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Modelling the rheological properties of gruels produced from selected food products from Cameroon

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This study investigated the flow behaviour of some food gruels obtained from pre-treated banana, sorghum or sesame flours. The Herschel-Bulkley and the power law models were used to evaluate the consistency and flow indices while an Arrhenius-type equation was used to analyse the effect of temperature on viscosity. The Ostwald de Waele model gave a good fit with experimental data, with p-values less than 0.01 and R^2 values greater than 0.96 for most of the experiments. The results revealed a pseudoplastic, dilatant and time independent character for the sorghum gruels while the sesame and banana gruels revealed a pseudoplastic and time-dependent character. The effect of temperature on viscosity led to an activation energy and second Arrhenius parameter varying from 964 to 21,070 J.mol^{-1} and from 81 to 34,484 Pa.s respectively. The concentration dependence of the consistency index was modelled using an exponential equation and showed a decrease with temperature.

Key words: Sorghum gruel, sesame gruel, banana gruel, power law, Arrhenius law, time dependency.

INTRODUCTION

In Africa and particularly in Cameroon, several foods are traditionally used in the preparation of infant gruels, especially during weaning. Amongst these foods, sorghum (Matalanis et al., 2009; Onyango et al., 2010; Onyango et al., 2011; Sanoussi et al., 2013; Okoye and Ojobor, 2016; Wanjala et al., 2016), sesame (Arslan et al., 2005; Razavi et al., 2007; Elleuch et al., 2007; Çiftçi et al., 2008; Onabanjo et al., 2009; Ikujenlola, 2014) and banana (Guerrero and Alzamora, 1997; Forster et al., 2003; Abbas et al., 2009; Honfo et al., 2011) are mostly preferred. The three foods are of potential sources of nutrients; carbohydrates for sorghum, proteins and lipids for sesame, minerals and vitamins for bananas. Sorghum and sesame, in addition to being available, are commonly used in the preparation of food supplements for infants. Banana is well appreciated by children and is used by mothers as baby desserts. Moreover, Banana in the form of flour and incorporated into the porridge allows easy storage. Cameroon's annual production of these foods is growing and has reached about 1,187,531 tons for millet/sorghum, 43,963 tons for sesame and 3,182,184 tons for banana in 2010 (Minader, 2012).

Conventionally, before being fed to infants, foods are generally transformed into flour for purée (also called porridge or gruel depending on the consistency) production, whose flow properties are not often mastered. Taking into account the reduced nature and low activity of infant gut (Sanogo, 1994; Giamarchi and Trèche, 1995;

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Laurent, 1998; Mouquet et al., 1998), it is important to master the rheological properties of gruels as they significantly affect the mechanism of absorption and digestion (Sanogo, 1994). Several rheological and textural studies on different flour-based products have been presented in the literature. Matalanis et al. (2009) studied the textural and thermal properties of sorghum starch pastes; Onyango et al. (2011) presented the effect of cassava starch on the rheological and crumb properties of sorghum-based batter and bread respectively. Abdelghafor et al. (2015) studied the effects of sorghum flour addition on rheological pasting properties of hard white winter wheat; Mahajan and Gupta (2015) compared the elasticity behaviors of sorghum and wheat flour doughs. Other authors studied the rheological behaviour of banana purée (Guerrero and Alzamora, 1997), suspensions made of banana and wheat flours (Mohamed et al., 2010), semi-solid sesame paste (Abu-Jdayil, 2003; Çiftçi et al., 2008) and sesame-based products (Razavi et al., 2007; Akbulut et al., 2012). However, the results obtained cannot accurately predict the rheological behaviour of infant gruels, due to the difference in consistencies between infant gruels and other flour-based products. Although some rheological studies have been carried out on infant gruels (Mouquet and Trèche, 2001; Trèche and Mouquet, 2008; Gnahé Dago et al., 2009; Nwakego Ayo-Omogie and Ogunsakin, 2013), they involved specific operating conditions with neither models presented to predict the effect of temperature and concentration on the rheological parameters, nor curves to study the time dependency of the gruels.

This study was therefore undertaken to evaluate the flow properties of sorghum, sesame and banana gruels, present models to describe the effects of concentration and temperature on the rheological parameters and study the effect of time on the flow properties.

MATERIALS AND METHODS

Raw materials for gruel production

The raw materials considered for gruel production were sorghum (*S. bicolor* cv. *Safrari*), white sesame (*S. indicum*), both obtained from the Institute of Agricultural Research for Development (IRAD) at Maroua (Far-North Region, Cameroon) and ripe banana (*Musa acuminata*, *Cavendish*) obtained from a local market in Ngaoundere (Adamawa Region, Cameroon).

Sample preparation

The sorghum and sesame were separately treated as described in the literature (Elmaki et al., 1999; Elkhalifa and Bernhardt, 2010; Tizazu et al., 2010) sorted, winnowed, and washed twice with distilled water. The cleaned grains were soaked in distilled water for 24 h at 22 ± 1°C with the soaking water renewed at the twelfth hour. After soaking, the seeds were then drained using a sieve, spread on a wet tissue that was made to imbibe water every 24 h, and allowed to germinate in the dark over a period of 72 h at 22 ± 1°C (Hahm et al., 2009). The germinated seeds were dried at 40 ± 1°C for 48 h. After cutting-off and discarding their cyanide-containing radicles (Traoré et al., 2003), the dried seeds were ground and sieved to obtain small particle-sized flour (< 1 mm).

The bananas were peeled, cut into slices of about 5.0 ± 0.5 mm thickness and subjected to a combined dewatering-impregnation-soaking process/blanching as described by Jiokap Nono et al. (2002). They were then dried (40 ± 1°C for 72 h) to reduce water activity, limit protein denaturation/browning reactions and then ground to small particle sizes (< 1 mm).

The flours were mixed for 5 min with water at 45°C (quantity depending on the required concentration) and the mixture (1 litre) was placed in a stainless steel pot (2 litres capacity) and cooked with gentle heat using a two burner gas stove for 10 min at atmospheric pressure, after reaching 95°C. The mixture was slowly stirred during cooking using a stainless steel spoon. As mentioned by Trèche (1995), this procedure leads to the production of low viscosity purées and as such most appropriate for infants.

