraction of gelatinized starch or cooking degree percentage α_t at time t in the flours was estimated by the ratio of the gelatinization energy measured (J.kg^{-1} of dry weight) ΔH at time t over ΔH_0 at time t_0 in Eq. (7) as per Spigno et al., 2004. The analysis was performed in duplicate, and the mean values were calculated for 10 varieties.

$$\alpha_t = \frac{\Delta H_t}{\Delta H_0} \times 100 \quad (7)$$

Hot flour dispersion viscosity profiles were investigated using an RVA model, RVA-4 series (Newport Scientific, Warriedwood, Australia). Viscosity (usually expressed in RVU units, or in cP equivalent to mPa.s) was recorded with the following temperature profile: held at 50°C for 1 min, heated from 50 to 90°C at 6°C.min^{-1}, held at a 90°C plateau for 5 min, and then cooled down to 50°C at 6°C.min^{-1} with continuous stirring at 160 rpm, and using 8% flour suspensions (w/V distilled water) with silver nitrate amylase inhibitor ($AgNO_3$ 0.002 mol.L^{-1}) as per Dufour et al. (2009). The usual amylographic parameters described by these authors were recorded or computed (pasting temperature (PT), pasting time (Pt), peak viscosity (PV), peak viscosity time (PVt), hot paste viscosity, HPV; the viscosity at the end of the plateau, VEP; the cool paste viscosity at 50°C, CPV; cooking ability, CA; breakdown, BD; setback, SB; consistency, CS). Each viscosity-time profile was fitted with a cubic smoothing spline. Then, the maximum slope (SLO) representing maximum viscosity per unit time (Almeida-Dominguez et al., 1997a) of the ascending viscosity curve from pasting temperature to peak viscosity (cP.min^{-1}), was identified by the first analytical derivative of RVA viscosity profile (cP) vs. time (min) using Matlab v6.5 (The MathWorks Inc., Natick, MA, USA). The cooking degree derived from the maximum slope of the RVA profile was estimated by analogy to Eq. (3) as the fraction of reactant that has been converted in specified time t (SLO at initial – SLO at t) over what must react for the reaction to reach completion (SLO at initial – SLO at equilibrium or infinite) for 10 varieties. All amylographic parameters were obtained in duplicate, and the mean values were calculated. Investigations of potential correlations and multiple linear regressions were also carried out using the Statistica software package.

3. Results and discussion

3.1. Standardization of textural analysis

Contrary to the textural tests with the 40° edge angle plastic conical probe, the preliminary trials carried out with cylindrical borers and craft knife were revealed being not suitable for an accurate characterization of the evolution of the texture during cooking (data not shown). Various textural responses were obtained depending on the variety and the cooking time. For a given clone, no significant statistical influence of the cut cross-section was demonstrated ($p \leq 0.01$), suggesting that all textural data of both of the cylinder cross-sections could be combined and computed together. Moreover, similar coefficients of variation (CV) were obtained when considering the firmness, the area under the curve and the linear distance textural criteria for a given uncooked clone (13.8, 13.8 and 14.5% respectively). Since the maximum force F as firmness is the easiest criterion to compute as well as being commonly considered, this trait was selected. Among textural profiles, an increase of the number of macroscopic ruptures with cooking time was observed when forces vs. displacement curves were checked. This meant minimizing the number of ruptures taken into account for an optimized textural analysis, while keeping the maximum amount of data. Hence, the data up to 8.5 mm probe displacement into the banana cylinders was selected, which produced a computation of 36 out of 1962 texture profiles with an effective macroscopic rupture detected (below 5% of ruptures taken into account by analogy to $p \leq 0.05$). The corresponding firmness coefficient of variation fluctuated in the 5.9 to 13.4% range between uncooked varieties.

3.2. Textural characteristics and changes in cooked bananas

Banana varieties can be partially differentiated on a firmness basis (Table 1), as earlier suggested on 3 landraces by Cano et al. (1997) and Ferris et al. (1999). Plantain landraces' initial texture was demonstrated to be significantly harder than other subgroups ($p \leq 0.05$), as reported by Ferris et al. (1999), Eggleston et al. (1991). The authors stressed that the texture of cooking bananas is softer than that of plantains. In particular, DH exhibited the hardest texture and is usually considered as the most appreciated landrace by Colombian consumers for fried products (Quintero et al. cited by Gibert et al., 2009). Contrary to the findings of Ferris et al. (1999), raw dessert banana texture (without combination with dessert hybrids) was not found to have a significantly lower firmness than that of cooking bananas at $p \leq 0.05$. A low texture variability between repetitions was observed at green stage of maturity, within a firmness range from about 14 to 32 N. It seemed that the raw textural measurement neither significantly helped to describe the culinary quality of the varieties nor the cooking behavior reported by the consumers.

However, a significant linear relationship was highlighted between initial textural criterion and dry matter content of the raw varieties, in spite of the Cachaco's atypical firmness (Fig. 1). Except for the Guineo AAA genotype, all cooking bananas exhibited a dry matter content above 32%, as earlier stressed by Gibert et al. (2009). Eggleston and Asiedu (1994) earlier showed that the texture level was correlated to the moisture content in cassava root. This implies that starch could contribute to the initial firmness of the varieties, as the main ingredient of dessert bananas and cooking bananas (Gibert et al, 2009).

