

Clustering of instrumental methods to characterize the texture and the rheology of slimy okra (Abelmoschus esculentus) suspensions

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- 1 Short informative title: Clustering of instrumental methods to characterize the texture and the
- 2 rheology of slimy okra (Abelmoschus esculentus) suspensions
- 3 Short running title: Rheology and texture of slimy okra sauces
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14 BRIEF ABSTRACT FOR THE GRAPHICAL ABSTRACT

- Slimy okra suspensions are structured fluids with significant elongational properties.
- Measuring flow and stringy properties is sufficient to characterize their rheological and
 textural properties and necessary to discriminate them according to their processing and
 formulation.
- Rheological and textural properties are affected by formulation, drying and thermal
 processes.
- 21

22 ABSTRACT

- 23 Okra (Abelmoschus esculentus) is one of the ingredients widely used in African gastronomy because of
- 24 the unique slimy texture it gives to sauces. However, processing and formulation can affect the textural
- and rheological properties of these sauces, leading to unacceptable quality for the African consumer.
- 26 The aim of this study was to select the instrumental measurements best enabling i) characterization
- 27 of the rheology and texture of slimy sauces prepared from okra and ii) monitoring its evolution during
- the preservation process. 37 slimy suspensions (sauces and purées) were measured with 16 rheological
- and textural parameters. A Principal Component Analysis revealed that flow consistency index K and
- 30 flow behavior index n were well correlated with visco-elastic, adhesive and shear thinning properties,
- and that stringiness was well correlated with elongational, cohesive and ductile properties. These two
- 32 sets of measurement methods are sufficient to characterize their rheological and textural properties,
- and necessary to discriminate them according to their process and formulation.

34 KEYWORDS

35 Okra, Slimy sauces, Stringiness, Structured fluid, Rheology, Texture

36 1. INTRODUCTION

Various plant-origin ingredients are traditionally used in West and Central African cuisine because of the slimy consistency they give to sauces, soups and stews. This is the case of okra (*Abelmoschus esculentus* (L.) Moench), nkui (bark of *Triumfetta pentandra* A. Rich) and dika nut kernels (*Irvingia gabonensis* (Aubry Lecomte ex O'Rorke)) (Kouebou *et al.*, 2013; Mateus-Reguengo *et al.*, 2019; Ndjouenkeu, Goycoolea, Morris, & Akingbala, 1996). For consumers in sub-Saharan Africa, one of the essential functions of slimy sauces is to facilitate the swallowing of the starchy dough they are served with (Owoeye, Caurie, Allagheny, & Onyezili, 1990). For them, the "slimy" properties of okra are its main attribute, and therefore an essential quality ariterian (Use & Oiigke 1980).

44 main attribute, and therefore an essential quality criterion (Uzo & Ojiako 1980).

45 Okra sauces have never undergone rheological and textural characterization, but many studies have 46 focused on the rheological properties of okra extracts (mucilage, polysaccharides and pectins in 47 particular). In addition to their sliminess, they have original thickening, shear thinning, viscoelastic and 48 visco-elastic properties (Kontogiorgos, Margelou, Georgiadis, & Ritzoulis, 2012; Ndjouenkeu et al., 49 1996; Sengkhamparn et al., 2010), emulsifying properties (Kpodo et al., 2018) and elongationnal 50 properties (Yuan, Ritzoulis, & Chen, 2018) properties. The rheological properties of okra mucilage are 51 the result of complex interactions between the various macromolecular populations of which it is 52 composed (Ritzoulis, 2017), including very specific pectic compounds (Kpodo et al., 2018).

The textural properties of okra products, including sauces, can be significantly altered by preparation and stabilization processes. Studies that investigated the impact of the process on the textural 55 properties of okra focused on the viscosity (simple, kinematic, relative) of its mucilage or okra sauces.

56 They showed that the viscous properties of the product are degraded by drying (Falade & Omojola,

57 2010; Inyang & Ike, 1998), blanching (Inyang & Ike, 1998) and cooking (Woolfe, Chaplin, & Otchere,

- 58 1977). These effects on the rheological properties of okra are a major obstacle to the conservation of
- this vegetable before consumption in West Africa. In order to improve the processing conditions of this vegetable, it is therefore essential to have tools that allow the best enabling assessment of its
- 61 slimy properties.

62 Only a few old studies took an interest in the instrumental measurement of the slimy texture of food. 63 For Uzo & Ojiako (1980), the perception of the sliminess of a whole okra is correlated with the 64 kinematic viscosity of its mucilage. Other authors have shown correlations between the perception of 65 sliminess in the mouth and the shear thinning (Szczesniak & Farkas, 1962; Wood, 1974) or viscous properties (Richardson et al., 1989) of a food, while some did not find a correlation (Terpstra et al., 66 67 2009). As a result, no clear and consistent trend emerges from these sometimes contradictory results. 68 Moreover, measurements of viscous properties alone do not seem sufficient to appraise the quality of 69 slimy sauces, since African consumers base their assessment on their ability to elongate it (Fasogbon, 70 Taiwo, & Adeniran, 2017; Leakey et al., 2005). Finally, for Szczesniak & Farkas (1962), "a slimy material 71 was defined as one that is thick, coats the mouth, and is difficult to swallow". But this definition seems

to contradict the fact that for African consumers, slimy sauces facilitate swallowing.

In this context, the objective of this study is to select the instrumental measurements best enabling i) characterization of the texture of slimy sauces prepared from okra and ii) monitoring its evolution during the preservation process. The proposed strategy was to measure the rheological and textural properties of a wide range of samples of okra purées and sauces using different experimental methods described in the literature. These methods were then compared with each other to extract the most relevant instrumental parameters.

79 2. MATERIALS AND METHODS

80 2.1. Sample generation

81 In order to obtain slimy suspensions with the greatest possible variety of rheological and textural 82 properties, 37 samples were prepared by varying the formulation and using processes known to have 83 an impact on the texture of okra (Figure 1).

Two batches of fresh okra purée were prepared and frozen. Of these, 36 samples were formulated at different pH and dry matter contents (no.1-31), mixed with other slimy ingredients (no.32-33) or used in a traditional recipe (no.34-36). These preparations could then be cooked (no.5-22; no.33-37) or sterilized (no23-31). A 37th sample was obtained by cooking dried okra (no.37). Table 1 summarizes the formulations and processes undergone by each of the 37 samples. In some cases, the prepared samples were frozen a second time for the sake of convenience of the organization of the experiments.

90 2.1.1. Preparation of blanched okra purées

91 Whole fresh okras were purchased locally (Grand Frais and Paris Store, Montpellier, France). They were 92 first steam blanched at 90°C for 7 minutes. After manual removal of seeds and stalks, the okras were 93 ground with water (water/gumbo ratio = ¼; Stephan UMC5, Hameln, Germany, 2007). Given the 94 foaming properties of the product, this operation was performed at 35°C at a reduced pressure of 200 95 mbar. The resulting purées were vacuum-packed in polyethylene bags at 100 mbar (Multivac C200, 96 Wolfertschwenden, Germany, 2009), frozen and stored at -18°C. Before use, the purées were thawed 97 for 1 hour at 30°C.

- 98 Two batches of blanched okra purées were prepared from 10 and 20 kg of fresh okra, independently
- 99 of each other (8.1 and 7.8% dry matter and pH of 6.1 and 6.4 respectively). These blanched okra purées
- 100 were then used to prepare all samples except samples 31 and 37.
- 101 **2.1.2.** Preparation of standardized okra purées
- From the blanched okra purée, samples 1 to 4 were prepared by adjusting the water content withdistilled water, and pH by adding a 20% sodium carbonate solution (table 1).

