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Abstract

The aim of this study was to develop an instrumental method for measuring the texture of French fries and correlated it with sensory measurements. For seven samples of French fries with different crispness levels, a cone penetrometer test was conducted simultaneously with microphone recording of sound emissions. A descriptive sensory analysis was also performed on these samples. The results showed that the number of sound peaks, the linear distance of sound peaks, the area under the sound-displacement curve and the mean sound pressure were strongly positively correlated ($r \geq 0.80$; P-value < 0.02) with the crispness of the crust descriptor. The number of force peaks and the linear distance of the force peaks were correlated with all the acoustic parameters. These two mechanical parameters and the maximum force, were not correlated with crispness of the crust ($r = 0.50$; P-value < 0.05) but strongly correlated with product hardness ($r = 0.9$; P-value < 0.01). However, the combination of the acoustic and mechanical parameters appeared suitable for measuring the texture of French fries. An analysis of the variable importance by random forest showed that the main parameters for quantifying the texture differences were the number of sound peaks and the maximum force. The use of this instrumental method and sensory analysis showed that the deep-fat fried products were crispier than the air fried products with the same water loss.

Highlights (maximum 85 characters)

- ► Combination of acoustic and penetration tests are used to evaluate French fries texture
- ► A high correlation exists between the sensory crispness and the acoustic parameters
- ► The NSP and the Fmax makes it possible to clearly identify the crispness
- ► Deep-fat fried products are crispier than the air fried products with the same water loss

Keywords

French fries; Hot air frying; Texture; Sensory analysis, Crispness; Acoustic properties.

Abbreviations

Fmax	Maximum force
NFP	Number of force peaks
LDF	Linear distance of force peaks
F_Average	Average drop off of force peaks
Smax	Maximum of sound pressure
MS	Mean of sound pressure
AS	Area under sound displacement curve
NSP	Number of sound peaks
LDS	Linear distance of sound peaks
S_Average	Average dropp off of sound peaks
T	Temperature (°C)
i.m	Initial mass

1. Introduction

French fries are a specific solid with a moist and soft core and a crispy outer dry crust of approximately 1–2 mm (Bouchon & Aguilera, 2001; Pedreschi & Aguilera, 2002; Van Koerten, Schutyser, Somsen, & Boom, 2015). French fries are popular potato products in many countries because of their structure and attractive texture. Texture is one of the important quality aspects, and a crispy crust is a factor in the sensory properties of French fries (Pedreschi & Aguilera, 2002; Salvador, Varela, Sanz, & Fiszman, 2009). Crispness is one of the most important quality parameters in consumers' choice of a fried product (L. M. Duizer, Campanella, & Barnes, 1998; Luyten, Plijter, & Vliet, 2004; Salvador, Varela, Sanz, & Fiszman, 2009; Tunick et al., 2013). Many types of experiments have been conducted to determine crispness, but the best measurements to assess crispness remain to be established (Gondek, Lewicki, & Ranachowski, 2006; Luyten & Vliet, 2006; Castro-Prada, Luyten, Lichtendonk, Hamer, & Vliet, 2007). This sensory attribute is often evaluated by sensory panel tests. Unfortunately, sensory evaluations are expensive, unsuitable for routine testing and generally provide a more qualitative than quantitative comparison (Zdunek, Cybulska, Konopacka, & Rutkowski, 2011). Moreover, the results obtained from different sensory panels are difficult to compare (Roudaut, Dacremont, Vallès Pàmies, Colas, & Le Meste, 2002).