Significant differences in the experimental textures at different cooking times including 33 min and 83 min ($p \leq 0.05$) were observed between varieties (Table 1). The well-known Guineo clone exhibited nearly zero firmness at 83 min, and thus was experimentally confirmed as partially or completely disintegrating in boiling water (Quintero et al. cited by

Gibert et al. (2009). Conversely, the other clones Guayabo and Dominico, usually reported as being preferred for boiling in soups, exhibited a high remaining texture at 83 min, equivalent to that of the plantain subgroup. The plantain subgroups exhibited a significant higher firmness after 33 min and after a long cooking time (83 min) than the other subgroups ($p \leq 0.05$), with 2.15 N and 1.50 N respectively. Figure 2 showed that for 14 varieties out of 15, the F_{RT} ratio was higher than that reported in the literature for vegetables, suggested as being in the 6 to 12 range (Rizvi and Tong, 1997). No significant differences between the F_{RT} of cooking bananas and dessert bananas were revealed. Half of Colombian cultivated varieties exhibited a ratio below 20, whereas some atypical varieties such as F20, F18 and Gui exhibited high F_{RT} with about 36, 55 and 105, respectively. However, when computing F_{RT} on the basis of the ratio of the texture at 33 or at 83 min over the initial texture from Table 1, an equivalent order was obtained at the two cooking times. At 33 minutes' cooking, some larger differences were observed between varieties, with firmness 7 times higher for Ha or 6 times for Gua than that of the Gui clone. Without any explanation, the clones Gua, Ca, Ha and TM landraces exhibited the highest remaining texture. Such textural thermal resistance may be attributed to the pectin-containing cell walls, the molecular structure of the starch or even to the differences in condensed tannin structure between varieties. No relationship can be established between textural loss and the mode of consumption (as dessert bananas and cooking bananas). However, the high firmness losses exhibited by Gui, F18 and to a lesser extent F20 (20 to 40 times lower than their initial texture) manifest the soft textures expected for varieties used in soups. It seemed that the texture at about 30 minutes' cooking helped to identify the clones with the softer texture which are preferred by consumers. Hence, in order to predict the textural behavior of dessert bananas and cooking bananas at longer cooking times in a germplasms collection, the puncture test at 30 min seemed not only useful as an efficient tool, but also avoided the need for a trained sensorial panel.

All banana varieties exhibited a similar softening pattern when cooked in boiling water as shown in Fig. 3. As observed by Ngalani et al. (1997) and Qi et al. (2000), the banana pulp firmness decreased sharply during cooking. Homogeneous evolutions of relative textures were observed between plantain and dessert banana varieties, whereas Gui and F1 were dissimilar to the other cooking clones and hybrids, respectively. In particular, significantly different F/F_0 ratios and different cooking times to reach "a maximum retainable texture" or an asymptotic firmness were observed between varieties. Hence, instead of considering the texture at 120 minutes' cooking as the F_∞, a non-zero equilibrium firmness was considered at 83 min since no statistical differences between most F values were observed at longer cooking times, and the variability of F was enhanced above 83 minutes' cooking (larger standard deviations observed). It suggested a probable first-order textural softening reaction, according to the review of Rizvi and Tong (1997). Different rate constants among varieties were also assumed, which would require later confirmation by kinetics modeling.

Since the most appreciated varieties for boiling are the landraces known for partially or completely disintegrating in boiling water (Quintero et al., cited by Gibert et al., 2009), the evolution of 2 landraces with extreme firmnesses (considered as hard and soft clones: DH and Gui, respectively) were plotted on a semi-log scale, as a function of their apparent respective moisture content (%wb) during thermal treatment. After about 12 minutes' cooking, the remaining firmnesses were about 10% and 3% of their initial texture for DH and Gui landraces, respectively (Fig. 4). A restricted reduction of the texture could be observed after 15 minutes' cooking, whereas a continuous increase of water uptake was observed in the first 40 minutes. Hence, the texture evolution seemed not to be controlled by the water uptake throughout the cooking process, but especially for the first 15 minutes' cooking. The non-zero equilibrium texture was observed after a long cooking time, as earlier described by Rizvi and Tong (1997). A linear region with a steep slope followed by another linear region with a shallow slope was observed within the exponential decay of firmness. It seemed similar to that of the dual mechanism first-order kinetic model of softening described by Huang and Bourne (1983). This implies that is better to use the fractional form instead of the relative texture vs. time to characterize kinetics of texture degradation, which could be globally taken into account using fractional conversion (Rizvi and Tong, 1997).

