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Multi-response optimization of the energy value and rheological parameters in the formulation of a complementary infant-gruel flour

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The objective of this study is to present the formulation of complementary infant-gruel flour by applying the multi-response optimization with responses centered on physico-chemical properties, energy value and rheological parameters. A Scheffé simplex network-derived mixture design was adopted to determine the optimal proportions of malted sorghum, malted sesame and dried banana flours, which were the factors considered in the design. The different flour mixtures obtained from the design were cooked in water, using flour to water ratio of 3:7 (w/v) to obtain gruels, and the responses were analysed based on specifications for complementary foods for babies around 6 months old. The results revealed a zone of compromise whose optimal points corresponded to minimum-maximum specifications of 39 to 44% for malted sorghum, 26 to 36% for malted sesame and 20 to 35% for dried banana. The standard protocol for gruel flour production obtained can be used for local production of gruel flours.

Key words: Infant flour specifications, banana, sesame, sorghum, malting, mixture design.

INTRODUCTION

Maternal milk is the complete ideal food used for the feeding of infants from birth to the age of four months (Eidelman and Schanler, 2012). Above this age, the nutritional needs increase and maternal milk alone becomes insufficient (CODEX, 2006) requiring the use of complementary foods. During the transition period from exclusive maternal milk to adult foods, mothers have the choice of producing gruel (also called purée or porridge depending on the consistency) by themselves or using imported flours for gruel production (de Pee and Bloem, 2009). However, traditional gruels are less nutritional as their protein content and energy value remain lower than

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the limits fixed by the WHO: 0.055 g/g and 1 kcal/g, respectively (Onoja et al., 2014; Ndagire et al., 2015).

Even though imported flours present better nutritional properties, they are relatively expensive for most African households; meanwhile their production using local food products is possible (Adeniyi, 2012). In the commercial platform, they exist in two forms: Instant infant flours, easy to prepare by diluting in hot water and non-instant infant flours destined for cooking before consumption. Compared to instant infant flours, the production of non-instant infant flours is less complex and less expensive (Adeniyi, 2012; Obiakor-Okeke et al., 2014; Ikujenlola et al., 2017).

For non-instant infant flour production, a precise content of carbohydrates, lipids, proteins, mineral salts and vitamins is recommended to ensure the right nutritional complementation of maternal milk (CODEX, 2006). These basic nutritional components can be obtained from various food products depending on the geographical location. Cereals like sorghum, millet, corn and rice, are important sources of carbohydrates in infant flours (Anigo et al., 2010; Adeniyi, 2012; Obiakor-Okeke et al., 2014; Bolarinwa et al., 2016). Proteins are provided by powdered milk, black-eyed pea, soya beans and dry beans (Soro et al., 2013; Onoja et al., 2014; Ikujenlola, 2014; Ndagire et al., 2015). For the lipid needs, oily grains such as groundnuts, pumpkin seeds, sesame or vegetable oils are used (Onabanjo et al., 2009; Adeniyi, 2012; Ijarotimi and Keshinro, 2013). Concerning the mineral and vitamin needs common fruits or supplementary minerals and vitamins (de Pee and Bloem, 2009) are used.

Amongst the available cereals in Cameroon, sorghum and millet, whose production tonnage reached 1,187,531 tons in 2010 (MINADER, 2012) and 1,150,000 tons for sorghum after four years (FAOSTAT, 2014), are currently used traditionally in the production of infant flours. Sorghum is therefore a potential cereal in the preparation of infant flours, but it still needs some supplements in nutrients other than carbohydrates, which could be obtained from other sources. The lipid and protein fractions could be obtained from sesame (Elleuch et al., 2007), which is readily available (MINADER, 2012) and less allergic (Arjon et al., 2007) compared to other lipid sources. The choice of sesame is supported by the increase in its cultivated area in Cameroon, more than 21.4% in 2010 (MINADER, 2012) leading to a national production of 48,000 tons (FAOSTAT, 2014). Ripe bananas, well appreciated by weaning-age infants (Honfo et al., 2011) could be used to supplement for the vitamin and mineral contents (Abbas et al., 2009). Cameroon occupies the thirty-second position in the world's banana production with a tonnage production of 1,719,009 tons (FAOSTAT, 2014). Despite this wide variety of nutritional resources for the production of infant flour, there is little information regarding their use for infant flour production that respects the norms.

Concerning studies on flour-based products, several reports have been presented in the literature. Matalanis et al. (2009) studied the textural and thermal properties of sorghum starch pastes; Onyango et al. (2011) evaluated the effect of cassava starch on the rheological and crumb properties of sorghum-based batter and bread, respectively. Other authors studied the rheological behavior of banana purée (Ahmed and Ramaswamy, 2007; Alvarez et al., 2008; Maka Taga and Jiokap Nono, 2017), suspensions made of banana and wheat flours (Mohamed et al., 2010), semi-solid sesame paste (Abu-Jdayil et al., 2002; Çiftçi et al., 2008), sesame-based products (Alpaslan and Hayta, 2002; Razavi et al., 2007) and oil-in-water emulsions prepared with oil and protein isolates from sesame (Brewer et al., 2016). In addition, a recent study evaluated the effects of concentration and temperature on the rheological properties of sorghum, sesame and banana gruels (Maka Taga and Jiokap Nono, 2017). However, the aforementioned studies were geared towards investigating the rheological and textural properties of flour-based products formulated from ingredients other than a combination of sorghum, sesame and banana. The results presented are hence inadequate to accurately predict the rheological, nutritional and energy properties during the formulation of gruel flour using mixture design applied on sorghum, sesame and banana as input variables. The objective of this study is to formulate new complementary infant gruel flours, by combining malted sorghum, malted sesame and dried banana flours and to assess their nutritional, rheological and energy properties.