104 2.1.3. Preparation of cooked okra purées

From blanched okra purée, 15 samples (no.5-19) were formulated according to a three-factor Doehlert experimental design (Doehlert, 1970). The pH varied from 4 to 8 (addition of citric acid solution at 0.3 $g \cdot mL^{-1}$ or sodium carbonate solution at 20 $g \cdot mL^{-1}$), the water content from 12 to 18 kg·kg_{DM} (addition of distilled water) and the Ca2+ ion content from 0 to 4.8 $g_{Ca2+} \cdot kg_{DM}$ (addition of calcium chloride to 7 $g \cdot mL^{-1}$). To complete the design of experiments, 3 other formulations were also chosen (samples 20-22). After packaging in 370 mL glass jars, all these purées were then cooked at 70 or 85°C for 20 mins in a water bath and cooled in a bath of melting ice for 30 mins.

112 **2.1.4.** Preparation of sterilized okra purées

113 Eight Sterilized okra purées (no.23-30) were prepared in the laboratory by varying the pH, water and 114 calcium contents in the same way as for cooked okra purées. Various sterilization treatments were 115 tested to cover the range of sterilization values conventionally used for canned vegetables ($2.5 < F_0 <$ 116 10 min). After formulation, the purées were packaged in 106 mL glass jars. They were preheated in a 117 water bath at 70 °C for 20 mins and then sterilized in an autoclave (SANOclav KL-71, Wolf, Geislingen, 118 Germany, 1985). The core temperature of the vials was recorded every 20 s during processing using 119 an on-board probe held in position in their geometric centre (PicoVACQ, TMI-Orion, Castelnau-le-Lez, 120 France).

A complementary test was carried out at pilot scale on unblanched okra and that were ground with their seeds (no.31). In this case, the product was packaged in tin-plated steel cans (390 g) and sterilized in a semi-industrial autoclave (118L, Type 50, Auriol, Marmande, France, 1990). The core temperature was measured every 20 seconds with a probe placed in the geometric centre of the box. The water content of the sterilized purée was 11.3 (kg/kg dry matter), but it was readjusted according to Table 1 before rheological and textural measurements were made.

The sterilization value F0 (mins) was conventionally calculated from core temperature measurements
 T (°C) as a function of time t (mins) by numerical integration of the Bigelow formula.

129 **2.1.5.** Preparation of Okra sauces

Based on a traditional Cameroonian recipe for okra sauce, three samples (no.34-36) were prepared using the following ingredients: fresh okra 46.9% (w/w), water 39.4%, onions 8.4%, sunflower oil 3.5%, garlic 1.0%, salt 0.5% and 0.3% of a traditionally called "potash". This "traditional alkaline salt" is known to have an improving effect on the texture of sauces made with okra or nkui (Ngoualem, Nguimbou, & Ndjouenkeu, 2019). The "potash" used contained 170.6g/kg sodium, 42.6g/kg potassium, 14.0g/kg calcium and 4.1 g/kg magnesium and had a high alkalizing power (3.69 meq·kg⁻¹). The whole preparation was cooked for 15 minutes at 70°C.

Two other sauces were prepared with slimy ingredients to boost the textural properties of Blanched okra purées. Sample no.32 was prepared by mixing 28% (w/w) nkui suspension, 29% water and 44% fresh okra purée. The nkui suspension used (dry matter content 1.3%) was obtained by decoction of frozen *Triumfetta pentandra* bark (JDC Africa, Paris) in boiling water for 10 mins (0.2 kg·kg-1) which was then stirred for 5 mins with a mixer equipped with a beater (RM8, Robot Coupe, Montceau-en-

- 142 Bourgogne, France) before being sieved (1mm screen). Sample no.33 was obtained by adding an
- 143 ogbono suspension to blanched okra purée in the proportions (0.5 kg·kg⁻¹). This ogbono suspension
- 144 had previously been obtained from dika nut kernels (*Irvingia gabonensis*) (Merveilles d'Afrique, Paris,
- 145 France), dried, ground and cooked in water for 30 mins (0.09 kg almond powder/kg water).
- 146 Finally, sample no.37 was prepared with dried okra from Mali (Ben Produits Exotiques, Paris, France).
- 147 The okra was rehydrated and cooked in water at 85°C for 10 mins. Before being readjusted for
- 148 rheological and textural measurements according to Table 1, the water content of the sample was 11.0
- 149 kg/kg (dry matter).
- 150 After preparation, with the exception of sample no.31, all these samples were vacuum-packaged in 151 polyethylene bags and then, for the most part, frozen at -18°C.
- 152 For the remainder of the article, the term suspension will be used to refer to all samples (purées and 153 sauces) used in this work.

154 **2.2. Instrumental measurement methods**

2.2.1. Physico-chemical measurements

The water content was determined by drying at 105°C for 24 hours and is expressed in kg/kg of dry matter (DM). The pH was measured using a TitroLine[®] 5000 pH meter (SI Analytics, Weilheim, Germany, 2017). The density of samples no.5 to 19 was evaluated by measuring the mass of a known volume of sample. Each pH, water content and density measurement was performed in triplicate.

160 **2.2.2. Textural characterization**

The operating conditions under which the Texture Analyser was used to perform penetration and
stretching texture measurements are summarized in Table 2. Penetration measurements (firmness
and adhesiveness) were performed in triplicate.

164 The experimental device used to measure the stringy nature is adapted from (Gilbert, Savary, Grisel, 165 & Picard, 2013), and is described Figure 2. In order to avoid the test to be affected by surface 166 heterogeneities and to guarantee the contact between the probe and the suspensions, the probe penetrated slightly inside (2 mm << depth of the steel cylinder) before stretching. After the recording 167 168 of the stretching test with a camera, the software VLC media player was used to extract the image 169 corresponding to the maximum filament breaking length prior to rupture. Then the length of the 170 filament was measured with the software imageJ. Each measurement was repeated 15 times. The 171 stringiness is the average of the 15 measurements.

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2.2.3. Rheological characterization

173 The operating conditions under which the rheometer was used to perform oscillatory and steady shear 174 measurements are summarized in Table 2. Each sample was measured 3 to 5 times with a rheometer. 175 In order to allow a relaxation phase, the oscillatory test only started 15 minutes after the mobile was 176 immersed in the solution. The steady shear measurement followed the oscillatory shear measurement. 177 From the measurements made in oscillation strain sweep, the Rheoplus software was used to calculate 178 the strain ($\gamma_{LVEG'}$) and the stress ($\sigma_{LVEG'}$) at the boundary of the Linear Viscoelastic Region (LVR), the moduli at the boundary of the LVR (LVEG', LVEG', LVEG* and LVEtanδ), as well as the modulus G'=G'', 179 180 the strain ($\gamma_{G'=G''}$) and the stress ($\sigma_{G'=G''}$) at the cross-over point. The Flow Transition Index (FTI) was calculated by dividing $\sigma_{G'=G''}$ by $\sigma_{LVEG''}$ (Corker, Ng, Poole, & García-Tuñón, 2019). From the steady shear 181 182 data, the apparent viscosities at 10 s⁻¹ and 100s⁻¹ were determined. The Rheoplus software was used 183 to calculate the consistency index K and the flow behavior index n using the Ostwald-de Waele 184 equation (Eq. 2).

185
$$\tau = K \dot{\gamma}^n \tag{2}$$

- 187 τ = shear stress (Pa)
- 188 $\dot{\gamma}$ = shear rate (s⁻¹)
- 189 K = flow consistency index (Pa.sⁿ)
- 190 n = flow behavior index
- 191 For the remainder of the article, the term instrumental parameters will be used to refer to all

variables obtained with the texturometer and the rheometer to characterize okra suspensions, whichare summarized in Table 2.

194 **2.3. Data processing and statistics**

Measurements made in oscillatory shear rheology were considered valid if the measured torque was
above the rheometer detection limit (50nNm). This was the case for all samples except sample no. 37,
for which oscillatory shear data were not taken into account.

The data were analyzed using R-3.5.1 software (R Core Team, 2018). The coefficient of variation was the indicator used to assess the repeatability of our measurements for each parameter and sample. A Principal Component Analysis (PCA) on the 16 rheological and textural parameter and 37 samples was performed using the FactoMineR package (Lê, Josse, & Husson, 2008). A Pearson correlation matrix was produced using the corrplot package v0.84 (Wei & Simko, 2017). The other graphical representations were produced using the ggplot2 (Wickham, 2016), ggrepel (Slowikowski, 2018) and ggpubr (Kassambara, 2018) packages.