3.3. A novel approach to cooking degree

Figure 5 shows typical RVA viscoamylographic profiles of a banana flour sample of the 'DH' variety before and after boiling for 0, 8, 13, 23, 38, 48, 120 min. Many changes in the flour viscosity profiles were observed throughout the cooking process. The evolution of the RVA profile at different cooking temperatures has been previously illustrated (Guha et al., 1998). The authors suggested to compute the area under the peak exhibited by cooked samples, relative to that of raw samples (100% ungelatinized) to estimate the extent of gelatinization by RVA. The peak viscosity, the hot and cold paste viscosity, the final viscosity, the breakdown and consistency factors, as well as the pasting time and pasting temperature, were observed in this case decreasing throughout the cooking process (Fig. 5). However, it should be noted that the PT becomes harder to estimate after some time, since the viscosity was slightly increasing from the beginning of the holding stage (disappearance of the initial baseline). This phenomenon is commonly observed when characterizing a partially cooked matrix, and could be overcome by lowering the initial holding stage temperature to around 20°C instead of 50°C. Complementary setback and cooking ability parameters were observed to decrease throughout the cooking process. Moreover, it could be observed that the slope of the ascending viscosity curve (SLO in cP per unit time) from the pasting temperature to peak viscosity of the flours decreased from 1135 cP.min^{-1} to 170 cP.min^{-1} approximately, depending on the cooking time. The evolution of SLO is plotted on the right-hand side of Fig. 6 with a cross symbol (+) for the 4 varieties. The trend of slope evolution seemed similar to that of the relative texture vs. cooking time with the successful attempt at fitting using a first-order decay model with confidence interval 95% (triangular symbols on left-hand side of the figure). Nevertheless, the transient phenomenon would have been better described using some additional experimental points at the initial cooking stage (in the 0 to 5 min range). Moreover, Almeida-Dominguez et al. (1997b) earlier found some significant correlation between the RVA slope and maize kernel hardness. Since the DH variety was demonstrated as having higher pasting temperature and onset temperatures than bananas belonging to other subgroups (Dufour et al., 2009), the landrace should require longer cooking times. The water diffusion has also been suggested as a better index for discriminating differences in cooking quality than the instrumental method softening pattern (Beleia et al., 2004). Almeida-Dominguez et al. (1997a) also established a relationship between the RVA slope, the rate of water uptake during simmering and the required cooking times.

3.4. Impact of cooking degree on textural characteristics

The softening patterns of the cylinders of the 4 varieties submitted to a boiling process with and without being sealed under vacuum into a heat-resistant pouch are shown on the left-hand side of Fig. 6. It suggested that the initial rate constants for firmness loss via the (1-f) conversion technique were initially different, and then dimensionless textures seemed to merge as equilibrium approached. The figure was plotted on an xy linear scale to facilitate comparison between the texture fractional conversions throughout the cooking processes with their respective degrees of conversion. However, the plot of the logarithm of (1-f) vs. time was linear through a log cycle (data not shown) as described by Rizvi and Tong (1997), thereby confirming the reaction as first-order. Some significant differences were observed between the softening patterns of the 2 thermal processes for Gui, Cav and to a lesser extent for DH, whereas the F1 hybrid variety only exhibited slight differences.

A strong contribution by processing conditions were expected in the differences in textural softening patterns, since the cylinders were watertight and vacuum sealed to avoid mass transfer, although we were not expecting significant influence on heat transfer coefficient using 3 layered heat-resistant pouches with non-limiting external thermal conditions applied. The non-zero equilibrium firmnesses were not significantly different between the processing conditions ($p \leq 0.05$) of the 4 varieties. It can be observed from Fig. 6 (center 4 figures) that a minimum of 80% texture loss ($1\text{-}f < 0.2$) corresponds more or less to a 100% cooking degree for both thermal treatments. The starch was fully gelatinized in the 8 to 13 min range between varieties. The slight texture evolution may be related to the continuous granule swelling after full starch gelatinization. It was earlier observed that the remaining firmness after about 12 min was below 10% of the initial level, with continuous water uptake until 40 min (Fig. 4). Hence, the texture evolution seemed not be controlled by the water uptake throughout the cooking process, but to be mainly related to the gelatinization process in the first 15 minutes' cooking, with the probable disappearance of the crystalline structure of the starch and of the solid granules. Even though Verlinden et al. (1995) concluded that gelatinization could only contribute to a limited extent to the texture of potatoes depending on the chosen model, it seems that during the banana boiling process the firmness loss was mainly related to the degree of starch gelatinization. The contribution of starch to the texture was earlier assumed (Gibert et al., 2009) since those authors reported a low starch content in pulps consumed uncooked (sweet bananas at ripe stage of maturity), thereby making cooking dessert bananas for consumption a useless action. An empirical equation connecting the relative firmness and the degree of cooking was also suggested by Sajeev et al. (2008) on cassava tubers. Here, a first-order decay model successfully fitted the experimental data regarding the cooking degree (Fig. 6).

The heating conditions applied to the watertight banana cylinders were confirmed as significantly influencing the gelatinization rate at an equivalent time required for full cooking of unpacked samples. A lag phase was observed for the cooking degree of 3 varieties out of 4 when cooked in vacuum sealed pouches. Double the time was required for the gelatinization of watertight Gui and Cav landraces, whereas 27 min was required for full gelatinization of DH, instead of 8 min in boiling water. The water uptake seemed to significantly accelerate the cooking process. The longer time required for full gelatinization of the watertight plantain cylinders may be related to the lower amount of free water available than with the other varieties. A critical moisture content of 61% (Donovan, 1979) or even 70% (Eliasson, 1980) is reported for optimal full starch gelatinization, which is close to the moisture content of the Colombian DH variety (Gibert et al., 2009). Similarly to the F1 softening pattern described earlier, the trend of the extent of gelatinization was equivalent for both thermal processing conditions for this clone. Hence, it confirmed that the degree of starch gelatinization could be related to the banana firmness during the cooking process, and confirmed that softening seemed not to be driven by water transfer.