MATERIALS AND METHODS

Food products for gruel flour production

The food products used for gruel flour production were sorghum (*S. bicolor* cv. Safrari), white sesame (*S. indicum*) and ripe banana (*Musa acuminata*, Cavendish). Sorghum and sesame were obtained from the Institute of Agricultural Research for Development (IRAD) at Maroua (Far-North Region, Cameroon) while banana was obtained from a local market in Ngaoundere (Adamawa Region, Cameroon). The bananas were ripened to reach a colour index ranging from (6-7) based on the commercial peel colour scale (Aurore et al., 2009).

Physicochemical analyses

The water content was determined by AOAC (1990) method, the ash content by AFNOR (1981) method and the total nitrogen after mineralization of the samples according to Kjeldahl method (AFNOR, 1984). The colorimetric technic of Devani et al. (1989) was used for the nitrogen 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 Dinitrosalicylic acid) colorimetric method of Fischer 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). The lipid content was determined after hexane soxhlet

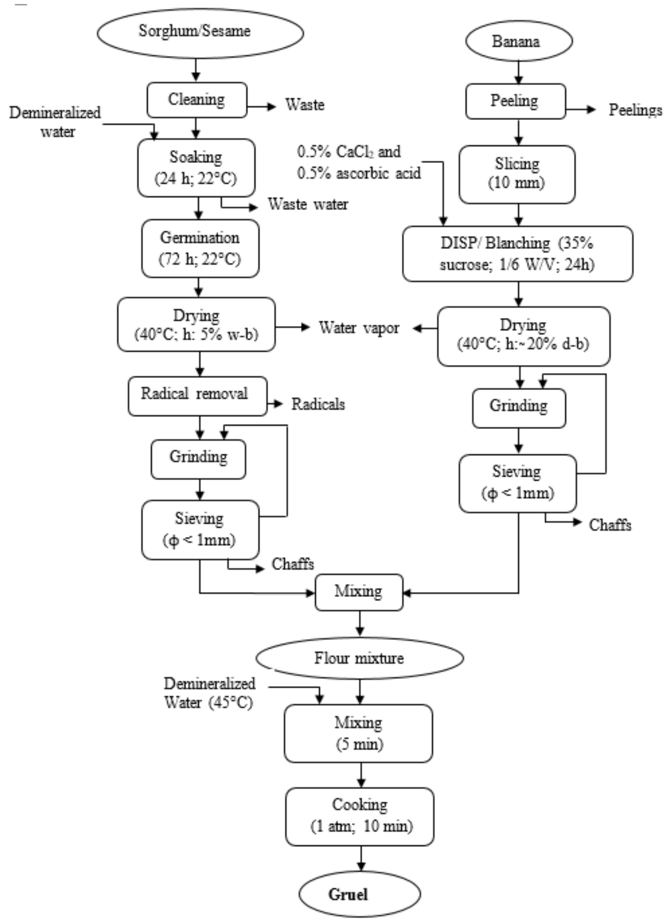

Figure 1. Process diagram for the production of a gruel using sorghum, sesame and banana. DISP: Dewatering-Impregnation-Soaking Process.

extraction as described by Boureley (1982).

Dynamics of germination rate and determination of the germination time

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 until stabilization, which corresponded to the time of germination. Equation 1 was used to determine the germination rate, where N_g and N_0 are respectively the number of germinated grains at a given time and the number of initial good grains. The time required for germinating each cereal was determined and used during the gruel flour production (Maka Taga and Jiokap Nono, 2017).

$$Gr = (N_g/N_0).100 \quad (1)$$

Process for flour mixture and gruel production

The sorghum and sesame were separately treated as described by Elkhalifa and Bernhardt (2010) and 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 at 22 ± 1°C over a period. 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 flour of particle-size less than 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 (using a flour to water ratio of 3:7 w/v) and the mixture (1 L) was placed in a stainless-steel pot (2 L 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 and Mouquet (2008), this procedure leads to the production of low viscosity purées and as such, most appropriate for infants. The overall process that was used for the preparation of the gruel flour mixture using the different ingredient is presented in Figure 1.

Table 1. Recommended specifications for complementary foods (from 4 months to 3 years old).

Reference	Units	Component	Minimum	Maximum	Comment
*	g/100 g of gruel	Carbohydrates	7.5	20	
		Lipids	3.1	5.4	
		Proteins	3.6	6.6	
	g/100 g db	Carbohydrates	25	70	
		Lipids	10	18	
		Proteins	12	22	
	Kcal/ 100 g gruel	Energy value	80	/	
	Kcal /100 g db	Energy value	400	/	
**	cP	Viscosity	/	1000	Around 6 months
	cP	Viscosity	/	2000	Around 8 months
Present work	(-)	Flow behaviour index	/	/	Maximize
	$Pa.s^{-n}$	Consistency index	/	/	Minimize

*: CODEX (2006) and Mouquet et al. (1998). **: Gerbouin-Rerolle (1996).

Table 2. Presentation of the different factor levels.

Factors	Lower level	Center	Upper level
Germinated sorghum (SOG, X_1)	0	0.5	1
Germinated sesame (SEG, X_2)	0	0.5	1
Dried banana (BS, X_3)	0	0.5	1

Determination of the energy value

The energy value was calculated by the EEC (1990) conversion method, based on the fact that 1 g of carbohydrate provides 4 kcal, 1 g of lipid provides 9 kcal and 1 g of protein provides 4 kcal. Therefore, the energy value (Ve) was calculated as follows (Equation 2):

$$Ve = 4X+9Y+4Z \quad (2)$$

Where X, Y and Z are respectively the dry matter percentages of carbohydrates, lipids and proteins.