Several studies were carried out on the crispness of French fries using mechanical tests (penetration, compression, bending). During a texture analysis, a force can be exercised on a fried sample when a probe moves through it that imitates a first bite of the product. Subsequently, the force-deformation curve is used to calculate the quantitative parameters related to the crust fragility (Miranda & Aguilera, 2006; Van Koerten, Schutyser, Somsen, & Boom, 2015). However, the results of the force-deformation often do not show clearly a correlation with sensory crispness. Nevertheless, Van Loon (2005) showed a correlation between the number of peaks in the force-deformation and sensory perception of crispness of French fries. Instrumental techniques present some advantages, especially in industrial environments in which quick and easy-to-use methods are in great demand and are economically more profitable (Saeleaw & Schleining, 2011). Other new texture measurement techniques, such as acoustic measurements, have been used on crispy products other than French fries, such as chips, wafer products, and have found high correlations with sensory measurements (L. Duizer, 2001; Marzec, Cacak-Pietrzak, & Gondek, 2011; Saeleaw, Dürrschmid, & Schleining, 2012; Çarşanba, Duerrschmid, & Schleining, 2018). The combination of acoustic and mechanical techniques has been shown to better describe food texture than either of the two techniques alone (L. Piazza & Giovenzana, 2015; Laura Piazza, Gigli, & Ballabio, 2007). The tests, mainly 3-point bending, penetration, and compression methods, predicted the snack crunch (L. Duizer, 2001) and showed good correlations between the acoustic-mechanical and sensory parameters. Other studies have also shown that the sounds produced during food disintegration play an important role in the perception of the texture of food materials (L. Duizer, 2001; Luyten & Vliet, 2006). Sometimes these sounds describe the overall quality of a food product better than any other sensory characteristic (A. marzec, G. cacak-pietrzak & E. Gondek, 2011). The mechanical (penetration test) and acoustic evaluation of crispness was also used to describe the texture of cookies (Chen, Karlsson, & Povey, 2005), extruded bread (Marzec, Lewicki, & Ranachowski, 2007), toasted nuts (Salvador, Varela, Sanz, & Fiszman, 2009) and apples (Zdunek, Cybulska, Konopacka, & Rutkowski, 2011).

The aim of this study was to develop an instrumental method for measuring the texture of French fries, and especially the crispness of the crust. A penetration test was conducted simultaneously with microphone recording of sound emissions. A descriptive sensory analysis was performed to evaluate the textural attributes, and the relationships between the sensory parameters and the instrumental measurement parameters were analysed. Finally, this approach was used to compare two products with contrasting texture made using deep fat frying and air frying.

2. Materials & Methods

2.1. Raw materials

The experiments were carried out with frozen French fries (Mc-Cain Tradition) purchased at a local supermarket and stored in a cold room at – 18 °C. The frozen French fries were resized to 60 mm in length and 10 mm thick (10×10×60 mm) with a specific cutter. Each experiment was conducted with 0.300 kg of sized French fries.

2.2. Frying equipment

Two main fryers were used: a commercial oil bath fryer (Filtra One FF162100 Seb) with a power of 1900 W, a chip capacity of 1.20 kg and an oil capacity of 2.10 L, and hot-air frying equipment (Airfryer Philips XL HD9240/90, Avance Collection, Amsterdam, The Netherlands) with a power of 2100 W.

2.3. Sample preparation

French fries with different crispness levels were obtained by adapting the frying equipment type, water loss and frying temperature.. Each experiment was carried out with 0.300 kg of sized French fries. Three French fries samples were fried at 180 °C with a conventional deep-fat fryer for final water losses of 60 %, 50 % and 45 %. Four French fries samples were prepared using the hot air fryer. Three of them were fried at 140 °C, 180 °C and 200 °C until the water loss reached 50 %. The fourth sample was fried at 180 °C until a water loss of 60 %. The samples were coded according to their frying conditions, as shown in Table 1. All French fries samples were analysed in under 5 min. The water loss was defined as the mass of water lost during frying divided by the initial mass (i.m) of the sample before frying.

2.4. Instrumental texture analysis

A penetration test was conducted with a conical probe with a 60° angle. Mechanical (penetration test) and acoustic measurements were made using a texture analyser (TA.XT.plus, Stable Micro Systems (SMS), Surrey, U.K) using a 5 kg sensor connected to a microphone (Brüel Kjaer, Type 2671 Naerum, Denmark). This set was placed in the Thermal Cabinet (TC/LN2 for the TA.XTplus Texture Analyser), which was regulated at 50 °C. The microphone included an acoustic envelope detector (AED) to avoid background noise. It was calibrated with a type 4231 acoustic calibrator (1 Hz, Brüel Kjaer) at 94 and 114 dB sound pressure. The acoustic detector included a sound amplification element that was set to level 2. The microphone position was 1.6 cm from the sample at an angle of 50°. Different test speed (0.2 mm.s^{-1}, 0.5 mm.s^{-1}, 1 mm.s^{-1} and 2 mm.s^{-1}) and deformation level (50 % and 80 %) were tried. The thermal cabinet was turned off during the measurement due to the background noise of its fan. It was used as a partition for the external environmental noise and for the sound emitted by the sample. The conical probe was applied at a position of 20 mm from the extremity of the French fry (1/3 of the length of the French fry). Each French fry was penetrated only once. The measurements were carried out in triplicate with approximately fifteen French fries per test.