Physicochemical analysis

The waste content (*Wc*) of cereals was calculated as presented in equation 1, where *M* (10 g) is the mass of sample and M_g, the mass of good grains in the sample. The cleanliness of the grain was evaluated according to the CODEX (1989) with maximum admissible value for sorghum equal to 8%.

$$Wc=[(M-M_g)/M].100 \qquad (1)$$

The rate of germination (*Gr*) was determined through a germination test using 100 good grains initially soaked in distilled water. The soaked grains were then spread on a wet filter paper, put in a petri dish maintained at 22±1°C and the filter paper was watered every 12 h. The germinated grains were counted each day till stabilization, corresponding to the time of germination. In Equation 2, N_g and N_0 are respectively the number of germinated grains at the end of germination and the number of initial good grains.

$$Gr = (N_g/N_0).100 \qquad (2)$$

The mass of 1000 grains (*Mm*) which gives an idea on the quantity of matter and especially starch available in the grains was calculated as shown in Equation 3. M_g is the mass of good grains in the sample, N_0 the number of good grains in the sample and *MS* the mass of dry matter in 100 grams of good grains.

$$Mm= [(M_g.1000.MS)/(N_0 .100] \qquad (3)$$

The length of the bananas was measured using a tape while the diameter was obtained using a Mitutoyo digital caliper. The classification of banana ripening was done using a colour index (Aurore et al., 2009).

The water content was determined by the AOAC (1990) method, the ash content by AFNOR (1981) method and the total nitrogen by the Kjeldahl method (AFNOR, 1984); the nitrogen content was multiplied by 6.25 to obtain the protein content; the colorimetric technic of Devani et al. (1989) was used for the chemical dosing and the protein content was determined using the conventional conversion coefficient of 6.25 (AOAC, 1975). The determination of reducing sugars was done by the DNS (3,5 dinitro salicylic acid) colorimetric method of Fisher and Stein (1961) and the total available sugars were determined in the same way after hydrolysis of the sugars by hydrogen sulfate (H_2SO_4, 1.5 N).

Measurement of rheological properties

Experimental procedures

Rheological analyses were conducted using a Brookfield DV-III

Ultra rheometer (model HBDV-III Ultra, 8534447, Brookfield Engineering Lab., Massachusetts, USA). The disk-shaped spindle HA/HB-2 of 133 mm height; 47.12 mm diameter and 1.65 mm thickness was used.

Three gruels were prepared at different flour concentrations (dry matter): 15, 25 and 35% w/w. After cooking, 500 ml of each was put in a graduated beaker and gently stirred while cooling in a temperature-controlled bath at different temperatures (30, 40, 50 or 60°C). Analyses for each experiment were conducted in triplicate with a scanning speed ranging from 0.01 to 250 rpm. The concentrations of 15, 25 and 35% were chosen in view of the fact that the average dry matter concentration of infant gruel is around 25%. A study of the effect of the concentration shows the cases of dilutions (15%) where swallowing is easy and nutrients are insufficient; and cases of very viscous porridge (35%) where nutrients would be sufficient and swallowing difficult. The usual consumption temperature is around 45°C. While feeding the child, this temperature may drop and reach room temperature. A study of the effect of the temperature up to 60°C allows us to have at least three points which will be used to determine the activation energy.

Determination of rheological parameters

The apparent viscosity was calculated as described by Anonymous (1998) with a dimensionless factor of the spindle equals to 3200/N, where N (rpm) is the rotation speed. For the disk-shaped spindle N°2, the shear rate $\dot{\gamma}$ (s^{-1}) was determined as presented in Equation 4 (Mitschka, 1982):

$$\dot{\gamma} = (0.119 \,.\, \mathrm{Tw}) / \mu \qquad (4)$$

Where T_w (%) and μ (Pa.s) are respectively the torsion torque and the apparent viscosity for each value of the rotation speed.

The threshold shear stress ($\boldsymbol{\tau_c}$), the flow index (*n*) and the consistency index (k) were determined by adjustment, either using the Herschel-Bulkley model (Equation 5) or using the power law model (Equation 6):

$$\tau = k \cdot (\dot{\gamma})^n + \tau_c \qquad (5)$$

$$\tau = k \cdot (\dot{\gamma})^n \qquad (6)$$

The model with a better coefficient of determination and p-values less than 0.05 was chosen.

Evaluation of the effect of concentration and temperature

In literature, there is limited information regarding models presenting a correlation between rheological parameters and substrate concentration for the case of gruels. However, for other types of food pastes, an exponential model (Equation 7) has been presented to describe the consistency index behaviour in function of the concentration (Arslan et al., 2005).

$$k = k_0 \cdot exp(a \cdot C) \qquad (7)$$

For each operating temperature, the relationship between consistency index and substrate concentration was studied using Equation 7.

The dependency of apparent viscosity on temperature was evaluated using an Arrhenius-type equation (Equation 8):

$$\mu = A \cdot exp(E_a/(R \cdot T)) \qquad (8)$$

Where T is the absolute temperature in kelvin, in the range 30 - 60°C; A (Pa.s) is the Arrhenius constant; E_a ($J.mol^{-1}$) is the activation energy and R ($J.K^{-1}.mol^{-1}$) is the perfect gas constant. Measurements were conducted at a constant shear rate of 100 rpm (3.8 s^{-1}).

Study of the time effect

The effect of time on each gruel was studied at 30°C by monitoring the evolution of gruel viscosity (30% gruel) with time at a constant shear rate of 100 rpm (3.8 s^{-1}). The hysteresis curves were obtained by increasing, directly followed by reducing, the rotating speeds. This procedure for the forward and backward curves was done without interruption.

Model fitting and statistical analysis

The fitting of the models was done using the Sigmaplot © Software Version 11 (wpcubed, GmbH, Germany) while the mean comparison was carried out with Duncan's multiple range test ($P < 0.05$) using IBM SPSS Statistics software version 20.0.0.