Rheological measurements

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. The apparent viscosity was calculated as described by Anonymous (1998) with a dimensionless factor of the spindle equal 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 3 (Mitschka, 1982):

$$\dot{\gamma} = (0.119 \, . \, Tw) / \mu \quad (3)$$

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

The rheological parameters (consistency index 'k' and flow behaviour index 'n') were determined by adjustment, either using the Herschel-Bulkley model (Equation 4) or using the power law model (Equation 5):

$$\tau = k \cdot (\dot{\gamma})^n + \tau_c \quad (4)$$

$$\tau = k \cdot (\dot{\gamma})^n \quad (5)$$

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

Mixture design and response surface methodology

The mixture design method was used to determine the optimal mixing proportions of the three different ingredients (sorghum, sesame and banana flours) used in the production of a gruel flour mixture respecting the nutritional, rheological and energy specifications presented in Table 1. In the mixture design, the factors were the proportion of each ingredient involved in the gruel flour mixture, that is: The proportions of malted sorghum (SOG, X_1), malted sesame (SEG, X_2) and dried banana (BS, X_3). The values of the factors (X_i) were thus comprised between 0 and 1 ($0 \leq X_i \leq 1$) as shown in Table 2. Based on the specifications for infant flours presented in Table 1, the responses were the soluble sugar content (Y_1), total sugar content (Y_2), lipid content (Y_3), protein content (Y_4), energy value (Y_5), viscosity (Y_6) flow behavior index (Y_7) and consistency index (Y_8) of the gruel flour mixture. The first four responses were determined using the nutritional properties of the individual flours present in the flour mixture as shown in Equation 6:

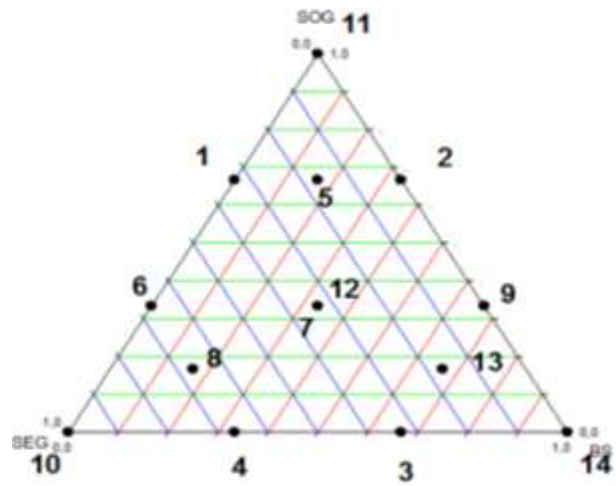

Figure 2. Simplex lattice mixture design experimental points for the effects of malted sorghum (SOG, X1), malted sesame (SEG, X2) and dried banana (BS, X3).

Table 3. Standard values and acceptable range of model validation indicators.

Model validation indicators	Standard values	Acceptable range	References
Adjusted R^2	1	> 80%	Joglekar et May (1987)
AAD	0	[0-0.3]	Baș and Boyac (2007)
Bias factor	1	[0.75-1.25]	Dalgaard and Jorgensen (1998)
Accuracy factor	1	[0.75-1.25]	Dalgaard and Jorgensen (1998)

$$Y_j = \sum_{i=1}^{3} c_i * X_i \quad (6)$$

Y_j $(j = 1, 2, 3, 4)$ are the responses applied to the flour mixture, c_i the content of the different nutritional classes of the i^{th} ingredient and X_i the different factors. Concerning the gruels from different flour mixtures, responses were obtained through physico-chemical analyses. The energy value (Y_5) for the flour mixtures and gruels was calculated as presented in Equation (2), while the viscosity (Y_6), flow behavior index (Y_7) and consistency index (Y_8) of the gruels from flour mixtures were determined using Equations (3), (4) and (5). Since the study involved three dependent factors with no constraints, the experimental domain was the internal surface of an equilateral triangle. The Scheffé matrix, whose simplex network was (3,3) and having 10 initial points was used for the study. Three test points were added as well as a repetition at the center, to verify and ameliorate the precision of the experiments (Mathieu and Phan-than-luu, 2001), making 14 points presented in Figure 2.

Modelling and multi-response optimization

The relationship between the factors and responses was modelled using a polynomial model of the form shown in Equation (7):

$$Y_j = \beta_{1,j}X_1 + \beta_{2,j}X_2 + \beta_{3,j}X_3 + \beta_{12,j}X_1X_2 + \beta_{13,j}X_1X_3 + \beta_{23,j}X_2X_3 + \beta_{123,j}X_1X_2X_3 \quad (7)$$

Y_j $(j = 1 \text{ to } 8)$ are the responses or dependent variable, X_i the factors or independent variables, $\beta_{1,j}$, $\beta_{2,j}$ and $\beta_{3,j}$ the linear factor coefficients, $\beta_{12,j}$, $\beta_{13,j}$ and $\beta_{23,j}$ the quadratic factor coefficients and $\beta_{123,j}$ the cubic factor coefficients. The Statgraphics software, Centurion XV version 15.2.06 (Statpoint Technologies, Inc., Warrenton, VA, USA), was used for modelling, statistical analysis, optimization and plotting. The validation of the models was done by comparing the values of the adjusted coefficient of determination (R^2_{aj}) (Equation 8), the average absolute deviation (AAD) (Equation 9), the bias factor (B_f) (Equation 10), and the accuracy factor (A_f) (Equation 11), to the reference values presented in Table 3.