The following parameters—maximum force (Fmax, N), number of force peaks (NFP), linear force peak distance (LDF, Nm), maximum sound pressure level (Smax, dB), mean of sound pressure (MS, dB), area under the sound displacement curve (AS, dB m), number of sound peaks (NSP), linear distance of sound peaks (LDS, dB m) and average drop-off of sound peaks (F_Average, dB)—were evaluated with the software Exponent (Stable Micro Systems) from the force-deformation curves and acoustic displacement (Figure 1) in a range from 0 to 5 mm corresponding to 50% deformation. The definitions of the instrumental parameters are described in detail elsewhere (Varela, Salvador, & Fiszman, 2008; L. Piazza & Giovenzana, 2015; Kirmaci & Singh, 2016). The sound pressure levels and force-deformation curves were recorded with a detection threshold of 5 dB and 0.05 N, respectively. The same threshold values were used for the detection of the number of sound peaks and the number of force peaks.

2.5. Sensory analysis

2.5.1. Experimental conditions

A quantitative descriptive analysis (QDA) was used to evaluate the sensory characteristics of the samples. The sensory profiles were performed in the sensory analysis laboratory of the QualiSud UMR (CIRAD, Montpellier)). The room is composed of 15 individual boxes including a small sink and an adaptable light. During the tasting sessions, the room temperature and relative humidity were monitored and averaged 22 ± 4 °C and 29 ± 6 %, respectively. Three or four French fries per experimental conditions were presented in monadic form, 1 to 2 minutes after frying, in petri dishes to keep the product warm. The panel consisted of 13 subjects (6 women and 7 men) aged 24 to 50 years, who were trained and qualified for sensory analysis (repeatable, homogeneous).

2.5.2. Descriptors

Five descriptors of relevance were selected based on previous studies and considering the purposes of our study. The sensory descriptors studied were crispness of the crust, product hardness, softness of the core, floury of the core and boiled potato taste. The descriptors were evaluated on a continuous scale from the lowest intensity (value 1) to the highest intensity (value 5). The definitions of and evaluation protocols for the sensory descriptors are described in Table 2.

2.5.3. *Jury training*

Before the tasting started, four training sessions, according to ISO 8586 (2012), were carried out on four types of French fries. These were fried to present the average and extreme intensities of each descriptor. The tasting panel was trained on the different descriptors in the first two training sessions. The last two training sessions were dedicated to assessing the panel's ability to use the descriptors. The scores assigned by the judges were compared to those given by consensus, and judges were asked to comply with the desired benchmark. The jury's training was validated by a statistical analysis, analysing their repeatability. Non-repeatable judges were eliminated for the remainder of the evaluation. Thirteen judges were validated.

2.5.4. *Tasting sessions*

The seven French fries samples were coded and then submitted to the jury for analysis, giving a score ranging from 1 to 5 for each descriptor out of four tasting sessions. At each tasting session, three to four samples were presented in succession. The order of the samples was determined randomly. The tasting was then carried out in duplicate for each sample.

2.6. Statistical analysis

The statistical analysis of the results was carried out using XLSTAT version 2017 (ANOVA and PCA test) and R programs (decision tree test “rpart”). The ANOVA procedure at a significance level at 0.05 and the Tukey test were applied to assess significant differences between the investigated parameters. A correlation analysis (PCA) and a decision tree followed by a random forest were also conducted. An ensemble learner was built on decision trees, in which each decision tree was made with a bagging of observations and instrumental parameters. The mean decrease in accuracy caused by a parameter was determined during the out-of-bag error calculation phase from running the random forest 1000 times (number of trees = 1000, sample size = 63%, and no. of variables tried at each split = 2). The parameter importance estimated from the random forest was defined as the percentage of misclassifications.

The results of the PCA analysis were presented as a two-dimensional graph: a graph that represents both variables and samples in two dimensions.