RESULTS AND DISCUSSION

Raw material characterization

The average length and diameter of the bananas were respectively 18±1 cm and 3.9±0.2 cm while the colour index according to the commercial peel colour scale was located between 6 and 7. This classification of banana ripening was done using a colour index as presented by Aurore et al. (2009). Table 1 presents the physical characteristics and germination rates of sorghum and sesame. According to the CODEX (1989), the percentage of waste obtained for sorghum and sesame are low (1.62 and 0.41% respectively), reflecting the good quality of the grains. The weight of 1000 grains shows that sorghum grains are on average twice as heavy as, and more uniform than sesame grains. The weight of 1000 grains gives an indication of the quantity of matter (mainly starch in the case of cereals) that can be extracted from the different seeds. The observed difference in grain weight could be essentially due to variations in grain dimensions (Purseglove, 1972), growing conditions of the plant or storage conditions after harvest (FAO, 1989). Under the tested experimental conditions (22±1°C and saturated atmosphere), the stabilization phase during germination occurred at the third day with a respective rate of 95 and 99% for sorghum and sesame. It was also observed that, the germination rate of sesame was higher than that of sorghum throughout the germination period. The observed low percentage germination of sesame compared to that of sorghum can be due to the fact that, radicals grow during germination mainly by using carbohydrate reserves and sorghum has more carbohydrates than sesame. The results were different from that of Hahm et al. (2009) who obtained a sesame germination rate greater than 99% after four days of germination at 35°C and in a saturated atmosphere. This

Table 1. Percentage of waste, weight of 1000 grains and germination rate of sorghum and sesame.

Grains	Percent of waste	Weight of 1000 grains (g)	Germination rate (%)
Sorghum	1.62 ± 0.36	50.71 ± 1.73	95.33 ± 1.53
Sesame	0.41 ± 0.13	23.80 ± 6.05	99.67 ± 0.58

Table 2. Proximate analysis of the raw materials and corresponding flours.

Substrate	Humidity (g/100g w-b)	Total sugars (g/100g d-b)	Soluble sugars (g/100g d-b)	Lipids (g/100g d-b)	Total proteins (g/100g d-b)	Ash (g/100g d-b)
SON	11.47 ± 0.91^{d}	78.04 ± 10.47^{bc}	1.29 ± 0.10^{b}	1.88 ± 0.86^{a}	6.14 ± 0.27^{a}	0.98 ± 0.02^{bc}
SOG	11.33 ± 1.15^{d}	72.49 ± 2.53^{b}	5.43 ± 0.32^{d}	1.09 ± 0.56^{a}	6.02 ± 0.36^{a}	0.99 ± 0.01^{c}
SEN	3.33 ± 1.15^{a}	2.59 ± 0.64^{a}	0.57 ± 0.11^{a}	57.24 ± 2.39^{c}	21.65 ± 0.52^{b}	0.93 ± 0.04^{a}
SEG	6.00 ± 0.00^{b}	2.40 ± 0.40^{a}	1.02 ± 0.52^{b}	50.71 ± 2.52^{b}	18.91 ± 0.16^{b}	0.95 ± 0.01^{ab}
BF	76.67 ± 1.15^{e}	77.31 ± 11.25^{bc}	3.53 ± 0.76^{c}	0.36 ± 0.13^{a}	3.87 ± 0.98^{a}	0.96 ± 0.01^{ab}
BD	8.44 ± 0.51^{c}	85.37 ± 2.02^{c}	5.75 ± 2.36^{d}	0.46 ± 0.09^{a}	3.06 ± 0.86^{a}	1.00 ± 0.01^{c}

On the same column. data followed by the same superscript letter are not significantly different at the 5% level. SON: non-germinated sorghum ; SOG: germinated sorghum; SEN: non-germinated Sesame; SEG: germinated sesame; BF: fresh banana; BD: dried banana.

observed difference in the germination time could be attributed to differences in germination temperatures and absence of an initial soaking step (24 h soaking at 22°C in our case). In addition, several authors have shown the importance of the soaking step in the efficiency of the germination (Elmaki et al., 1999; Eneje et al., 2004).

Table 2 presents the physico-chemical characteristics of the raw materials and the derived flours. The results show that for sorghum and banana, the carbohydrates occupy more than 77% of the dry matter, followed by proteins (more than 3%), while for sesame, lipids come first (57%) followed by proteins (22%). These results are similar to those reported by Onyango et al. (2011) for sorghum; Forster et al. (2003) and Abbas (2009) for banana and Elleuch et al. (2007), Ciftçi et al. (2008) and Hahm et al. (2009) for sesame. The germination presents a significant effect ($P<0.05$) on the carbohydrate content of sorghum and on the lipid content of sesame, as also reported by Hahm et al. (2009). Compared to total sugars, soluble sugar contents are much lower for all the biological materials. However, the soluble sugar content was observed to be higher after germination, due to the increase in α-amylases activity (Elkhalifa and Bernhardt, 2010) resulting in a corresponding increase in starch hydrolysis. The osmotic dehydration applied to banana explains the higher soluble sugar content in the dried fruits compared to the fresh fruits (Jiokap Nono et al., 2002). This is advantageous as the presence of soluble sugars in flour destined for infant gruel increases the energy intake of the child (Gerbouin, 1996; Joshi and Verma, 2015). All the treatments applied do not have significant effect on the ash and protein contents; this is important for weaning foods where proteins have an important role (Elkhalifa and Bernhardt, 2010).