The evolution trend of cooking degree by RVA (SLO estimate) seemed similar to those of the calorimetric analyses. A temporal correlation between the onset of softening and the cooking degree by both DSC and RVA can be assumed. The extent of conversion using SLO was shown as being intermediate between both cooking degree percentages by DSC (water and watertight cylinders boiled). Since the DSC operating conditions meant low amounts of even well-mixed flour samples (10 to 11 mg of flour used), it could be assumed that the cylinder cooking gradient may interfere with the DSC estimate of cooking degree, and to a lesser extent with the RVA slope estimate of cooking degree (2.5 to 2.8 g of flour used). In addition, some fruit variability can be also suggested to contribute to the cooking degree fluctuation, as observed by Gibert and Pain, 2008. Those authors highlighted some biological heterogeneity within plantain pulps using a dynamic isoconversional approach with DSC (non-isothermal), and showed the contribution of the banana sampling area in the computed apparent cooking activation energy with DSC, and its dependence on the extent of conversion. Hence, the RVA estimate of cooking degree (observed to be slightly delayed from the DSC reference estimate) could be considered as an accurate approach with regard to the significant evolution of the slope throughout the cooking stage, the easiness of the method and the wide availability of the apparatus used for the estimation. Thus, the rate of viscosity development (SLO) was suggested for potential use as a cooking extent indicator.

3.5 Kinetic considerations and attempt at predicting the cooking and textural properties

Due to the relatively low F_{RT} (Fig. 2) and the dual mechanism first-order kinetic model of softening observed (Fig. 4) the firmness evolution was computed in the form (1-*f*) for better identification of the model parameters. The decay kinetics model applied was illustrated as being suitable for fitting the experimental data of the 15 varieties (Fig. 3), in relation to a first-order softening process ($R^2 \geq 0.98$). At a 95% confidence level, the goodness of fit was satisfying with a low computed RMSE (Table 1). The *D* values fluctuated in the range 3.8 to 10.4 min among clones (at 90°C) without significant differences revealed at subgroup level ($p \leq 0.05$). Except for the F1 hybrid, most dessert bananas and cooking bananas exhibited relatively low times for firmness decimal reduction, whereas some plantains such as Af, DH and Ha showed high *D* values with an intermediate to high initial and equilibrium texture. The F1 hybrid was atypical, with a high *D* value and high retainable texture, similar to those of most plantain landraces.

Various cooking behaviors observed had previously been connected to water uptake, which was observed to be higher in plantains (Ngalani et al., 1997) and to their significantly higher initial dry matter content, as one of the major quality traits for the differentiation of banana subgroups (Gibert et al., 2009). Attempts at establishing a linear correlation between the quality attributes gave significant but weak correlations between the dry matter contents of the clones and the RVA slope cooking degree measurement ($p \leq 0.01$, r^2=0.53), and between the RVA cooking degree and the ΔH of the uncooked varieties at equivalent analytical moisture content ($p \leq 0.001$, r^2=0.75). However, Champagne et al. (1999) reported that none of the cooked rice textural attributes measured by descriptive analysis were modeled with high accuracy. Eggleston et al. (1994) reported that boiled tuber texture depends on many physicochemical properties and their interaction; thus, it could be hazardous to expect a relationship between any particular component and texture.

Here, a multiple regression combining the CA, PT and SLO values for predicting the RVA measured cooking time emerged. The following empirical equation, $\alpha_t = +2.455*PT + 0.122*CA + 0.954*SLO^{-1} - 204.844$ was obtained ($p \leq 0.01$, R^2=0.80). This preliminary mathematical relation between the cooking time (corresponding to 100% extent of reaction) and some amylographic criteria would have to be subsequently confirmed on a germplasms collection where neither environmental contributions nor any environmental interaction with the genetic origin of the traits could be suspected.

Since the banana cylinders were cooked at atmospheric pressure and various RVA slopes were obtained, some heat and mass transfer studies should be conducted to investigate the hydration rate during the cooking process (water gain, solute losses), the temperature distribution into the cylinders, and the apparent thermal conductivity for the different varieties. It could then reinforce the present results, while improving understanding of the cooking behaviors of high starch banana resources. It could furthermore confirm that the textural softening process of Musaceae is mainly related to the extent of the gelatinization process. Complementary investigations of the molecular structure of starch could probably improve understanding of the specific cooking behavior of some Musaceae in excess water, where various retainable textures were observed after long cooking times in boiling water at atmospheric pressure.

4. Conclusion

A protocol was standardized for characterizing hot firmness of various bananas varieties, which was suitable whatever the cooking time of the samples. Significant progress has been made in the knowledge of the textural characteristics of bananas, banana subgroups, and of their kinetics of textural loss during thermal treatment in excess water. The puncture test applied to dessert bananas and cooking bananas at 30 minutes' cooking time was suggested as being an efficient tool for predicting firmness at longer boiling times. Using a fractional conversion technique, a first-order model was a good fit for the experimental softening pattern of various cultivated bananas. An original amylographic method was developed for estimating the extent of reaction. The texture evolution during boiling was demonstrated as being related to the extent of gelatinization of the starch granules, particularly in the first 15 minutes' cooking, and seemed not to be driven by water uptake. However, a significant relationship was observed between firmness and dry matter in raw varieties. An empirical equation was also suggested as able to make an early prediction of gelatinization time, based on banana flour functional characteristics.