$$R^2_{aj} = \sum_{i=1}^{n} \frac{(Y_{cal,i} - \bar{Y}_{obs})^2}{(Y_{obs,i} - \bar{Y}_{obs})^2} \quad (8)$$

$$AAD = \frac{\sum_{i=1}^{n} \frac{|Y_{obs,i} - Y_{cal,i}|}{Y_{obs,i}}}{n} \quad (9)$$

$$B_f = 10^{\left(\frac{1}{n}\sum_{i=1}^{n} \log\left(\frac{Y_{cal,i}}{Y_{obs,i}}\right)\right)} \quad (10)$$

$$A_f = 10^{\left(\frac{1}{n}\sum_{i=1}^{n} \left|\log\left(\frac{Y_{cal,i}}{Y_{obs,i}}\right)\right|\right)} \quad (11)$$

Y_{obs} is the observed experimental response, Y_{cal} the predicted response and n the total number of experiments. After validation of the models, analysis of variance (ANOVA) was used to identify the factors or factor interactions, which significantly influence the responses. A factor is significant at 95% interval if its p-value is less than 0.05. The multi-response optimization was used to determine the factor levels that met the nutritional requirements presented in Table 1. This optimization approach applies to all the experimental designs that use response surface methodology (RSM), which is a mathematical and statistical tool that uses quantitative data to determine an adequate functional relationship between a response of interest and a number of associated control (or input) variables. Such a functional relationship is usually unknown but can be approximated by a low-degree polynomial model (Khuri and Mukhopadhyay, 2010). RSM simultaneously solves multivariate equations, to optimize processes or products as applied in the literature (Sefa-Dedeh et al., 2003; Wang et al., 2007; Fikiru et al., 2016; Kouteu Nanssou et al., 2016). The determination of the factor levels that met the required gruel specifications was done by building the so called «desirability» function based on the values of the responses, which was maximized, minimized or fixed with respect to the objectives of the optimization. In the case of our study, Y_6 was minimized, Y_7 maximized, Y_2, Y_3, Y_4 and Y_5 fixed while Y_1 was maximized and minimized. The built «desirability» function was then used to superpose the different responses in order to determine the definitive optimal zone (Statpoint, 2005).

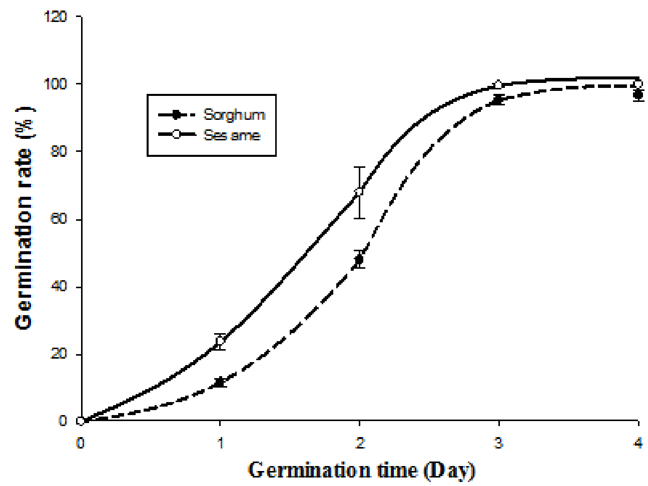

Figure 3. Dynamics of the germination rate of sorghum and sesame grains

RESULTS AND DISCUSSION

Germination of the food products

Figure 3 presents the germination rates of sorghum and sesame grains. The results showed that the germination rates of sorghum grains were higher than those of sesame throughout the germination period, and increased with the germination time to a steady value of 95 and 99% (from the third day), respectively for sorghum and sesame. The results were contrary to that of Hahm et al. (2009), who obtained a steady germination rate for sesame, as from the fourth day at 35°C and in a saturated atmosphere. This 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 addition, several authors have shown the importance of the soaking step in the efficiency of germination (Eneje et al., 2004; Elkhalifa and Bernhardt, 2010). In essence, the moisture gained by the grains during soaking favours the germination step during which the formation of gibberellic acid is completed. The transportation of the later through the aleuronic layer of the grains induces the production of degradation enzymes (Palmer, 2006) which thus lyses the aleuronic layer and facilitates the expulsion and growth of the radical.

Physico-chemical characteristics of the different flours

Based on our previous study (Maka Taga and Jiokap Nono, 2017), the sorghum and banana 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%). Germination was observed to have a significant effect (P<0.05) on the carbohydrate content of sorghum and on the lipid content of sesame. Compared to total sugars, the soluble sugar contents of all the biological materials were lower. However, the soluble sugar content was observed to be higher after germination, due to the increase in α-amylases activity resulting in a corresponding increase in starch hydrolysis (Elkhalifa and Bernhardt, 2010). The osmotic dehydration applied to banana explained 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 infant gruel flour increases energy intake of the child (Van Hoan et al., 2010).

The protein content of malted sesame was highest (18.91%) compared to that of dried banana and malted sorghum. All the applied treatments caused a slight, but non-significant decrease in the protein content of all the products. This can be explained by the fact that proteolytic activity increases with germination time, resulting in the production of free amino acids which will be consumed to produce energy required for germination. According to Elkhalifa and Bernhardt (2010), there is also a simultaneous increase in protein synthesis, which justifies the non-significant decrease in protein content observed in sorghum and sesame. For banana, drying at a temperature of about 40°C minimizes protein denaturation (Jiokap Nono et al., 2002).