The analysis of the experimental design was performed using the rsm package (Lenth, 2009). From results of the Doehlert experimental design, correlations were established with a second-order polynomial model (Eq. 3) to determine the effects of the main formulation parameter on textural properties:

(3)

209
$$Y = a_0 + \sum_i a_i X_i + \sum_i a_{ii} X_i^2 + \sum_{ij} a_{ij} X_i X_j$$

Where Y is the response (Consistency Index K, Flow behavior index n, Stringiness), X_i is factor i (pH,
Water Content, ion calcium content), a₀ is the constant of the model, a_i is the linear effect of X_i, a_{ii} is
the quadratic effect of X_i, and a_{ij} the effect of interaction between X_i and X_j.

213 3. RESULTS AND DISCUSSION

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3.1. Rheological and textural properties of okra suspensions

The wide measurement ranges of the samples (Table 2) show that the rheological and textural properties of the samples are different from each other. It is possible to deduce some rheological properties of the analyzed okra suspensions.

3.1.1. Textural properties

From a textural point of view, okra suspensions have more or less solid properties (45 < Firmness <260 mN) and adhesive properties (60 < Adhesiveness < 690 N.m). The upper boundary of the stringiness parameter (9.4 cm measured for samples no.35 and 36) shows that some okra suspensions can have remarkable elongational properties. This is consistent with the study of the elongational properties of okra mucilage conducted by Yuan *et al.* (2018). This result also shows that it is possible to measure instrumentally the stringy properties which African consumers evaluate by hand and visually.

225 **3.1.2.** Rheological properties

The LVR of all suspensions extended to a strain of $\gamma_{LVEG'} = 0.1\%$. The interval [18%; 35%] in which the values of LVEtan δ (Table 2) are included, means that in the LVR, the suspensions have mechanical properties of viscoelastic solids, varying in magnitude depending on the samples. However, they are not real gels (LVEtan $\delta > 10\%$).

- 230 When the strain exceeds the threshold of $\gamma_{LVEG'} = 0.1\%$, the decrease in G' indicates that the material
- begins to deform in a non-reversible way (i.e. yield) due to the progressive but irreversible destruction
- of its internal structure under the effect of the strain. Some suspensions retain preponderant solid and
- elastic properties (G'>G'') up to very significant strains ($\gamma_{G'=G''}$ = 250%). Others are very fragile and go
- 234 from solid behaviour (G'>G'') to liquid behaviour (G'<G'') at low deformations ($\gamma_{G'=G''}$ <10%).
- 235 The shear stresses required to irreversibly deform okra suspensions ($\sigma_{LVEG'}$) or cause them to flow 236 $(\sigma_{G'=G''})$ vary from one sample to another (Table 2). Yield stress is a characteristic property of structured 237 fluids (Nakauma, Ishihara, Funami, & Nishinari, 2011) that can be estimated with $\sigma_{G'=G''}$ (Walls, Caines, 238 Sanchez, & Khan, 2003). The FTI is the ratio between $\sigma_{G'=G''}$ and $\sigma_{LVEG'}$ and can be used to characterize 239 how the internal structure of the suspensions breaks. The closer the FTI is to 1, the more brittle the 240 suspensions are (Corker et al., 2019). On the opposite, the higher the FTI is, the more ductile the 241 material is, i.e. it has the ability to deform plastically without breaking. The FTI measurement range 242 shown in Table 2 indicates that some suspensions are not very resistant to deformation (min_{FTI} = 17) 243 while others are very ductile ($max_{FTI} = 380$).
- 244 These rheological properties, which are original for sauces, are certainly linked to the existence of 245 complex molecular structures. Observation of the curves from the oscillation strain sweep test (Figure 246 3) revealed that for the majority of samples (33/36 samples), at the end of the LVR, there was a slight 247 increase in the value of G", which is characteristic of a "weak strain overshoot" type behavior (Hyun, 248 Kim, Ahn, & Lee, 2002). According to Hyun et al. (2002) and Mezger (2006), the complex structure 249 made of polymer chains resists strain up to a certain threshold. Beyond this, the structure begins to 250 crack and friction between the different layers causes G" to increase. When the strain reaches a new threshold, G''' decreases as the structure breaks completely allowing the chains and/or 251 252 microstructures to align in the direction of flow. This behavior would be favored by the presence of 253 long side chains, their arrangement in space under the effect of electrostatic repulsion and the degree 254 to which they entangle with each other to form a more or less flexible structure. In the case of okra 255 suspensions, this explanation is plausible since it has been shown that okra pectins are of variable 256 length and branching, with more or less long side chains (Kpodo et al., 2018) and that they can entangle 257 with each other via hydrogen, hydrophobic and calcium bonds (Ritzoulis, 2017). In fact, the samples 258 (no.8, 10, 21, 22, 24, 30 and 34) for which the weak strain overshoot behavior is the greatest (i.e. 259 max_{G"/G"0} > 1.1) have fairly high pH values and their formulation has often been enriched with divalent 260 cations (Table 1). Only samples n°2, 3 and 33 have a strain thinning behaviour (max_{G'/G''0} = 1) which can 261 be explained by the disentanglement of the polymer chains and their progressive alignment in the 262 direction of flow as the strain increases (Hyun et al., 2002). These differences in behavior indicate that 263 the internal structures of the suspensions react differently to the increase in strain.

The consistency index K and the flow behavior index n are used to characterize their flow properties. The measurement ranges of parameters K and n (see Table 2) are in line with those obtained on other fruit and vegetable purées (Holdsworth, 1971). The fact that n is less than 1 for all samples means that okra suspensions have a shear thinning behavior.

These results show that different instrumental methods can be used to characterize the rheological and textural properties of okra suspensions. The next step is to identify instrumental parameters that are necessary and sufficient to characterize and monitor the evolution of the specific rheological and

- textural properties of these sauces as a function of their formulation and the preservation process
- 272 applied.

273 **3.2. Repeatability of instrumental measurements**

A significant proportion of samples have a coefficient of variation (CV) greater than 10% for most measurements obtained by oscillatory shear rheology (LVEG', LVEG", LVEG*, G'=G", $\gamma_{G'=G"}$, $\sigma_{LVEG'}$, FTI and $\sigma_{G'=G"}$, Figure 4). LVEtan δ is the only parameter obtained in dynamic rheology for which all the points have a CV < 10% and which can therefore be considered as repeatable. This low repeatability of oscillatory shear measurements comes in addition to the fact that they were not valid for one sample (no. 37).

The median CV of the stringiness measurement is about 8% (Figure 4). For 75% of the samples, it is less than 10% and less than 15% for the remaining 25%. This indicates a good level of repeatability for the stringiness measurement. For parameters measured with the texturometer (firmness, stickiness) and in steady shear rheology (K, n, η_{10} et η_{100}), the measured VC for almost all samples is less than 10% and the median CV is less than 5%. The repeatability of these 4 parameters is therefore excellent.

285 However, we notice that for the consistency index K, a minority of samples (samples no.2, 31 and 37) 286 have a CV of close to 15%. For these samples, the repeatability of K is less good but remains at an 287 acceptable level. These samples are among the most watery and have a very low consistency index K 288 (< 30 Pa.sⁿ, Figure 5). These results may indicate that for the consistency index K, there is a limit of 289 quantification below which the measurement is less repeatable and which can lie between 30 and 50 290 Pa.sⁿ. The water content alone does not fully explain the lower repeatability of the consistency index 291 K measurements for these 3 points since sample no.32 has a CV lower than 5% while its water content 292 is high (26.3 %).