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Table 1. Experimental firmness of raw banana (F0), at 33 minutes' cooking (F33) and at equilibrium (F83). Decimal reduction of texture and goodness of fit

Experimental data				Model		
Variety	F0 (N)	F33 (N)	F83 (N)	D (min) at 90°C**	R^2	RMSE
Dessert bananas						
Cav	18.44±1.00	1.07±0.14	0.61±0.11	7.26±0.39	0.993	0.025
Ro	22.96±1.31	1.91±0.52	1.07±0.47	5.97±0.37	0.989	0.038
TM*	22.54±2.01	1.75±0.77	1.25±0.30	3.81±0.05	0.991	0.035
Mean ±std *(n)*	21.53±2.73a *(59)*	1.52±0.59a *(23)*	0.94±0.43a *(26)*	5.68a	/	/
Dessert hybrids						
F1	16.48±1.40	1.75±0.67	1.57±0.51	9.16±0.69	0.980	0.049
F18	17.13±1.22	0.54±0.15	0.31±0.06	6.41±0.20	0.999	0.012
Mean ±std *(n)*	17.02±1.53b *(45)*	1.12±0.77ab *(21)*	0.94±0.73a *(24)*	7.78a	/	/
Cooking hybrids						
F20 *(n)*	21.74±1.17a *(4)*	0.91±0.02ab *(2)*	0.60±0.01a *(2)*	4.71±0.32a	0.998	0.016
Cooking bananas						
Ca	13.96±0.76	1.74±0.39	1.04±0.42	4.06±0.59	0.993	0.025
Gua	24.61±2.49	2.45±0.45	1.71±0.57	5.43±0.45	0.989	0.041
Gui	19.05±2.29	0.43±0.16	0.18±0.03	5.58±0.15	0.996	0.021
Mean ±std *(n)*	20.44±4.05a *(62)*	0.98±0.91ab *(27)*	0.83±0.69a *(10)*	5.02a	/	
Plantains						
Af	29.56±3.10	1.91±0.33	1.40±0.17	10.38±0.51	0.997	0.019
DH	32.14±2.00	2.14±0.46	1.35±0.26	8.57±0.29	0.995	0.024
Do	26.10±3.17	1.86±0.25	1.37±0.43	4.75±0.23	0.994	0.027
Do Q	26.46±2.99	2.01±0.65	1.12±0.30	4.47±0.38	0.993	0.026
Ha	24.01±1.86	2.79±0.22	1.93±0.47	10.41±0.66	0.994	0.028
Ma	26.13±3.01	2.28±0.63	1.75±0.52	5.32±0.26	0.993	0.025
Mean ±std *(n)*	28.03±3.83c *(92)*	2.15±0.51c *(39)*	1.50±0.46b *(39)*	7.32a	/	/

Means in the same column followed by a different letter represent significant differences ($p \leq 0.05$).

* Mean TM firmness measured at 78 min instead of 83 min.

** Mean temperature of banana cylinder by the time of cone penetration in the depth range 0 to 8.5mm.

Figure captions

Fig. 1. Correlation between firmness and dry matter content of the raw banana varieties. Af, Africa; Ca, Cachaco; Cav, Cavendish; Do, Dominico; DO Q, Dominico from Quindío; DH, Dominico Harton; F 1; Fhia 1; F 18, Fhia 18; F 20, Fhia 20; Gua, Guayabo; Gui, Guineo; Ha, Harton; Ma, Maqueño; TM, Tafetan Morado.

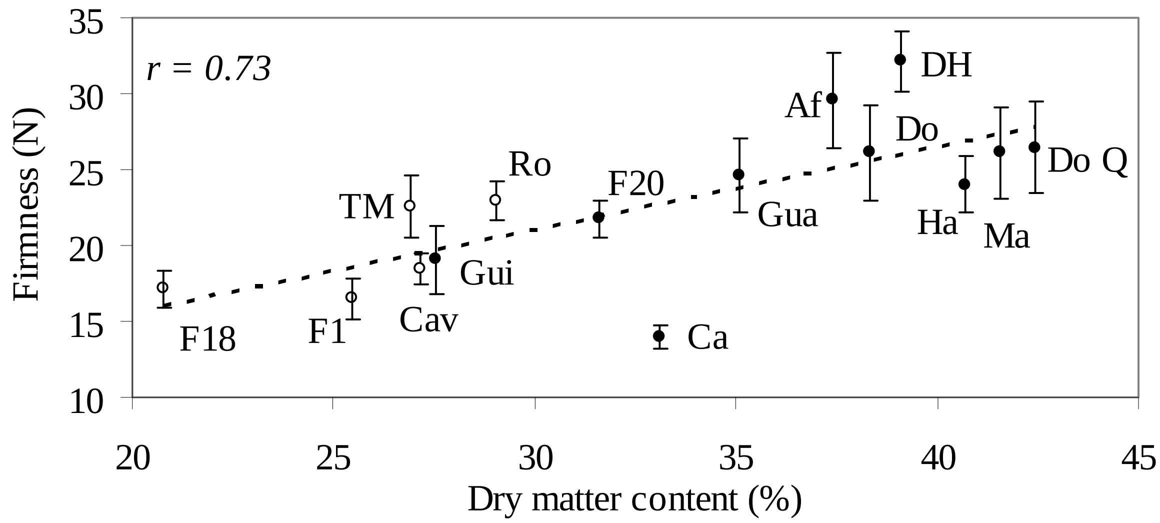
Fig. 2. Factor of reduction of texture (F_{RT} defined in Eq. 4) of 15 banana varieties (with black or white bars for cooking bananas and dessert bananas, respectively).

Fig. 3. Changes in relative firmness F/F0 of the 4 banana subgroups as affected by cooking process. The plantain subgroup includes: Af, Africa; Do, Dominico; DH, Dominico Harton; Ha, Harton and Ma, Maqueño. The dessert banana subgroup includes: Cav, Cavendish; Ro, Rollizo; TM, Tafetan Morado. The cooking banana subgroup: Ca, Cachaco; Gua, Guayabo; Gui, Guineo. The hybrids: F 1, FHIA 1; F 18, FHIA 18; F 20, FHIA 20.