For sorghum and banana, the effects of treatments on the lipid contents showed a similar tendency to that of protein, but decreased significantly (p<0.05) in the case of sesame as presented in Table 4. According to Hahm et al. (2009), the breakdown of lipids and sugars releases energy required for protein synthesis during germination. The low sugar content of sesame (2.59%) however favors the preferential utilization of lipids for germination while in the case of banana, its lipid content is low and the drying temperature of 40°C limits the lipolytic activity (Cheftel et al., 1983).

The different treatments did not significantly affect the ash content of most of the products. According to Hahm et al. (2009), germination only slightly increases the ash content by increasing phosphorous, sodium and calcium contents. The ash content is not affected by the drying procedure, as they are non-volatile under the experimental temperature used.

Comparison between the properties of the flour mixtures and derived gruels

Table 5 presents the differences in the responses between the flour mixtures and the derived gruels using the various combinations presented by the experimental matrix. The difference (diff 1) between the soluble sugar content of the flours (Y_1 (f)) and those of the derived gruels (Y_1 (b)) for experiments 6, 8, 11, 12 and 13 showed an increase in soluble sugar content of the gruel. This difference increased with the proportion of germinated sorghum (X_1) and could be an important ameliorating factor of the soluble sugar content (Y_1) after cooking. In the case of total sugars, the content also increased in the gruel for all the experimental points, being more significant for experiments 2, 3, 4, 6 and 13 where factor X_3 (dried banana flour) is low (0 - 0.33). This implies factor X_3, associated with other factors could contribute to decrease the total sugar content of the gruel compared to that of the flours (Table 5). The lipid content (Y_3) however decreased for almost all the experimental points particularly for points 2, 3, 10 and 13 where factor X_2 (germinated sesame) is high (between 0.67 and 1). For low values of factor X_2 (between 0 and 0.33), only a slight increase in lipid content was observed (experiments 1, 6, 7 and 9). This tendency could be explained by the high lipid content (50%-db) of factor X_2, favouring interaction (for large quantities of factor X_2) with other components present in the medium, thereby, decreasing its lipid content. The protein content (Y_4) of the gruel increased for all the experimental points, except for point 2 where only factors X_1 and X_2 are present. Concerning the energy value of the gruel (Y_5) it also increased for all the experimental points, except point 10 where only factor X_2 (germinated sesame) was present in the mixture. Factor X_2 has the highest lipid and protein content but the lowest sugar content. Considering the difference in lipid content between the flour and the gruel (diff 3), this factor contributes to the observed decrease in lipid content and since lipids possess the highest energy density, the overall energy value will consequently decrease. This is justified by experiments 5 and 6 having the highest increase in energy value with low proportions of X_2 (between 0 and 0.33).

Model equations, statistical validity and factor effects

Table 6 presents the observed and calculated responses for each experiment of the mixture design and the models for the nutritional, rheological and energy responses are presented in Equations 12 to 19. The models were reduced cubic polynomials whose coefficients express the positive or negative intensity of the factor effects on the corresponding responses. Concerning the rheological responses, the Ostwald de Waele model was used since it showed a good fit (P-values less than 0.01) compared to the Herschel-Bulkley model.

$$Y_1 = 11.047X_1 + 0.377X_2 + 3.468X_3 - 2.432X_1X_2 - 12.546X_1X_3 - 2.904X_2X_3 + 35.519X_1X_2X_3 \quad (12)$$

$$Y_2 = 79.864X_1 + 7.69215X_2 + 85.300X_3 + 78.256X_1X_2 - 8.526X_1X_3 + 60.06_1X_2X_3 - 236.464X_1X_2X_3 \quad (13)$$

$$Y_3 = 2.227X_1 + 41.193X_2 + 0.836X_3 - 4.111X_1X_2 - 0.263X_1X_3 - 11.315X_2X_3 + 91.717X_1X_2X_3 \quad (14)$$

$$Y_4 = 10.668X_1 + 20.745X_2 + 4.763X_3 - 11.041X_1X_2 + 2.934X_1X_3 + 0.0845X_2X_3 + 73.532X_1X_2X_3 \quad (15)$$

$$Y_5 = 372.876X_1 + 490.563X_2 + 365.920X_3 + 190.412X_1X_2 + 16.676X_1X_3 + 154.391X_2X_3 + 60.788X_1X_2X_3 \quad (16)$$

$$Y_6 = 157.022X_1 + 646.021X_2 + 2851.970X_3 - 912.050X_1X_2 - 4087.650X_1X_3 - 4834.110X_2 + 7007.600X_1X_2X_3 \quad (17)$$

$$Y_7 = 0.566X_1 + 0.327X_2 + 0.126X_3 + 0.149X_1X_2 + 0.364X_1X_3 + 1.212X_2X_3 - 3.276X_1X_2X_3 \quad (18)$$

$$Y_8 = 609.970X_1 + 1943.840X_2 + 8093.410X_3 - 4798.710X_1X_2 - 16721.700X_1X_3 - 20101.500X_2X_3 + 49819.400X_1X_2X_3 \quad (19)$$

Table 7 presents the values of the statistical parameters used for judging the validity of the models. The results show that all the model responses satisfied the validation criteria except the consistency index model (Y_8) that did not respect all the criteria, its accuracy and bias factors could not be calculated due to the negative values present among the predicted values.

In fact, the consistency coefficient models that verify the validation criteria are mostly temperature dependent (Abu-Jdayil et al., 2002; Alpaslan and Hayta, 2002; Razavi et al., 2007) and very few are simultaneous temperature and concentration dependent or only concentration dependent (Alvarez et al., 2008) as in our study. This explains why model Y_8 was not considered for the multi-response optimization. The validated cubic models obtained in this study could therefore be used in theoretical prediction of the nutritional, energy and

Table 4. Proximate composition of the raw materials*.