293 294

3.3. Reduction of the number of instrumental parameters

3.3.1. Correlation of instrumental parameters with each other

295 In the Figure 6, it can be seen that a 2-dimensional space allows to represent 86% of the variance 296 carried by the 16 parameters. The first dimension of the PCA (Figure 6A) is well correlated (p < 5%) with the parameters η_{10} (r = 0.99), K (r = 0.98), LVEG' (r = 0.97), LVEG* (r = 0.97), η_{100} (r = 0.97), $\sigma_{LVEG'}$ (r 297 298 = 0.97), firmness (r = 0.95), $\sigma_{G'=G''}$ (0.94), n (r = -0.91), LVEG'' (r = 0.88), adhesiveness (r = 0,86) and 299 LVE tan δ (r = -0.77). To a lesser extent, it is also correlated with the water content measurement (r = -300 0.50). The first component of PCR can therefore be interpreted as a dimension positively correlated 301 with the viscous, elastic, shear thinning and adhesive properties of suspensions. The negative 302 correlation of the water content (supplementary variable) with the first dimension illustrates this interpretation. The second dimension of the PCA is well correlated (p < 5%) with the parameters $\gamma_{G'=G''}$ 303 304 (r = 0.89), G'=G" (r = -0.78), stringiness (r = 0.75) and FTI (r = 0.68). This second dimension is therefore 305 positively correlated with the ductility and stringy properties of suspensions. It certainly corresponds 306 to the cohesiveness when defined as "the extent to which a material can be deformed before it 307 ruptures" (Brenner et al., 2014).

The meaning given to the two dimensions makes it possible to characterize the differences between the types of samples. On the first dimension of Figure 6B, the "Cooked okra purées" are clearly distinguishable (right) from the three other sample groups (left). On the second dimension, three groups of samples can be distinguished: Sterilized okra purées (bottom), Standardized okra purées and Cooked okra purées (middle) and Okra sauces (top). The study of their viscous, elastic, shear thinning and adhesive properties made it possible to distinguish two groups of suspensions, while the study of their ability to resist plastic deformation without breaking made it possible to distinguish three groups 315 of suspensions. Two dimensions are therefore sufficient to characterize the rheological and textural 316 properties of slimy suspensions and necessary to differentiate them. This is consistent with the 317 proposal of van Vliet (2002), for whom it is the combination of several parameters (viscosity, shear 318 rate thinning behaviour and elongational flow) that would allow a good estimate of the slimy level of 319 a solution. This result is also in line with the work of Yuan, Ritzoulis & Chen (2018) and Leakey et al. 320 (2005) for whom it is the combined study of the viscous and elongational properties of okra mucilage; 321 for the former, and of soups made with dika nut kernels; for the latter, that would best describe the 322 original mechanical and textural properties of these slimy ingredients. Finally, in the context of 323 research seeking to identify "gum based thickeners" with "ease of swallowing" properties, E. K. Hadde 324 & Chen (2019) have shown the interest of jointly studying these two dimensions.

325

3.3.2. Identification of the parameters best correlated with the others

326 At the top left of the figure 7, a group of parameters, all correlated to each other, is clearly apparent 327 (LVEG", σ_{LVEG} , LVEG^{*}, LVEG^{*}, η_{10} , K, fimness, η_{100} , $\sigma_{G'=G''}$, adhesiveness, n and LVEtan δ). These 328 parameters are also those that contribute significantly and strongly to the formation of the first 329 dimension of the PCA (Figure 6A). Within this group, K and n are the two repeatable measurements 330 (CV<10%, see Figure 4) that are best correlated with the other parameters. Indeed, the intensity 331 correlation of K with the other parameters of this group is between 0.77 and 0.98 while the intensity 332 correlation of n is between 0.76 and 0.88. K and n are therefore the most relevant parameters to 333 characterize the first dimension of the PCA. From a practical point of view, it is not necessary to select 334 one of these two parameters since they are measured at the same time and are complementary in 335 characterizing the flow of suspensions.

At the bottom right of figure 7, the parameters $\gamma_{G'=G''}$, G'=G'', FTI and stringiness form a second group that corresponds to the second dimension of the PCA (figure 6A). Within this group, the parameters $\gamma_{G'=G''}$ and stringiness are the two parameters best correlated with the other parameters since the intensities of their correlations with the other parameters in this group are respectively between 0.52 and 0.74 and between 0.42 and 0.57. It seems more interesting to select stringiness because it is the only one of these four parameters to allow a valid measurement of sample no.37 and it has a better repeatability than $\gamma_{G'=G''}$, G'=G'' and FTI (Figure 4).

343 344

3.3.3. Comparison of the differentiating power of the consistency index K with the other parameters of the "consistency dimension"

K is very well correlated with the shear thinning (Figure 8A) and viscoelastic (Figure 8B) properties of okra suspensions as well as with their yield stress (Figure 8C) and firmness (Figure 8D). Since the flow behavior index n is less well correlated with these parameters than with K (Figure 7) and the amplitude of its measurement range is less important (Table 2), its correlations with these parameters has not been plotted in order not to multiply the graphical representations.

350 In the Figure 8A and Figure 8B, we observe that compared to flow behaviour index n and LVEtan δ , K 351 makes it easier to distinguish the 4 samples (no. 7, 8, 15 and 17), for which the value of K is high (> 300 Pa.sⁿ), from the rest of the Cooked okra purées. In Figures 6C and 6D, it can be seen that K allows a 352 353 better discrimination of samples with a value lower than 100 Pa.sn, than the parameters $\sigma_{G'=G''}$ and 354 firmness. In Figures 8C and 8D, we can see that compared to $\sigma_{G'=G''}$ and firmness, K allows to better 355 differentiate samples with a value lower than 100 Pa.sⁿ. This confirms that among the parameters of 356 the first dimension, the consistency index K is the most suitable for differentiating samples from each 357 other, including for high and low values of its measuring range. However, like the other parameters of the consistency dimension (Figure 6A and Figure 7), K does not allow a clear distinction between 358 359 samples of the Sterilized okra purées, Standardized okra purées and Okra sauces types which have 360 similar values.

3.3.4. Comparison of the discriminating power of stringiness with the other parameters of the "ductility-cohesiveness" dimension

As suggested by the correlation coefficients in Figure 7, it can be seen in Figure 9 that the correlations between the parameters carried by the "ductility-cohesiveness" dimension are of lower quality than for the "consistency dimension" parameters (Figure 8). This is due in particular to the presence of a few samples (No. 23, 28, 32, 35 and 36) for which the values obtained are very different from the lot.

367 In Figure 9A, 7/9 of Sterilized okra purées samples have a G'=G" value similar to that of the Cooked 368 okra purées group. Moreover, Okra sauces and Standardized okra purées samples have comparable 369 values. In Figure 9B, the Okra sauces samples have values of $\gamma_{G'=G''}$ comparable to those of the Cooked 370 okra purées group. In Figure 9C, except for samples 32 and 33, it is not possible to distinguish between 371 Okra sauces, Standardized okra purées and Cooked okra purées samples using the measured FTI 372 values. Therefore, the parameters G'=G'', $\gamma_{G'=G''}$ and FTI, shown vertically in Figures 9A, 9A and 9C, do 373 not allow the sample groups to be correctly distinguished from each other. On the other hand, 374 Stringiness, represented horizontally on the 3 graphs in Figure 9, makes it possible to clearly distinguish 375 three groups of samples: Sterilized okra purées on the left, Standardized okra purées and Cooked okra 376 purées in the centre, and Okra sauces on the right. Stringiness is therefore the parameter that best 377 complements K since, unlike K (Figure 8), stringiness clearly distinguishes samples of the "Okra sauces", 378 "Sterilized okra purées" and "Standardized okra purées" types.

379 **3.3.5.** Space formed by the stringiness and flow parameters to characterize the samples 380 The two-dimensional space formed by the combination of stringiness with K or n makes it possible to 381 clearly distinguish the 37 suspensions that have been produced by varying the formulation and 382 production process of the suspensions (Figure 10A and B). With the exception of sample no.37, the 383 four types of samples form homogeneous groups and are clearly distinguishable from each other.