Effects of temperature and concentration on the rheological behaviour of the gruels

Sorghum purée at 15 and 25% w/w presented a two-phase behaviour, the first at shear rates less than 1.2 s^{-1} and the second at shear rates greater than 1.2 s^{-1}, while that of 35% showed a single phase behaviour (Figure 1). Similar to the first phase of 15 and 25% w/w concentrations, the 35% concentration showed a pseudoplastic behaviour (decrease of the viscosity with the spindle's rotation speed) throughout the range of the shear rate. The observed pseudoplastic behaviour could be due to the progressive breakdown of inter-molecular forces resulting from the breakdown of hydrogen bonds that maintains the main structural component of sorghum (Steffe, 1996; Guerrero and Alzamora, 1997). Concerning the dilatant behaviour observed at lower concentrations, it could be accounted for reformation of already broken bonds at high shear rates. These behaviours were observed for the four tested temperatures (30°C, 40°C, 50°C and 60°C). Very few studies have been carried out on the rheological properties of sorghum gruels and those presented in the literature relate to the rheological properties of sorghum starch during gelatinization (Vallons et al., 2009; Matalanis et al., 2009; Onyango et al., 2010; Onyango et al., 2011) but not after cooking as it is the case in the present work.

Unlike sorghum gruels, all the three concentrations of sesame gruels presented a single phase pseudoplastic behaviour throughout the tested range of shear rates (Figure 2). The decrease in resistance to flow could be due to structural deformation, bursting of lipid droplets (main component of sesame) and breakdown of primary and secondary bonds by shear-induced hydrodynamic

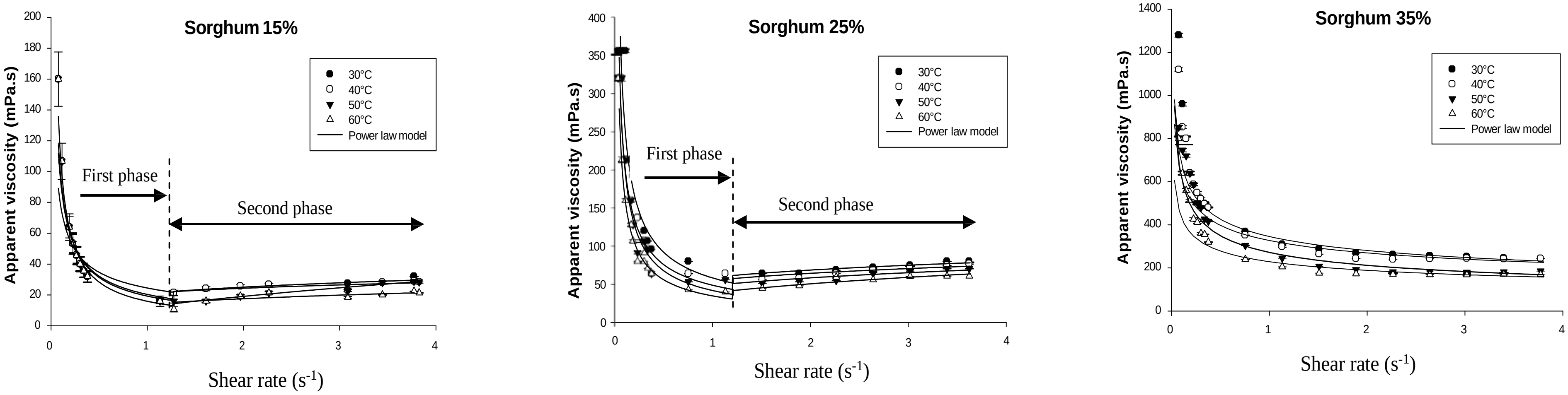

Figure 1. Effects of the rotation speed on viscosity of sorghum gruels at different concentrations and temperatures.

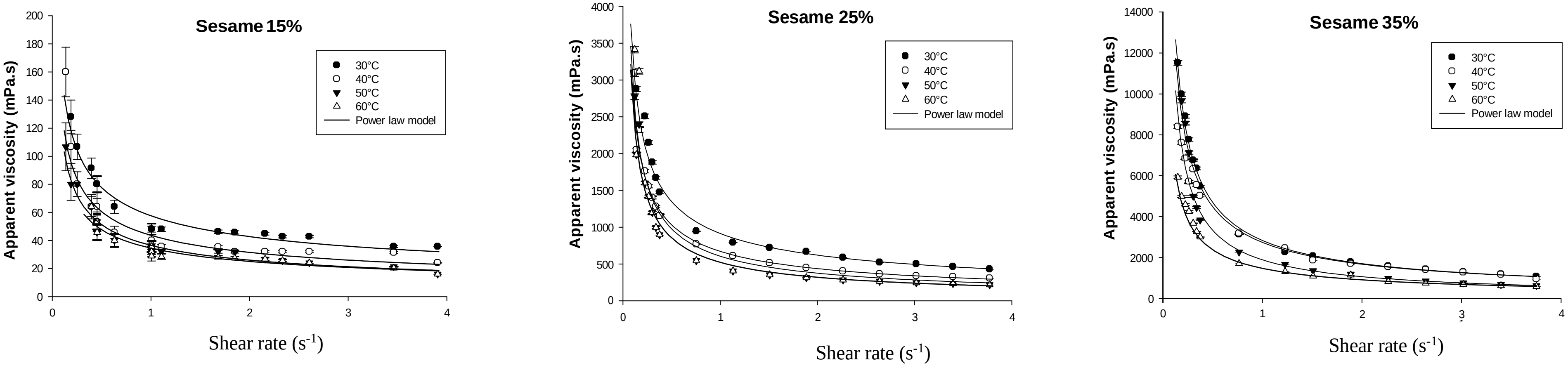

Figure 2. Effects of the rotation speed on the viscosity of sesame gruels at different concentrations and temperatures.

forces (Arslan et al., 2005). Similar to the case of sorghum, this behaviour was observed for the four tested temperatures. Similar behaviours have been observed by other authors on sesame pastes, mixed or not mixed with other products (Arslan et al., 2005; Razavi et al., 2007; Çifçi et al., 2008; Akbulut et al., 2012) and on oil/water emulsion of protein isolates and sesame oil (Lokumcu Altay and Ak, 2005).