Fig. 4. Texture evolution of Dominico Harton (DH) and Guineo (Gui) landraces on a semi-log scale as affected by cooking time. Corresponding evolution of moisture content (%wb) in the same thermal conditions.

Fig. 5. Typical viscoamylographic profiles of DH flour with α-amylase inhibitor before (raw flour) and after being processed at different cooking times from 0 to 120 min in boiling water, with the corresponding temperature profile (▬).

Fig. 6. Comparison of the cooking degrees of 4 varieties Cav, Cavendish (Cav), Dominico Harton (DH), Guineo (Gui) and Fhia 1 (F1) obtained from fractional form of the firmness loss during cooking in different conditions (△ and ● for water cooking and cooking without water transfer, respectively on left side) and obtained from variation of the maximum slope (+) by RVA (right side).



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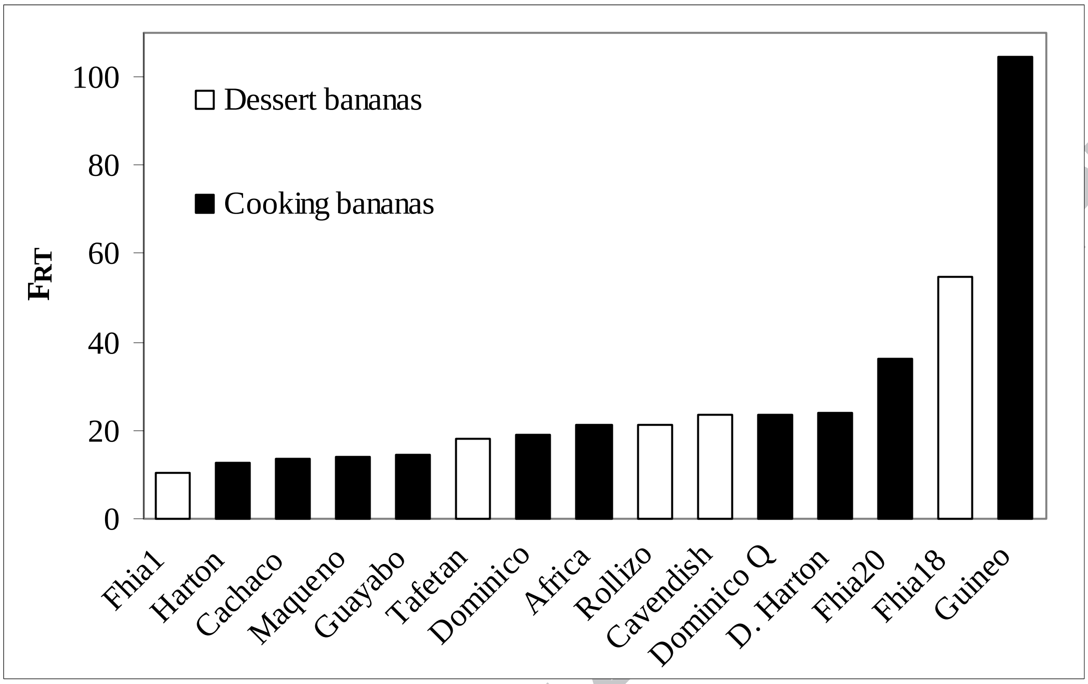

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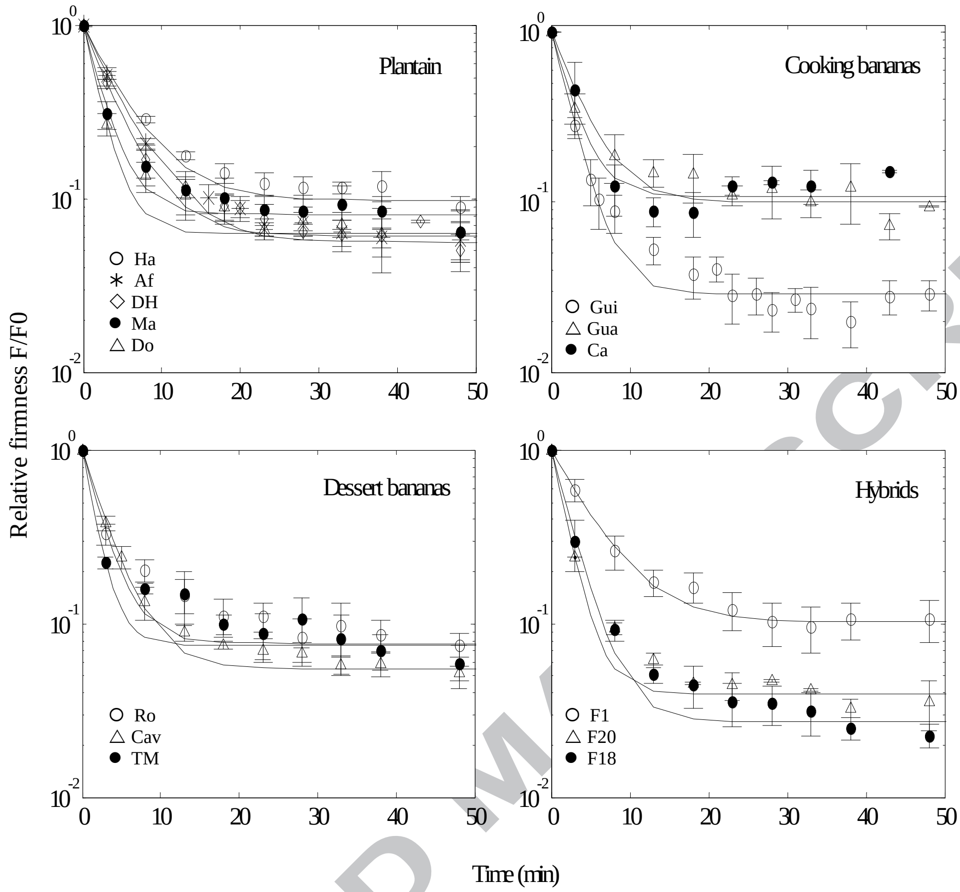