384 In Figure 10A and B, it can be seen that some samples have a similar flow properties but a very different 385 stringiness level (see samples no.23 and no.36 for example). This result is consistent with the work of 386 Hadde & Chen (2019) who showed that fluids could have similar properties when subjected to "shear 387 deformation" but very different properties when subjected to "extensional deformation". In Figure 388 10A and B, we can see that the opposite is also true: some samples may have similar properties when 389 subjected to "extensional deformation" but very different ones when subjected to "shear 390 deformation" (see samples no.17 and no.30 for example). The combination of flow and stringy 391 properties measurements is therefore suitable for discriminating slimy suspensions.

392

3.4. Ability of the stringiness and flow parameters to characterize the impact of the process and formulation on the textural properties of okra

393 394

3.4.1. Impact of the process on the textural properties of okra

The graphs in Figure 11 distinguish the effects of water content and process on both stringiness and suspension flow. The increase in the water content of the suspensions leads to a decrease in their consistency index K (Figure 11A) and a degradation of their shear thinning properties (increase of n in Figure 11B). However, its effect on stringiness is not obvious (Figure 11C).

Cooked okra purées and Sterilized okra purées have a similar water content (respectively between 11.9 and 17.9 and between 11.8 and 18.2 kg/kg dry matter, Table 1). Figure 11A, Figure 11B and Figure 11C show that compared to Cooked okra purées, Sterilized okra purées have a lower consistency index K, a higher flow behaviour index n and a lower stringiness level. This means that sterilization degrades the consistency, shear thinning properties and elongational properties of okra suspensions. These results confirm and supplement the researchs of Inyang & Ike (1998) and Woolfe, Chaplin, & Otchere (1977), who observed degrading effects of blanching and cooking on okra viscous properties. The increase in LVEtan δ induced by sterilization (data not shown) reveals that heat treatment degrades the internal structure of okra suspensions. Since the degree of methylation of okra pectins is quite low (<26% according to Kpodo *et al.* (2018)), this degradation is certainly the consequence of the depolymerization of okra pectins by β -elimination or acid hydrolysis (Moelants, Cardinaels, Van Buggenhout, *et al.*, 2014).

In Figure 10, it can be seen that the sample prepared from dried okra (no.37) has very different characteristics from other Okra sauces samples but very similar to those of Sterilized okra purées. In Figure 11, we can see that compared to samples with a close water content (n°3, 16 and 31), sample n°37 is the least consistent sample and shear thinning (Figures 11A and B) and is not very stringy (Figure 11C). These results supplement those of Falade & Omojola (2010) and Inyang & Ike (1998) who showed that the drying process had an effect on the viscosity of the dried okra. It suggests that the conditions under which okra is dried in West Africa can probably be improved.

- 418 On the three charts in figure 11, it can be seen that the characteristics of the 35 and 36 samples are 419 identical. Freezing has no impact on the stringiness and flow characteristics of okra suspensions. This
- 420 confirms and supplement the results of Olorunda & Tung (1977) and Falade & Omojola (2010).

On the three charts in Figure 11, we can see that the Okra sauces to which other slimy ingredients have been added (no.32-36) have remarkable elongational properties and this for different water content levels. This means that the addition of two slimy ingredients in samples 32 and 33 increased the elongational characteristics of okra suspensions. It can be seen that the three traditional recipes (no.34 - 36) in which other ingredients, including "potash", have been added, are the most stringy. The presence of this alkaline and mineral-rich ingredient, known for its effect on okra texture (Ngoualem et al., 2019), certainly contributes to the high level of stringiness observed for these samples.

428

3.4.2. Impact of the formulation on the textural properties of okra

Table 3 shows that water content has a significant and dominant linear effect on all three parameters and a significant quadratic effect on K and n. The pH has a significant quadratic effect on n of the same order of magnitude as the linear effect of water content. The calcium ion content has a significant linear effect at the 15% threshold on K and n and at the 10% threshold on n but has no effect on the stringiness.

- 434 The linear effect of the water content on K ($a_2 = -125.7$) and n ($a_2 = 0.037$) indicates that the increase 435 in water content decreases the consistency index K of the purées and their shear thinning properties. 436 The quadratic effects of water content on K (a_{22} =67.5) and n (a_{22} =0.016) mean that these degradations 437 are less pronounced as the water content increases. This result is in line with that of Woolfe, Chaplin 438 & Otchere (1977) on okra mucilage. Other authors have observed similar effects of particle 439 concentration on other plant-tissue-based suspensions (Moelants et al., 2014). Increasing the water 440 content above a certain level reduces hydrodynamic interactions between particles, which modifies 441 the flow properties of purées (Moelants et al., 2014).
- 442 The pH has a quadratic effect on the flow behavior index n ($a_{11} = -0.032$). Its negative sign indicates the 443 presence of a maximum. Its intensity is of the same order of magnitude as that of the water content 444 (a₂ = 0.037), which shows that this effect is quite significant. Woolfe, Chaplin, & Otchere (1977) showed 445 relative viscosity of okra mucilage reaches and optimum when pH values are between 6 and 8. This 446 could be the consequence of the effect of pH on the spatial conformation of okra pectins, which can 447 change from a compact conformation at acidic pH to an extended one at neutral pH (Alba, Bingham, 448 & Kontogiorgos, 2017; Alba, Kasapis, & Kontogiorgos, 2015; Ritzoulis, 2017). Furthermore, Yuan et al. 449 (2018) showed that at pH4, within the okra mucilage, the particles were less numerous but larger than 450 at pH7, and that this imparted its viscosity. Here, it is interesting to note that the pH has been shown

to have a strong and significant effect on the density of okra suspensions. At acidic pH, suspensions
foamed (density < 1), which is in accordance with the emulsifying properties of okra pectins at acid pH
(Alba, Ritzoulis, Georgiadis, & Kontogiorgos, 2013). All these elements indicate that by acting on the
spatial conformation of okra pectins, pH modifies the properties of the matrix they form within the
purées, which has an effect on their flow properties.

456 The calcium ion content has a negative quadratic effect (a₃₃= -0.014) on n which is dominant compared 457 to its linear effect (a_3 = 0.0052). This means that the increase in calcium ion content causes the n 458 increase until it reaches an optimum. The other effect of the calcium ion content on the flow of the 459 purées is to reduce their consistency index K (a_3 = -13.3), which is consistent with the result of Woolfe, 460 Chaplin, & Otchere (1977) and Ndjouenkeu et al. (1996). It has been suggested that by "screening" the 461 negative charges of pectins on the surface of the particles, calcium ions facilitate the flow of purées 462 (Moelants et al., 2014). This effect is thought to have a stronger impact on their rheology than the gelling effect of Ca²⁺ ions on weakly methylated okra pectins. 463

464 The stringiness level of the purées increases linearly with their water content ($a_2 = 0.8$). Our results 465 may seem contradictory to those of Yuan et al., (2018) who showed that the increase in mucilage 466 concentration resulted in an increase in break-up time (equivalent to stringiness). The difference of 467 concentration used in the two studies (between 0.25 and 3.00% vs. between 4.9 and 7.4%) can explain 468 this difference. In fact, additional experimental work has shown that stringy properties of okra reached 469 a maximum at an intermediate concentration (data not shown). The relatively high concentrations 470 used may also explain why, unlike Yuan et al. (2018), no significant pH effects on the elongational 471 properties of okra purées were observed.

472 Of the three factors studied, it is the water content that has a central and dominant effect on the three 473 parameters. But while increasing it degrades the consistency and shear thinning properties of purées, 474 it increases their ductility. These three parameters therefore seem to measure the same phenomenon, 475 namely the structuring or softening of the structured fluid according to its concentration of bio-476 polymers and particles. On the micro scale, the increase in water content reduces hydrodynamic 477 interactions between particles and the ability of okra pectins to entangle to form a solid and elastic 478 structure. On a macro scale, with the increase in water content, the structure becomes more flexible 479 and its ability to resist plastic deformation without breaking increases: it becomes less fragile and more 480 ductile. While in the experimental field studied, the stringiness of suspensions is only sensitive to water 481 content, their flow properties are also sensitive to calcium ion concentration and pH. As we have 482 shown that the stringiness parameter has a better ability than the flow parameters to differentiate 483 between sample types, this confirms that it useful to keep all three parameters to study the impact of 484 the process and formulation on the rheology and texture of okra suspensions.