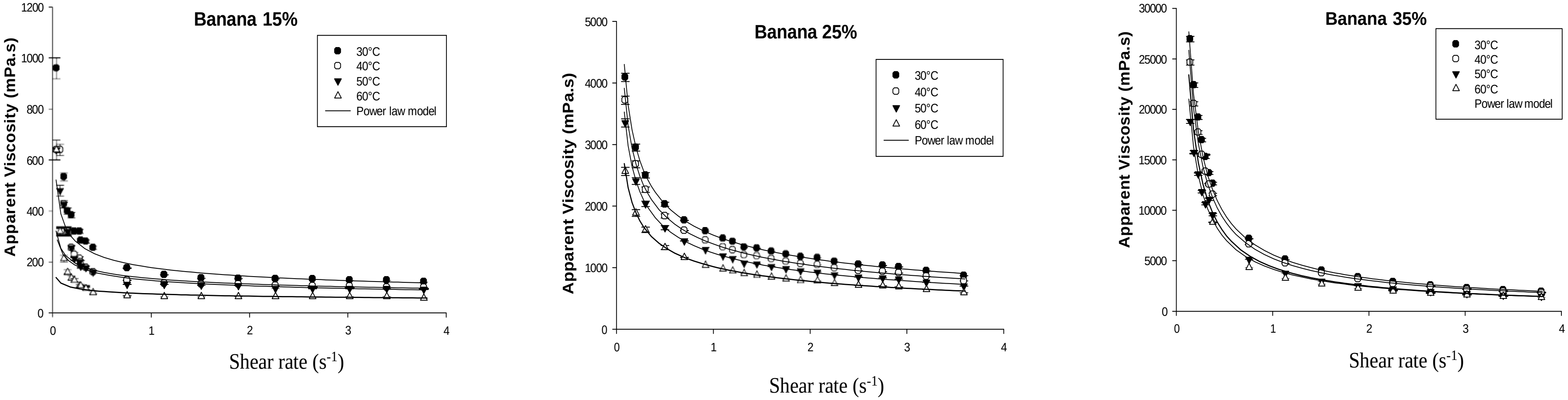

Figure 3. Effects of the rotation speed on the viscosity of banana gruels at different concentrations and temperatures.

Banana gruels showed a similar behaviour to that of sesame gruels (Figure 3). Similar behaviour of banana purée was also observed by Guerrero and Alzamora (1997). The viscosity values for the banana gruels were relatively high, compared to those of sesame and sorghum for each given temperature and concentration. This could be attributed to the differences in composition between the products (Table 2). For all the tested concentrations of the banana gruel, the viscosity as well as the consistency index globally decreased with increase in temperature, which can be attributed to the rupture of intermolecular bonds by thermal energy, leading to a decrease in the torque at a given speed of rotation. Ahmed and Ramaswamy (2007) also observed a decrease of the consistency index with temperature. Concerning the effects of concentration, the viscosity of the banana gruels increased with concentration while the flow behaviour index decreased, explained by the increase in the solid matter with concentration. Similar observations were obtained by Mohamed et al. (2010). Sorghum and sesame gruels presented similar evolution of viscosity, consistency and flow behaviour indices with temperature and concentration. However, the pseudo-stationary viscosity of banana gruels increased by a factor relatively high compared to those of sorghum and sesame gruels, as the concentration increased from 15 to 25 to 35%. Moreover, the flow index values obtained with sorghum gruels at 35% are due to the fact that this concentration (unlike the sorghum gruels at 15 and 25%) didn't present a two-phase behaviour.

Mathematical models for predicting the rheological parameters

The flow curves of all the three gruels showed a good fit with the Ostwald de Waele model (p-values less than 0.01), while the Herschel-Bulkley model was less suitable as it produced negative shear-stress thresholds. The corresponding values of the flow and consistency indices as well as the model statistical parameters are presented in Table 3. However, in the case of banana purée, the values of the flow index ($0.18 < n < 0.82$) were relatively higher than those presented in the literature (Guerrero and Alzamora, 1997) and this could be due to differences in raw material composition and treatment procedures. For each substrate concentration, the values of the consistency index for banana gruels were relatively high compared to those of sorghum and sesame gruels. The effects of concentration on the consistency index were conveniently described by the exponential model (Equation 7), with R^2 values ranging from 0.991 to 0.999 (Table 4) and Figure 4 presents the model fit with respect to experimental data. The values of the model parameter k_0, were comprised between

Table 3. Parameters of the power law model ($\tau = k \cdot \dot{\gamma}^{n}$) at different temperatures and substrate concentrations.