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 having 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.* : Maka Taga and Jiokap Nono (2017).

Table 5. Experimental design and observed values of the nutritional properties of flours and those of the derived gruels.

Run	Independent variables			Dependent variables (observed values)														
	X_1	X_2	X_3	Y_1(f)	Y_1(b)	Diff 1	Y_2(f)	Y_2(b)	Diff 2	Y_3(f)	Y_3(b)	Diff 3	Y_4(f)	Y_4(b)	Diff 4	Y_5(f)	Y_5(b)	Diff 5
1	0.33	0	0.67	5.64	3.77	-1.87	81.08	83.47	2.39	0.93	1.57	0.64	4.05	6.97	2.92	348.89	375.87	26.98
2	0.33	0.67	0	2.49	2.32	-0.17	25.76	46.12	20.36	34.43	22.96	-11.47	14.61	12.95	-1.66	471.41	482.94	11.53
3	0	0.67	0.3	2.60	0.75	-1.85	30.06	45.96	15.9	33.96	24.51	-9.45	13.63	15.56	1.93	480.37	490.72	10.35
4	0	0.33	0.67	4.17	1.84	-2.33	57.71	69.28	11.57	17.21	12.40	-4.81	8.34	10.34	2	419.12	430.12	11
5	0.17	0.17	0.66	4.91	2.22	-2.69	69.40	73.32	3.92	9.07	8.70	-0.37	6.20	10.00	3.8	384.01	411.54	27.53
6	0.67	0.33	0	3.96	7.47	3.51	49.13	71.86	22.73	18.16	19.28	1.12	10.32	13.88	3.56	401.18	464.50	63.32
7	0.33	0.34	0.33	4.07	2.96	-1.11	53.42	57.93	4.51	17.68	18.06	0.38	9.33	13.03	3.7	410.15	458.40	48.25
8	0.67	0.17	0.16	4.75	7.61	2.86	62.96	71.86	8.9	9.78	8.06	-1.72	7.68	12.10	4.42	370.56	408.34	37.78
9	0.67	0	0.33	5.54	5.35	-0.19	76.78	81.11	4.33	1.41	1.44	0.03	5.03	9.46	4.43	339.93	375.26	35.33
10	0	1	0	1.02	0.37	-0.65	2.40	2.70	0.3	50.71	43.16	-7.55	18.91	21.88	2.97	541.63	486.76	-54.87
11	1	0	0	5.43	10.78	5.35	72.49	81.21	8.72	1.88	1.08	-0.8	6.02	9.72	3.7	330.96	373.46	42.5
12	0.33	0.34	0.33	4.07	5.18	1.11	53.42	61.18	7.76	17.68	15.59	-2.09	9.33	15.25	5.92	410.15	446.03	35.88
13	0.17	0.67	0.16	2.54	3.47	0.93	27.91	61.90	33.99	34.20	27.00	-7.2	14.12	15.14	1.02	475.89	503.16	27.27
14	0	0	1	5.75	3.63	-2.12	85.37	87.08	1.71	0.46	0.22	-0.24	3.06	4.70	1.64	357.86	369.15	11.29

X_1: Germinated sorghum, **X_2**: Germinated sesame, **X_3**: Dried banana, **Y_1**: Soluble sugar content (% db), **Y_2**: Total sugar content (% db), **Y_3**: Lipid content (% db), **Y_4**: Protein content (% db), **Y_5**: Energetic value (Kcal. (100 gdry matter)$^{-1}$), **f:** flour, **b:** gruel. **Diff**: component difference between flour and gruel.

rheological properties of the gruel flour mixture under different proportions of sorghum, sesame and banana flours. Concerning the influence of the model coefficients, it was also observed that all the linear coefficients ($\beta_1, \beta_2, \text{and}\ \beta_3$) were positive, implying the individual factors (X_1, X_2, X_3) had a positive effect on the intensity of the responses.

The quadratic coefficients $\beta_1\beta_2$, $\beta_1\beta_3$ and $\beta_2\beta_3$

Table 6. Experimental design, observed and calculated values of the nutritional and rheological properties of the gruels from flour mixtures.

Run	Independent variables			Dependent variables															
				Y_1		Y_2		Y_3		Y_4		Y_5		Y_6		Y_7		Y_8	
	X_1	X_2	X_3	Obs	Cal	Obs	Cal	Obs	Cal	Obs	Cal	Obs	Cal	Obs	Cal	Obs	Cal	Obs	Cal
1	0.33	0	0.67	3.77	3.21	83.47	81.59	1.57	1.24	6.97	7.38	375.87	371.94	902.40	1045.29	0.38	0.35	566.23	1882.99
2	0.33	0.67	0	2.32	3.39	46.12	49.14	22.96	27.29	12.95	14.93	482.94	493.65	268.80	280.34	0.44	0.44	177.50	432.84
3	0	0.67	0.3	0.75	0.76	45.96	46.91	24.51	25.23	15.56	15.44	490.72	483.32	265.60	307.09	0.53	0.53	551.48	-473.30
4	0	0.33	0.67	1.84	1.79	69.28	72.78	12.40	11.77	10.34	10.11	430.12	441.78	998.40	1042.41	0.47	0.46	126.98	1576.56
5	0.17	0.17	0.66	2.22	3.09	73.32	74.98	8.70	8.09	10.00	2.80	411.54	413.28	1482.00	1148.28	0.32	0.35	3919.73	2519.05
6	0.67	0.33	0	7.47	6.95	71.86	73.20	19.28	14.30	13.88	11.57	464.50	454.42	150.40	117.34	0.51	0.52	259.51	-11.79
7	0.33	0.34	0.33	2.96	4.29	57.93	63.28	18.06	16.41	13.03	13.89	458.40	452.20	304.00	385.23	0.43	0.41	450.79	769.58
8	0.67	0.17	0.16	7.61	6.92	71.86	73.78	8.06	9.39	12.10	11.83	408.34	419.76	176.00	127.65	0.49	0.48	277.90	52.57
9	0.67	0	0.33	5.35	5.73	81.11	79.78	1.44	1.70	9.46	9.35	375.26	374.26	198.40	146.97	0.49	0.50	350.16	-611.49
10	0	1	0	0.37	0.38	2.70	7.69	43.16	41.19	21.88	20.74	486.76	490.56	668.80	646.02	0.32	0.33	1618.05	1943.84
11	1	0	0	10.78	11.05	81.21	79.86	1.08	2.23	9.72	10.67	373.46	372.88	128.00	157.02	0.57	0.57	199.37	609.97
12	0.33	0.34	0.33	5.18	4.29	61.18	63.28	15.59	14.41	15.25	13.89	446.03	452.20	259.20	385.23	0.38	0.41	69.76	769.58
13	0.17	0.67	0.16	3.47	2.39	61.90	43.41	27.00	27.94	15.14	16.63	503.16	490.08	342.40	309.94	0.47	0.43	849.04	437.86
14	0	0	1	3.63	3.47	87.08	85.30	0.22	0.83	4.70	4.76	369.15	365.92	2806.40	2851.97	0.13	0.13	8575.15	8093.41