485 4. CONCLUSION

486 Sixteen rheological and textural parameters were measured to characterize the texture and rheology 487 of okra slimy suspensions. These suspensions have viscoelastic, shear thinning, adhesive, stringy, 488 ductile and cohesive properties, and can be classified as structured fluids. A PCA showed that two 489 dimensions are sufficient to characterize their rheological and textural properties and necessary to 490 differentiate them. While the first dimension is correlated with their viscoelastic, shear thinning and 491 adhesive properties, the second dimension is correlated with their stringy, cohesive and ductile 492 properties. Consistency index K and flow behavior index n are two repeatable measures that are very well correlated with the other 10 parameters carried by the first dimension of the PCA. Stringiness is a 493 494 repeatable measurement that is well correlated with the other 3 parameters of the second dimension 495 $(\gamma_{G'=G''}, G'=G'' \text{ and FTI}).$

- Combining the consistency index K and the stringiness is very good at differentiating the samples with respect to the process and the formulation they have undergone. These instrumental parameters therefore seem complementary in their ability to i) characterize the degree of structure of the slimy suspensions as a function of their formulation and ii) monitor the degradation of their rheological and textural properties as a result of the process. This work therefore makes it possible to find levers to
- 501 limit the degradation of the rheological and textural properties of okra during processing. To this end,
- it would be helpful to study which biochemical mechanisms are involved in these degradations.
- 503 The fact that slimy sauces, like other slimy solutions such as hagfish slime (Böni, Fischer, Böcker, Kuster, 504 & Rühs, 2016), have remarkable stringy properties suggests that this characteristic could be related to 505 the sensory perception of the slimy texture. An adapted sensory analysis work will have to be carried 506 out in order to validate the existence of such a correlation. If this is confirmed, it will be possible to use 507 the set of measuring methods identified in this work to engineer the texture and the rheology of 508 African slimy sauces.

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513 ETHICAL STATEMENTS

- 514 The authors declare that they do not have any conflict of interest
- 515

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641 Tables legends

Table 1. Summary of main preparation process and formulation of the 37 samples used for rheologicaland textural analysis

Table 2. Instrumental methods and parameters selected for characterizing rheological and texturalproperties of okra suspensions

- Table 3. Effects of pH, water content and calcium ion content on the consistency index K, the flow
- 647 behavior index n and the stringiness of cooked okra purées (samples n°5-19)
- 648
- 649
- 650
- 651

Table 1 : Summary of main preparation process and formulation of the 37 samples used for

653 rheological and textural analysis

Sample Number		Name	рН	Water content (kg/kg dry matter)	Added calcium (g Ca ²⁺ /kg dry matter)	Thermal process Temperature (°C) x time (min) [F ₀ for sterilization (min)]
1			7.2	15.8	0	
2		Standardized okra purées		25.3	0	
3	Sta			19.0	0	
4				19.5	0	
5				14.9	2.4	
6			6.0 6.0	16.4	2.4	
7			4.5	11.9	2.4	
8			7.1	12.2	2.4	
9			4.6	17.2	2.4	
10			7.4	16.5	2.4	
11			4.6	14.5	0.7	
12			7.4	14.8	0.7	
13			4.6	14.9	4.1	70 x 20
14		Cooked okra purées	7.4	14.6	4.1	
15			6.0	12.2	0.7	
16			6.1	17.9	0.7	
17			6.0	12.0	4.1	
18			6.0	17.1	4.1	
19			6.0	14.6	2.4	
20			6.2	15.9	0	
21				15.1	4.8	
22			7.2 7.3	15.0	4.8	85 x 19
23			5.2	15.4	0	115 x 58 [F _{0 =} 5.4]
24	l		5.9	16.3	0	125 x 22 [F _{0 =} 3.4]
25			5.4	15.9	0	125 x 26 [F _{0 =} 7.3]
26			5.7	15.8	0	120 x 35 [F ₀₌ 6.7]
27	S	terilized okra purées	5.5	16.2	0	120 x 50 [F ₀ =9.9]
28	_		4.3	12.6	3	125 x 24 [F _{0 =} 7.5]
29			7.6	11.8	4.8	125 x 24 [F ₀₌ 8.1]
30			6.4	15.3	4.8	125 x 21 [F _{0 =} 5.6]
31	1		5.7	18.2	0	121 x 60 [F ₀ 4.2]
32		With Nkui	6.6	26.3	0	[.0]
33		With Ogbono	5.8	10.1	0	80 x 30
34	Okra	Traditional recipe 1	7.7	7.1	0	70 x 15
35	sauces ⁺	Traditional recipe 2	6.5	8.8	0	70 x 15
36		Frozen traditional recipe 2	6.5	8.8	0	70 x 15
37		Dried okra sauce	6.3	18.5	0	85 x 20
	+: See section 2.1.5. for further explanations about Okra sauce formulation and preparation.					

Table 2 : Instrumental methods and parameters selected for characterizing rheological and textural

655 properties of okra suspensions

Methods					Value	
Material	Type of measurement	Selected parameter	Description	References	range obtained with the 37 samples	
Wateria	Type of measurement	parameter	Elastic modulus at the end of	References	samples	
	decade; temperature = 25°C	LVEG'	the Linear Viscoelastic Region		[100; 7410] Pa	
		LVEG''	Viscous modulus at the end of the Linear Viscoelastic Region		[30; 1500] Pa	
		LVEG*	Complex modulus at the end of the Linear Viscoelastic Region	Mezger	[100; 7540] Pa	
Anton Paar MCR		LVEtanδ	Damping factor at the end of the Linear Viscoelastic Region	(2006) & Walls, Caines, Sanchez, & Khan (2003)	[18; 35] %	
301 rheometer		γ lveg'	Strain at LVEG' (limit of the Linear Viscoelastic Region)		0,10%	
equipped with the		σ _{LVEG'}	Stress at LVEG'		[0.1 ; 7.5] Pa	
starch cell C- ETD160/ST		G'=G''	Modulus at cross-over point		[10; 940] Pa	
and with		σ _{G'=G''}	Stress at cross-over point		[13; 470] Pa	
measuring		γ _{G'=G''}	Strain at cross-over point		[6; 250] %	
ST24- 2D/2V/2V- 30 (stirrer with 3 pairs of		FTI	Flow Transition Index = $\sigma_{G'=G''}/\sigma_{LVEG'}$	Corker, Ng, Poole, & García- Tuñón (2019)	[17; 380]	
blades)	Flow measurement under steady state : shear rate interval = [0.001; 1000] s ⁻¹ ; 5 measurement/shear rate decade; temperature = 25°C	к	Consistency index K calculated using the de Waele-Ostwald equation	Mezger (2006),	[3; 340] Pa.s ⁿ	
		n	Flow behavior index calculated using the de Waele-Ostwald equation	Holdsworth (1971)	[0.16; 0.66]	
		η ₁₀	Apparent viscosity measured at 10 s ⁻¹	Sharma, Kristo,	[2; 50] Pa.s	
		η ₁₀₀	Apparent viscosity measured at 100 s ⁻¹	Corredig, & Duizer (2017)	[0.6; 6] Pa.s	