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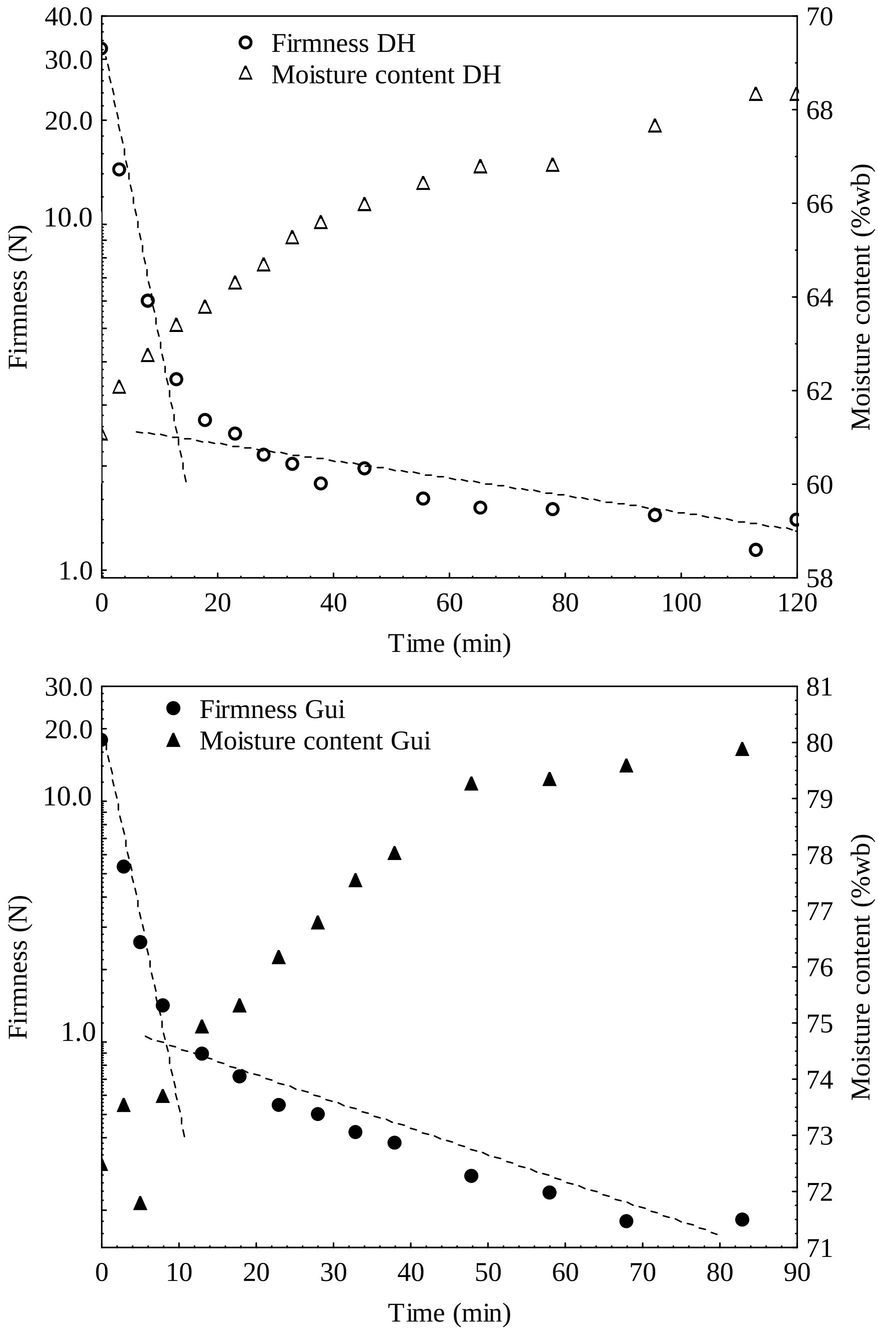