Substrate	T (°C)	Substrate concentrations (% w/w)								
		15			25			35		
		k (mPa.s^{n})	n (-)	R² adj	k (mPa.s^{n})	n (-)	R² adj	k (mPa.s^{n})	n (-)	R² adj
Sorghum (first phase)	30	24.49 ± 1.92^{a}	0.50 ± 0.09^{a}	0.735	58.41 ± 6.64^{a}	0.34 ± 0.08^{ab}	0.650	345.96 ± 7.93^{a}	0.70 ± 0.02^{a}	0.993
	40	20.34 ± 1.66^{b}	0.34 ± 0.07^{b}	0.653	48.83 ± 4.61^{b}	0.36 ± 0.07^{a}	0.753	327.47 ± 11.58^{b}	0.72 ± 0.03^{a}	0.984
	50	19.26 ± 0.95^{b}	0.30 ± 0.05^{b}	0.788	41.89 ± 4.07^{bc}	0.30 ± 0.07^{c}	0.678	229.30 ± 7.29^{d}	0.72 ± 0.03^{a}	0.988
	60	15.90 ± 1.04^{c}	0.17 ± 0.05^{c}	0.555	34.83 ± 1.90^{c}	0.31 ± 0.04^{c}	0.883	272.39 ± 9.66^{c}	0.64 ± 0.03^{b}	0.976
Sorghum (second phase)	30	20.95 ± 2.07^{a}	1.26 ± 0.08^{b}	0.982	75.92 ± 5.91^{a}	1.00 ± 0.07^{b}	0.967	345.96 ± 7.93^{a}	0.70 ± 0.02^{a}	0.993
	40	21.05 ± 2.53^{a}	1.21 ± 0.10^{b}	0.970	63.84 ± 5.14^{b}	1.10 ± 0.07^{ab}	0.973	327.47 ± 11.58^{b}	0.72 ± 0.03^{a}	0.984
	50	12.33 ± 1.25^{b}	1.63 ± 0.08^{a}	0.991	54.69 ± 4.91^{bc}	1.17 ± 0.08^{a}	0.974	229.30 ± 7.29^{d}	0.72 ± 0.03^{a}	0.988
	60	14.15 ± 2.15^{b}	1.31 ± 0.13^{b}	0.963	48.63 ± 4.24^{c}	1.15 ± 0.07^{a}	0.977	272.39 ± 9.66^{c}	0.64 ± 0.03^{b}	0.976
Sesame	30	55.77 ± 1.55^{a}	0.66 ± 0.03^{ab}	0.979	914.11 ± 13.27^{a}	0.44 ± 0.01^{a}	0.989	2836.07 ± 29.23^{a}	0.27 ± 0.01^{c}	0.984
	40	39.87 ± 1.54^{b}	0.72 ± 0.04^{a}	0.983	671.09 ± 6.05^{b}	0.38 ± 0.01^{ab}	0.994	2744.45 ± 36.33^{b}	0.29 ± 0.01^{b}	0.977
	50	33.77 ± 1.14^{c}	0.70 ± 0.03^{ab}	0.983	605.00 ± 18.40^{c}	0.31 ± 0.03^{c}	0.916	1892.62 ± 13.77^{c}	0.18 ± 0.01^{d}	0.982
	60	31.38 ± 1.71^{c}	0.65 ± 0.05^{b}	0.959	522.10 ± 13.01^{d}	0.29 ± 0.02^{bc}	0.915	1477.42 ± 11.35^{d}	0.31 ± 0.01^{a}	0.993
Banana	30	177.96 ± 5.60^{a}	0.69 ± 0.03^{b}	0.985	$1\,628.46 \pm 26.25^{a}$	0.52 ± 0.01^{b}	0.998	5603.62 ± 83.07^{a}	0.22 ± 0.01^{a}	0.971
	40	134.89 ± 3.81^{b}	0.75 ± 0.03^{b}	0.991	$1\,458.51 \pm 19.57^{b}$	0.36 ± 0.01^{c}	0.992	5234.80 ± 74.68^{b}	0.22 ± 0.01^{a}	0.973
	50	127.30 ± 4.18^{c}	0.74 ± 0.03^{b}	0.987	801.50 ± 31.9^{c}	0.19 ± 0.01^{d}	0.978	4170.64 ± 33.10^{d}	0.21 ± 0.01^{a}	0.990
	60	74.47 ± 3.28^{d}	0.82 ± 0.04^{a}	0.983	453.37 ± 6.31^{d}	0.75 ± 0.01^{a}	0.997	4369.43 ± 100.50^{c}	0.18 ± 0.01^{b}	0.900

For each substrate and on the same column, data with the same superscript letter are not significantly different according to the Duncan test (P<0.05).

Table 4. Effects of substrate concentration on the consistency index of the gruels at different temperatures: Model parameters for the equation: $\mathrm{k} = \mathrm{k}_0 * \exp(a * C)$.

T (°C)	Substrates											
	Sorghum (first phase)			Sorghum (second phase)			Sesame			Banana		
	$\mathbf{k_0}$	a	R² adj	$\mathbf{k_0}$	a	R² adj	$\mathbf{k_0}$	a	R² adj	$\mathbf{k_0}$	a	R² adj
30	0.90	0.17	0.994	1.85	0.15	1.000	35.39	0.13	0.967	56.13	0.13	0.992
40	0.55	0.18	0.995	1.26	0.16	0.998	15.37	0.15	0.994	45.23	0.14	0.992
50	0.83	0.16	0.991	1.49	0.14	1.000	22.89	0.13	0.980	12.47	0.17	0.999
60	0.27	0.20	0.994	0.74	0.17	0.999	23.68	0.12	0.970	1.64	0.23	0.999

0.27 and 1.85, 15.37 and 35.39 and 1.64 and 56.13 mPa.s^{-n} respectively for sorghum, sesame and banana gruels. In the case of banana gruels, the values of k_0 decreased with temperature as shown on Table 4. For all the studied gruels the parameter, a was comprised between 0.13 and