	Penetration : The sauce was poured and tossed in a glass beaker (depth = 3 cm: diameter = 6 cm)	Firmness	Maximum force measured at the end of the penetration into the product		[45; 260] mN
Stable Micro Systems TA.XT.plus Texture Analyser	3 cm; diameter = 6 cm). The sample was left to relax for 2 min, before a single compression test was performed with following settings: Pre- test, test and post-test speed = 2 mm.s ⁻¹ ; trigger force = 3 g; penetration distance = 3 mm. Temperature = 25°C (±1°C)	Adhesiveness	Area under the curve force corresponding to the work of adhesiveness while the probe is pulling up back from the sauce	Nishinari et al. (2019), Rosenthal (2010), Bourne (2002)	[60; 690] N.m
equipped with the same PVC cylindrical probe (diameter = 2 cm)	Stretching: The sauce was poured and tossed in a steel cylinder (diameter = 3 cm). The sample was let to relax for 2 min before that a single compression test was performed with following settings: Pre- test speed = 10 mm.s ⁻¹ , test and post-test speed = 40 mms.s ⁻¹ ; trigger force = 2 g; penetration distance = 2 mm. Temperature = 25°C (\pm 1°C)	Stringiness	Average breaking length of the filament	Gilbert et al. (2013)	[1.2; 9.4] cm

Table 3: Effects of pH, water content and calcium ion content on the consistency index K, the flow

659	behavior index n and the stringiness of cooked okra purées (samples n°5-19)	
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Coefficient ⁺	Consistency index K (Pa.s ⁿ)	Flow behaviour index n	Stringiness
Constant			
a ₀	203.9****	0.216****	3.8****
Linear			
a ₁	4.6	0.005	0.0
a ₂	-125.7*****	0.037****	0.8****
a ₃	-13.3*	0.0052*	0.1
Interactions			
a ₁₂	-14.8	-0.001	-0.2
a ₁₃	19.1	0.008	-0.2
a ₂₃	-0.5	-0.005	0.0
Quadratic			
a ₁₁	-3.4	-0.032****	-0.2
a ₂₂	67.5****	-0.016**	0.0
a ₃₃	4.4	-0.014**	-0.1
R ²	0.9817	0.9712	0.9539
<pre>+ Indices 1, 2, and 3 refer to pl Significance (p-value) : ***** </pre>			

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662 Figures legends

- Figure 1: Production diagram of the 37 samples used for rheological and textural analyses.
- 664 Figure 2: Drawing of the experimental set-up for stringiness measuring

Figure 3: Elastic (G') and Viscous (G'') moduli of the 36 samples (measurements of the sample no.37 were not valid) as a function of strain at 1Hz (A and B). Reduced moduli G'/G'_0 and G''/G''_0 versus strain, where G'0 and G''0 are the moduli measured at the beginning of the linear viscoelastic region (see (Hyun et al., 2002)).

Figure 4: Distribution of coefficient of variation (CV) measured on the 37 samples for the 16 rheological and textural parameters. The numbers indicate the samples for which an extreme CV has been measured. The 10% dashed line corresponds to the threshold above which the measurement was not considered repeatable.

- Figure 5: Variation coefficient of consistency index K vs measured consistency index K. The color gradient of the points corresponds to the water content (dry matter) of the measured samples. The sample number is written when the measured value is less than 50 Pa.sⁿ. The 10% dashed line corresponds to the threshold above which the measurement was not considered repeatable.
- 677 Figure 6: Principal Component Analysis (PCA) biplot of the 16 textural and rheological parameters and

the 36 samples. The explained variance for PC1 and PC2 is 66.61 % and 19.68 %. On the parameters

679 factor map (A), Water Content is a supplementary parameter that does not contribute to the formation

- of the components. On the Projection of individuals (B), the number indicates samples and confidence
- 681 ellipses were traced around the samples categories.

Figure 7: Pearson correlation coefficients matrix of the 16 parameters. The lower left half shows the Pearson correlation coefficients significant at the 5% threshold. The upper right half shows the graphical representation of these coefficients: their color depends on the sign of the correlation while the size of the disks and the intensity of the color represent the intensity of the correlation.

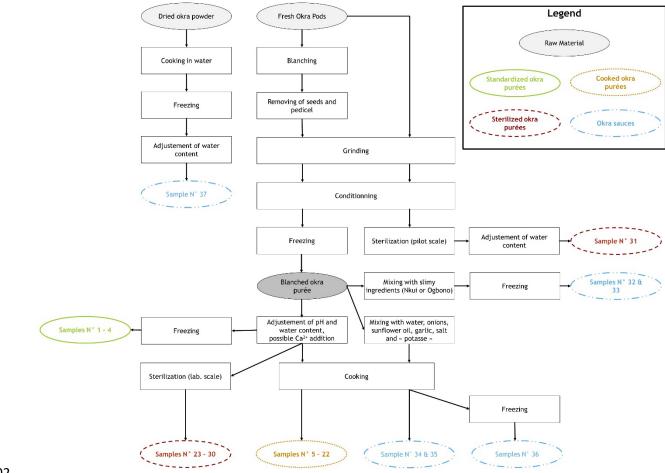
 $\begin{array}{ll} \mbox{Figure 8: Graphical illustrations of the correlation between the consistency index K and the main rheological and textural properties of the first dimension of the PCA: flow behavior index n (A), LVEtan \delta \\ \mbox{(B), } \sigma_{G'=G''}(C) \mbox{ and firmness (D). } \end{array}$

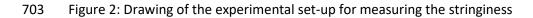
- Figure 9: Graphical illustrations of the correlation between stringiness and the main rheological and textural properties of the second dimension of the PCA: $\gamma_{G'=G''}(A)$, G'=G''(B), FTI (C).
- Figure 10: The two-dimensional space formed by stringiness in combination with the consistency indexK (A) and the flow behavior index n (B).

Figure 11: Water-dependence of flow consistency index K (A), flow behaviour index n (B) and stringiness (C) for the 37 suspensions.

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Figure 1: Production diagram of the 37 samples used for rheological and textural analyses.





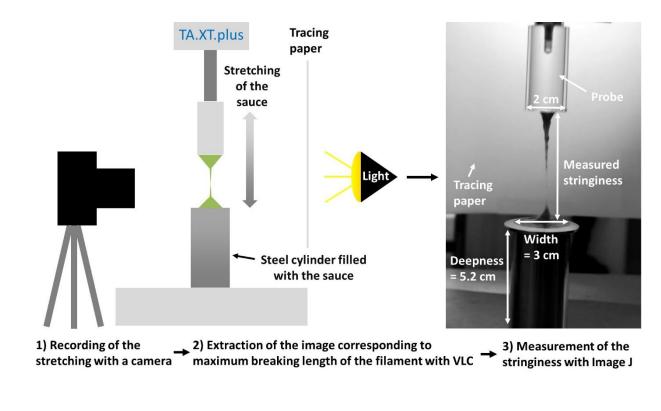
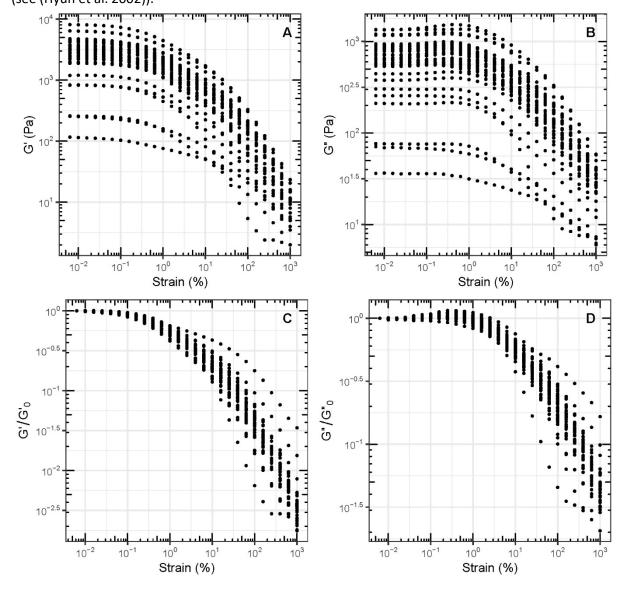