X_1: Germinated sorghum, X_2: Germinated sesame, X_3: Dried banana, Y_1: Soluble sugar content (% db), Y_2: Total sugar content (% db), Y_3: Lipid content (% db), Y_4: Protein content (% db), Y_5: Energetic value (Kcal. (100 gdry matter)$^{-1}$), Y_6: Viscosity (mPa.s), Y_7: Flow behaviour index (dimensionless), Y_8: Consistency index (mPa.s^n), [a]Obs: Observed value; Cal: Calculated value.

Table 7. Statistical parameters for model validation.

Validation parameters	Calculated parameter values							
	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7	Y_8
R^2aj	88.31	86.78	94.71	86.74	94.99	95.61	94.93	75.62
AADM	0.16	0.18	0.37	0.11	0.01	0.18	0.06	2.54
Bf	1.01	1.07	1.13	0.91	1.00	0.99	1.01	-
Af	1.17	1.14	1.20	1.16	1.01	1.19	1.06	-

showed a similar tendency in the case of responses Y_5 and Y_7, while for responses Y_1,Y_3,Y_6 and Y8 they were all negative implying the quadratic interactions (X_1X_2, X_1X_3 and X_2X_3) had a negative effect on the intensity of the responses.

The quadratic coefficients for responses Y_2 and Y_4, showed both positive and negative values implying they had both favorable and unfavorable effects on the responses. For the cubic coefficients, they were all positive, except for responses Y_2 and Y_7 where they had negative values.

Multi-response optimization

The factor combinations that simultaneously optimize the responses were obtained by maximizing the desirability function. The experimentally obtained minimum and maximum points, and desired responses are presented in Table 8. The results show that the zone of the desired values was included in that of the experimental values, which would have otherwise rendered the multi-response optimization impossible. Figure 4 shows

Table 8. Minimum and maximum observed values and Optimal combination of factors and responses.

Units	Responses	Observed values		Calculated Optimum		Desired values	
		Minimum	**Maximum**	**Minimum constraints**	**Maximum constraints**	**Minimum**	**Maximum**
g/100 g db	Soluble sugars	0.37	10.78	4.67	5.11	Minimize	Maximize
	Total sugars	2.70	87.08	66.77	63.25	25	70
	Lipids	0.22	43.16	13.72	17.59	10	18
	Proteins	4.70	21.88	13.15	13.99	12	22
Kcal/100 g db	Energetic value	369.15	503.16	439.22	459.49	400	
cP	Viscosity	128.0	2806.4	381.18	239.36	-	1000
Dimensionless	Flow behavior index	0.1701	0.9114	0.409	0.431	Maximize	
Dimensionless	Desirability		-	0.517	0.598	0	1