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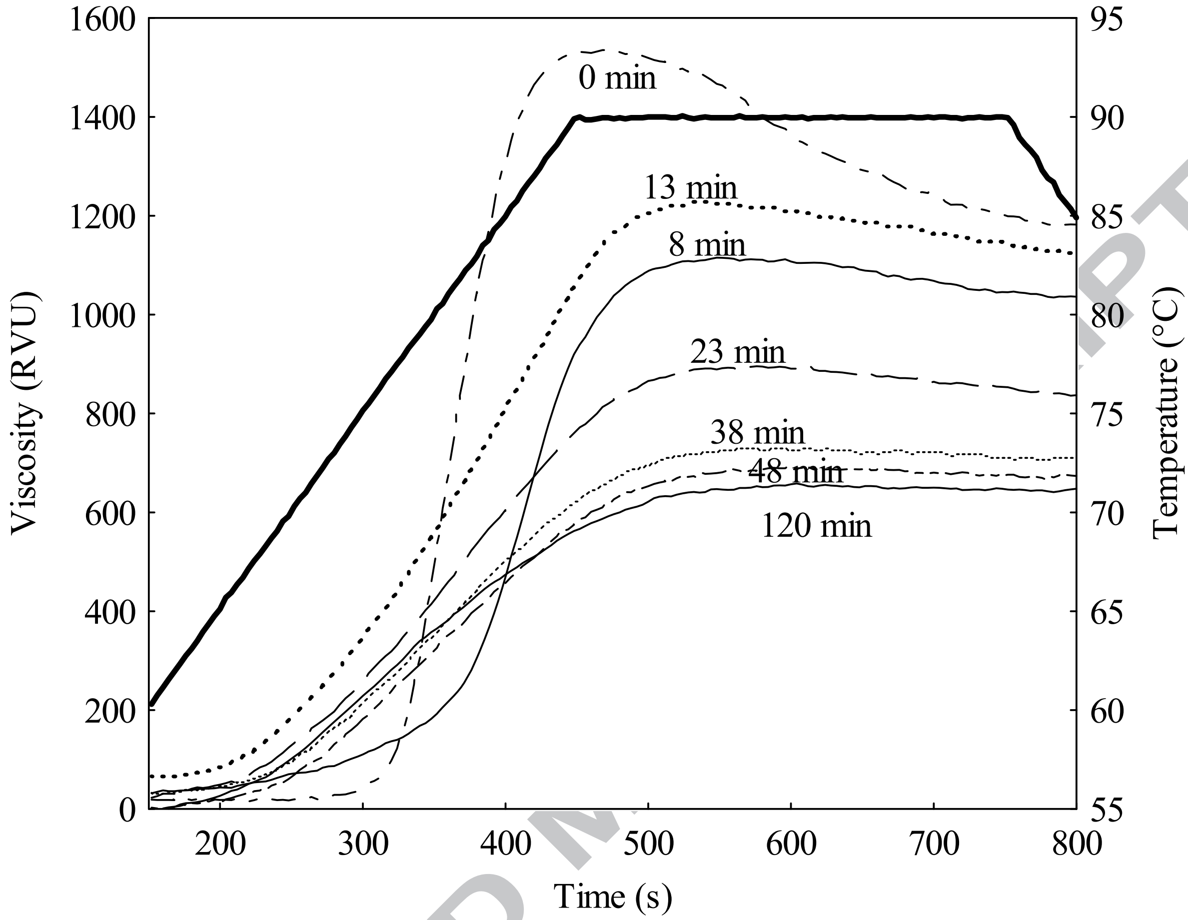

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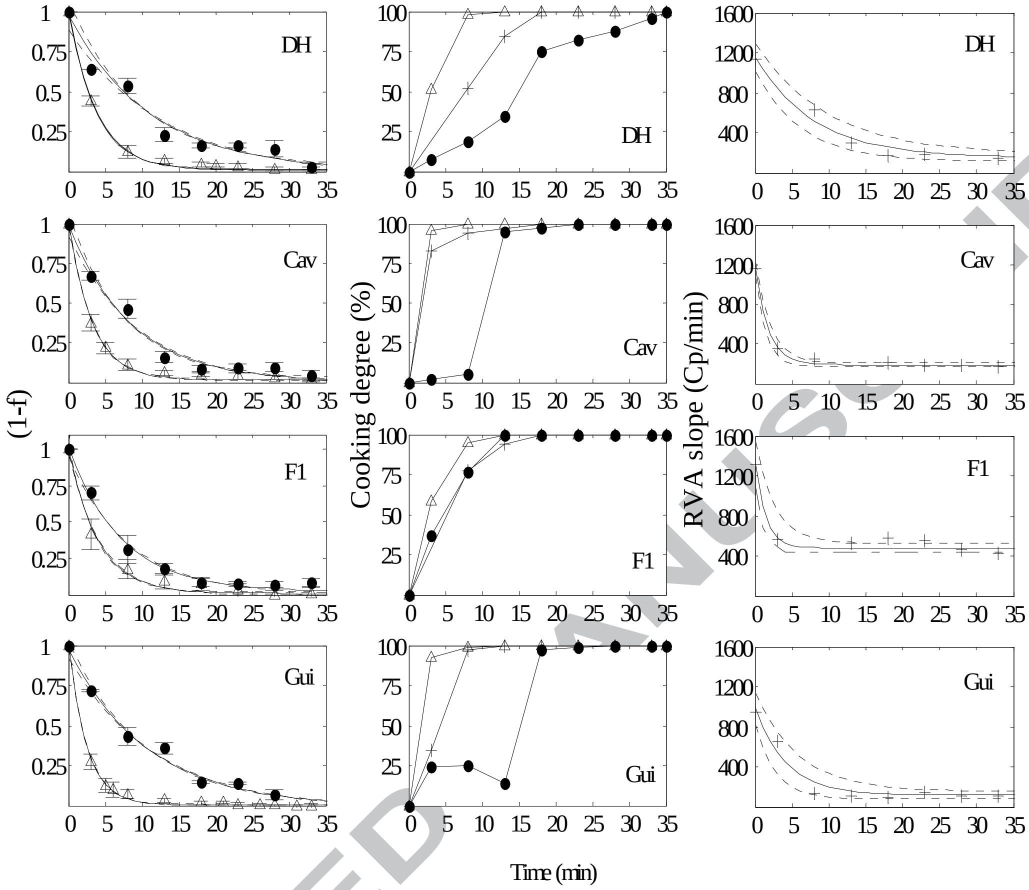

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