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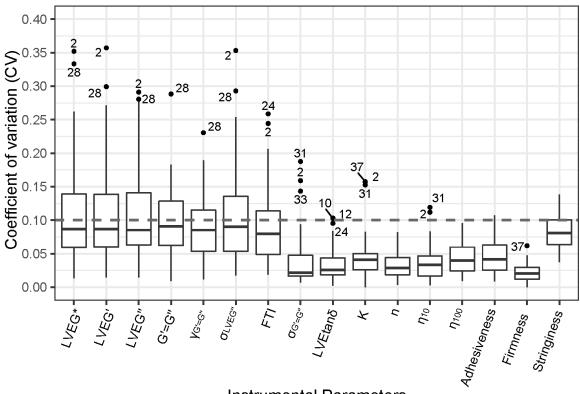
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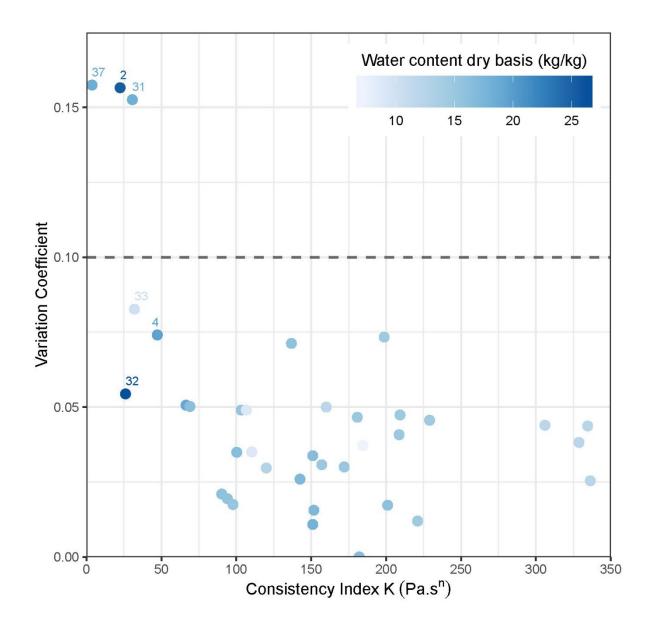
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Instrumental Parameters

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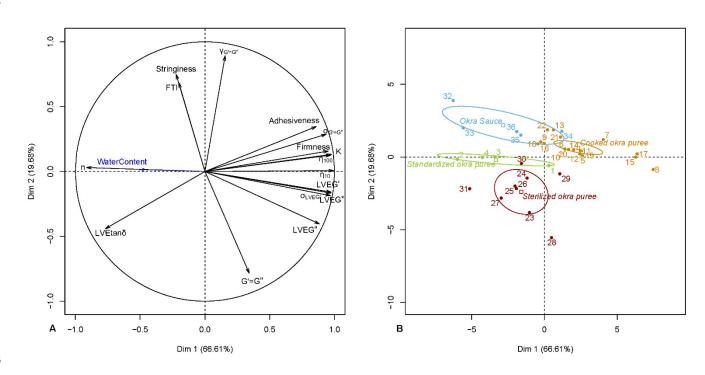
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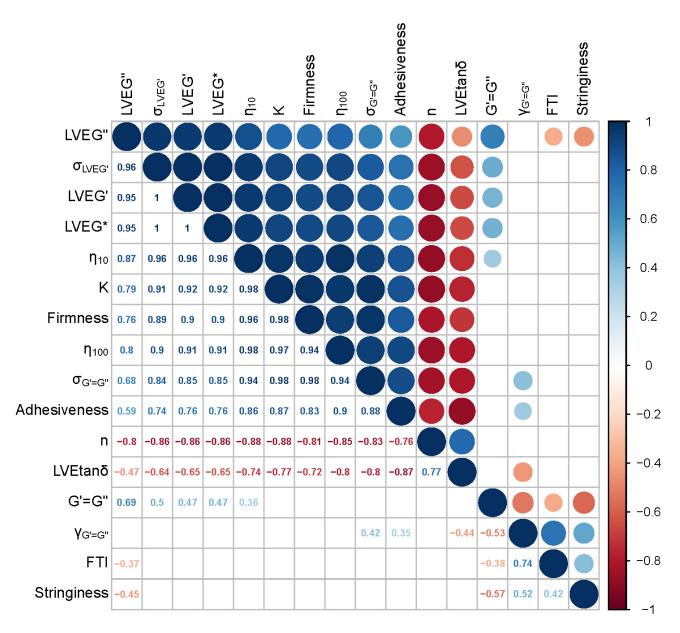
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- 734 Figure 7: Pearson correlation coefficients matrix of the 16 parameters. The lower left half shows the
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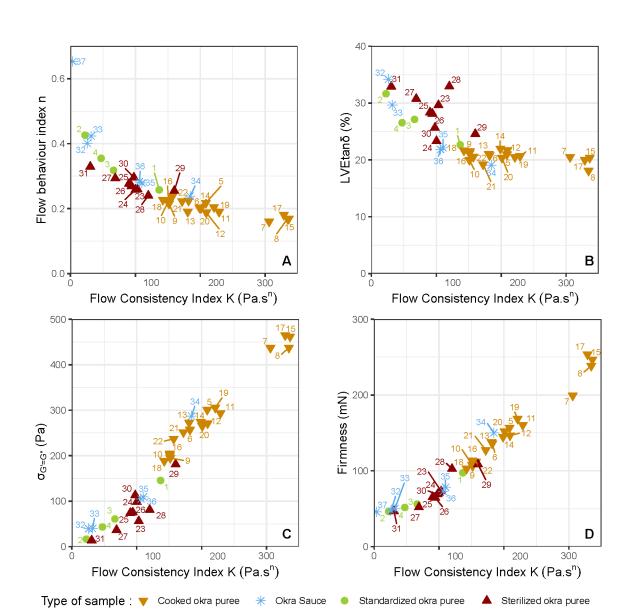
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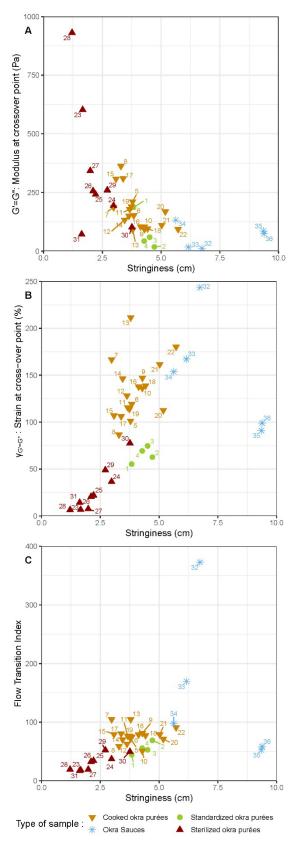
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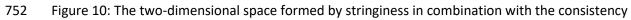
745 LVEtan δ (B), $\sigma_{G'=G''}$ (CD) and firmness (D).

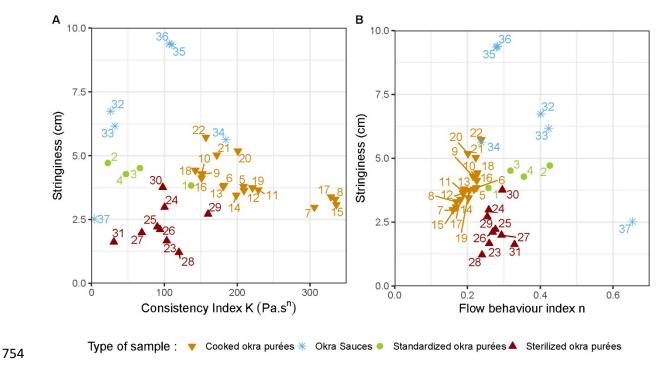


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Figure 9: Graphical illustrations of the correlation between stringiness and the main rheological and textural properties of the second dimension of the PCA: $\gamma_{G'=G''}(A)$, G'=G''(B), FTI (C).







753 index K (A) and the flow behavior index n (B).

756 Figure 11 : Water-dependence of flow consistency index K (A), flow behaviour index n (B) and

757 stringiness (C) for the 37 suspensions