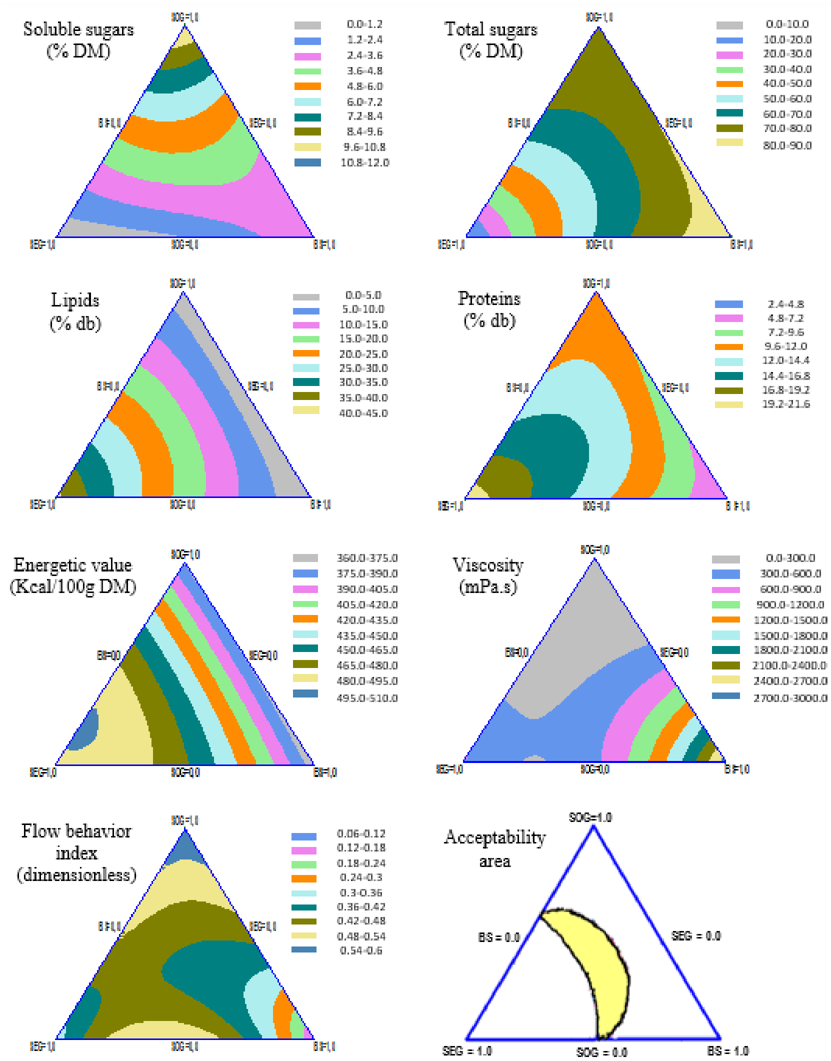

Figure 4. Ternary contour plots showing the effects of factors on the nutritional, rheological and energetic responses properties and the obtained acceptability area (obtained by superposing the contour plots of soluble sugars, total sugars, lipids, proteins, energetic value, viscosity and flow behavior index) that respects the desired gruel properties.

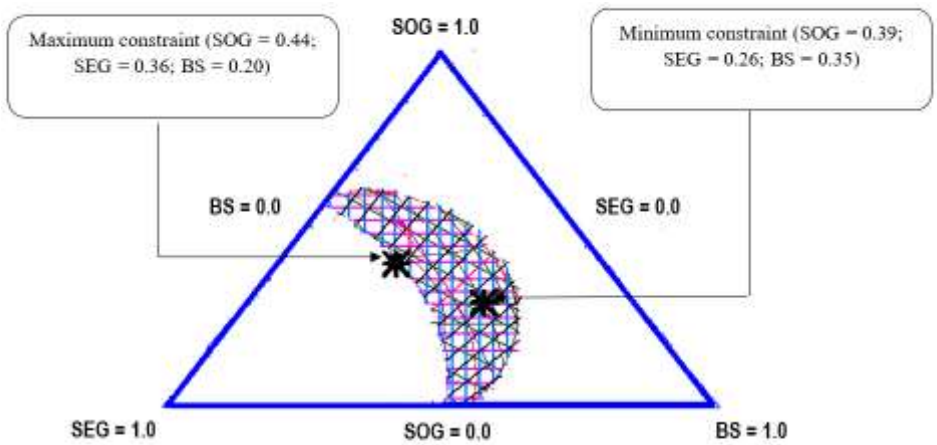

Figure 5. Maximum and minimum constraints of the gruel flour mixture located in the acceptability area.

Table 9. Optimal combinations, real and theoretical.

Units	Responses	Theoretical values	Real values	χ^2_{data}	$\chi^2_{\alpha=0.05}$
g/100 g db	Soluble sugars	4.77	6.03	6.74	12.59
	Total sugars	62.31	66.7		
	Lipids	17.76	16.38		
	Proteins	14.18	13.97		
Kcal/100 g db	Energetic value	460.69	458.09		
cP	Viscosity	261.40	204.80		
Dimensionless	Flow behavior index	0.695	0.749		

the contour plots of the different cubic models of the responses. The desirability function obtained was used to superpose the contour plots and determine the acceptable zone that respects the gruel flours specifications as shown in Figure 4 (acceptability area).

Table 8 presents the calculated optima of the gruel flour mixture, which contain respective sorghum, sesame and banana flour proportions of 0.44, 0.36 and 0.20 for the maximum constraint values and 0.39, 0.26 and 0.35 for the minimum constraint values. These two points are presented in Figure 5 and give an indication of the practical points, which could be applied. It represents factor proportions comprised between 0.39 and 0.44, 0.26 and 0.36 and 0.20 and 0.35 respectively for sorghum, sesame and banana flours.

Table 9 presents the experimental and predicted responses using an arbitrary point chosen from the acceptability area. Using the independence test at a 5% significance level, there was no difference between the experimental and predicted values. The predefined acceptability area can therefore be used for the formulation of infant flour using sorghum, sesame and banana.

Conclusion

The overall objective of this study was achieved by the successful formulation of a gruel flour mixture from sorghum, sesame and banana, which respects the norms in terms of rheological, nutritional and energy properties. The physico-chemical and rheological characteristics of the different ingredients were investigated and mixture design was presented as a valuable tool for determining the optimal mixing proportions of the factors. A standard protocol for producing the gruel flour mixture was also presented, including malting as an essential step for nutrient enhancement. Based on the results, the optimal proportions established for the gruel flour mixture were comprised between 0.39 and 0.44, 0.26 and 0.36 and 0.20 and 0.35 respectively for sorghum, sesame and banana flours. Since the study involved locally available food products, it is concluded that the protocol and results obtained can satisfactorily be applied for local production of gruel flours respecting the norms, thereby mitigating the inconveniences associated with imported flours. As perspectives, an associated techno-economic analysis should be carried out to further evaluate the economic viability of implementing such a project on a large scale.

CONFLICTS OF INTERESTS

The authors have not declared any conflict of interests.

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