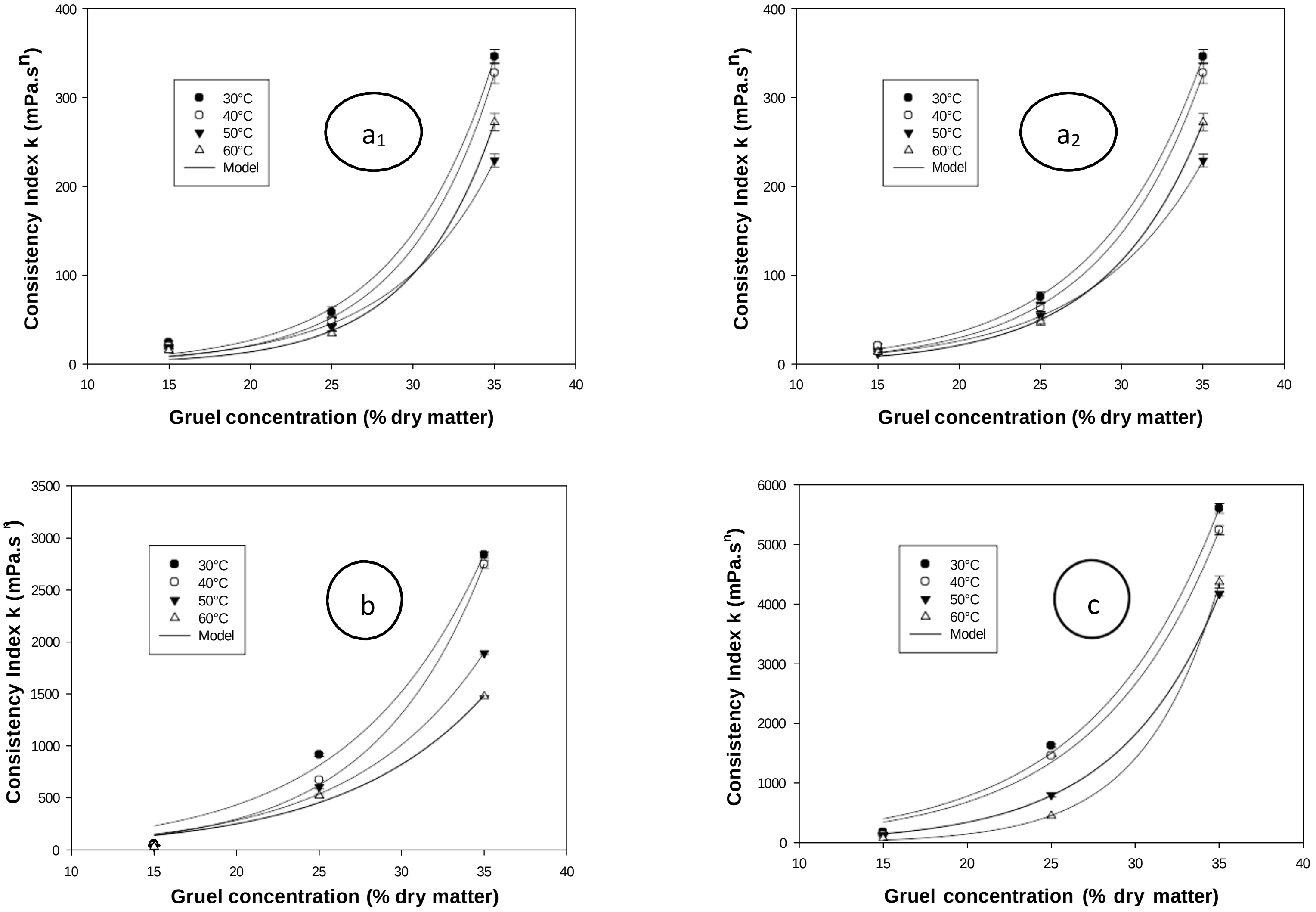

Figure 4. Experimental and model (Equation 7) curves for the gruel consistency index in function of the concentration and temperature: (a1) sorghum-first phase, (a2) sorghum-second phase, (b) sesame and (c) banana.

0.23. Concerning the flow behaviour index, no descriptive trend was observed regarding its variation with temperature and substrate concentration. Similar results were reported by Arslan et al. (2005).

The effect of temperature on the gruels' viscosity

Table 5. Arrhenius-type model parameters for the different gruels.

Substrate	Concentration (% w/w)	A (Pa.s)	E_a ($J.mol^{-1}$)	R² adjusted
Sorghum	15	$1\,406 \pm 13^a$	964 ± 6^c	0.983
	25	514 ± 24^c	$9\,992 \pm 17^b$	0.825
	35	$1\,020 \pm 39^b$	$14\,144 \pm 37^a$	0.968
Sesame	15	232 ± 2^b	$13\,225 \pm 58^c$	0.917
	25	$1\,373 \pm 7^a$	$18\,552 \pm 26^b$	0.964
	35	158 ± 8^c	$21\,070 \pm 38^a$	0.858
Banana	15	$10\,043 \pm 14^b$	$10\,233 \pm 54^c$	0.990
	25	$34\,484 \pm 12^a$	$12\,054 \pm 12^b$	0.946
	35	81 ± 2^c	$18\,825 \pm 17^a$	0.821

For each substrate and on the same column, data with the same superscript letter are not significantly different according to the Duncan test (P<0.05).

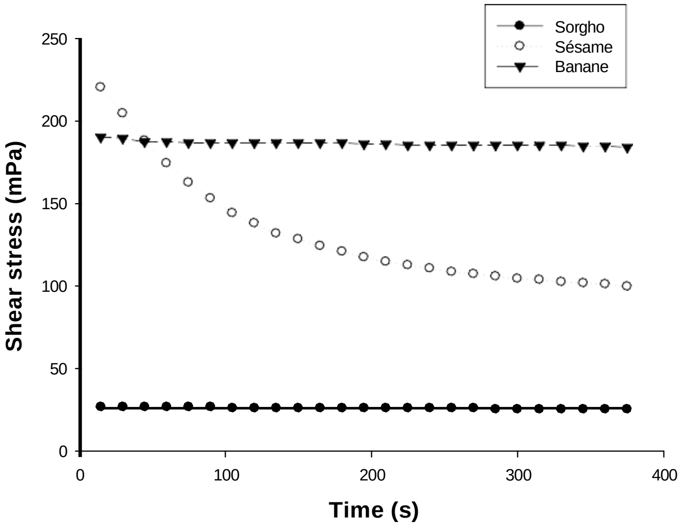

Figure 5. Test of the time sensitivity of sorghum, sesame and banana gruels (at 30% w/w each) at 100 rpm (3.8 s^{-1}) and 30°C.

followed the Arrhenius model (Table 5) with adjusted R² values ranging from 0.820 to 0.990. The value of the constant (A) varied with substrate, ranging from 514 to 1,406 Pa.s for sorghum purée, 158 to 1373 Pa.s for sesame purée, and 81 to 34,484 Pa.s for banana purée. This constant showed no trend regarding its variation with substrate concentration in the three different gruels. These differences could be attributed to the physico-chemical nature of the gruel, mainly their lipid and protein contents for sesame, and carbohydrate content for sorghum and banana; as well as their ease of forming hydrogen bonds. E_a, which measures the sensitivity of the purée viscosities to temperature, was highest for sesame purée (13,225 – 21,070 $J.mol^{-1}$), followed by banana purée (10,233 - 18,825 $J.mol^{-1}$) and then by sorghum purée (964 - 14,144 $J.mol^{-1}$). The value of Ea was observed to increase with flour concentration for all the purées. These results show that the energy required for the fluid to flow increases with concentration (Table 5) and this could be explained by the fact that the number of inter-molecular bonds involved in maintaining the structure of a substrate in a milieu increases as the concentration of the milieu increases. This trend was equally observed by Arslan et al. (2005) on sesame paste.

Effect of time on the rheological behaviour of the gruels

At a constant share rate of 3.8 s^{-1}, the shear stress decreased progressively with time but showed no significant drop for sorghum and banana gruels (Figure 5). To confirm the time dependency of the gruels, a "loop

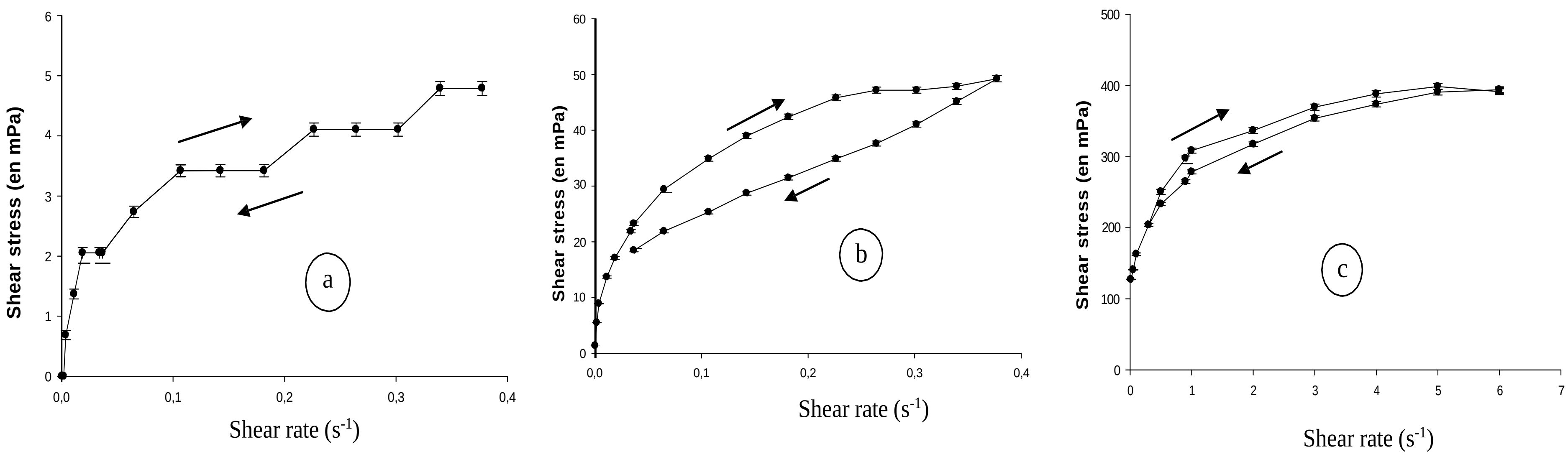

Figure 6. Forward and backward curves of the gruels (30% w/w) at 30°C: (a) Sorghum, (b) sesame and (c) banana.

test" was conducted. The forward-backward curves of the gruels (Figure 6) indicate the absence of a hysteresis loop for sorghum (Figure 6a), confirming thereby the time-independency of sorghum gruel. A hysteresis loop existed for sesame and banana gruels, with ahigher amplitude for the former than for the latter (Figures 6b and c). Lokumcu Altay and Ak (2005) also observed a hysteresis loop on tahin and attributed this behaviour to the thixotropic nature of the substrate. Abu-Jdayil (2003) and Habibi-Najafi and Alaei (2006) also noticed a thixotropic character on sesame-based products.Gruels prepared from infant flours are rich in starchy and protein foods and have a viscosity that increases very rapidly as a function of their dry matter concentration. This makes the gruels difficult to swallow, digest and absorb by children due to reduced activity and capacity of their organs. The rheological study of each of the constituents could make it possible to orient the formulated mixture of these foods, and also to envisage fluidification treatments for the manufacture of infant flour. The gruels derived from these flours should have rheological properties which facilitate the ingestion by the children, while taking into account the nutritional aspects.

Conclusion

This study evaluated the rheological properties of infant gruels produced from sorghum, sesame or banana as base constituents. The sorghum gruels showed dilatant properties at high shear rates and pseudoplastic properties at low shear rates, while the sesame and banana gruels were pseudoplastic fluids throughout the range of shear rates. A good correlation was obtained between the consistency coefficient and concentration for each temperature. For all the gruels, the viscosity reduced with temperature and increased with concentration. The effect of temperature on the gruels' viscosity followed the Arrhenius law. The activation energies were highest for sesame gruels, followed by banana gruels and then sorghum gruels. The later presented a time-independent behaviour, whereas banana and sesame gruels had a time-dependent behaviour. The results of this study could be exploited for the formulation and improvement of derived products, as well as for the dimensioning of equipment and for the conception of production units.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

Abbreviation

M, Mass of sample (g); ***M_g,*** Mass of good grains in the sample (g); ***Wc,*** *W*aste content (%); ***Gr,*** Germination rate (%); ***N_g,*** Number of germinated grains at the end of germination (-); ***N_0,*** Number of good grains (-); ***Mm,*** Mass of 1000 grains (g), ***MS,*** Mass of dry matter in 100 grams of good grains (g), **N,** Rotation speed (rpm); **τ,** Shear stress (Pa), ***R,*** Universal gas constant (Jmol^{-1}K^{-1}); **$\dot{\gamma}$,** Shear rate (s^{-1}); **T_w,** Torsion torque (%); **μ,** Apparent viscosity (Pa.s); **τ_c,** Threshold shear stress (Pa); **n,** Flow index (-); **k,** Consistency index (mPa.s^n); **k_0,** Consistency index model parameter (mPa.s^n); **α,** Consistency index model parameter (100g/g); **A,** Arrhenius constant (Pa.s); **E_a,** Activation energy (J.mol^{-1}); ***T,*** Absolute temperature (K).

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