3. Results and discussion

3.1. Sensory analysis

The ANOVA's results of the sensory analysis are summarized in Table 3. Seven high-contrast texture samples were generated based on final water loss, frying method and frying temperature. Five sensory descriptors were analysed. The floury of the core was not significantly different for the seven samples. Its value ranged from 1.9 to 3.1. This descriptor is not presented in Table 3. The crispness of the crust, product hardness, softness of the core descriptors and boiled potato taste made it possible to classify the seven samples into 4, 4, 2 and 3 groups, respectively. The variation coefficient of these descriptors in the range from 4 and 10% was satisfactory. It was mainly the crispness of the crust (F-value = 44) and product hardness that differentiate the samples (F-value = 20). This is demonstrated in Figure 2, which presents the bi-plot PCA on covariance, regarding the sensory descriptors data set for the seven French fries samples. The average jury scores for the two tasting sessions are represented in Figure 2. The first two dimensions explain 91.2 % of the variability (56.8 % F1, 34.4 % F2). The crispness of the crust and boiled potato taste descriptors contribute highly to the F1 axis respectively 62% and 20%. The product DF180_60 and

AY140_50 strongly drives the F1 axis. The axis F2 was more explained by the descriptors softness of the core (39.5 %), floury of the core (32.7 %) and product hardness (23.3 %). There was no correlation between the product hardness and the crispness of the crust ($r = 0.47$; P-value < 0.05). Çarşanba, Duerrschmid, & Schleining (2018) also showed on wafer products that hardness and crispness were also slightly correlated. In addition, the product hardness was strongly negatively correlated with the softness of the core ($r = -0.83$; p-value < 0.02). The crispness of the crust was strongly negatively correlated with only the boiled potato taste ($r = -0.88$; P-value < 0.01). The PCA (Figure 2) shows that the seven French fries samples were repeatable quite varied and well dispersed, thus explaining the different sensory descriptors. Afterwards, these seven samples with contrasting textures were used to characterize the performance of the instrumental measurements of texture.

3.2. Instrumental analysis: acoustics and force-deformation test

Four different test speeds were used (0.2 mm.s^{-1}, 0.5 mm.s^{-1}, 1 mm.s^{-1} and 2 mm.s^{-1}), and two deformation levels (50 % and 80 %). The results showed that the use of a high test speed (2 mm.s^{-1}) dit not allow a significant difference between products, but a too low test speed (0.2 mm.s^{-1}) produces high significant differences but with a high variation coefficient (55 %). A moderate test speed of 0.5 mm.s^{-1}was used to make a successful compromise to minimize the variation coefficient. The deformation levels has no significant effect. The deformation level 50 % was used.

Figure 1 shows typical force-distance and acoustic amplitude-distance curves for two products: one very crispy and the other slightly crispy. In Figure 1 a), more acoustic and mechanical events were observed than in Figure 1 b). In Figure 1 b), when the force was at a maximum (1.2 N), no acoustic event was observed, whereas in Figure 1 a), when the force was at a maximum (1.4 N), there were more acoustic events. This shows that the two products have different behaviours.

The maximum deformation forces did not exceed 5 N with a conical probe. This value was in the same order of magnitude as reported by Kirmaci and Singh (2016) with a penetration probe. The sound pressure level did not exceed 150 dB, which was in the same order of magnitude as those determined by Çarşanba, Duerrschmid, & Schleining (2018) and Chen, Karlsson, & Povey (2005) on wafer products and biscuits respectively. The sound pressure level was difficult to compare with the literature, as it depended largely on the amplification level and the microphone location with regard to the sample and on the product (Tunick et al., 2013). In most cases, the sound pressure level ranged from 60 dB to 90 dB (Sanz, Primo-Martín, & van Vliet, 2007; Saeleaw et al., 2012; Çarşanba, Duerrschmid, & Schleining, 2018) for a crispy product.

These profiles (acoustic-distance and force-distance) made it possible to retrieve the mechanical (penetration test) and acoustic parameters. All the experimental results are gathered in Table 3 with an ANOVA (p-value < 0.05). Four mechanical (penetration test) parameters were analysed, including the average drop-off of force peaks, which did not allow any significant difference between the seven products. Thus, it will not be discussed later. The number of force peaks (NFP) separated the samples into four different groups. This parameter ranged from 13.3 to 1.9 among groups with a relative uncertainty smaller than 25 %. The maximum force (Fmax) and linear distance of force peaks (LDF) separated the samples in the same way. These parameters made it possible to distinguish two product groups. For the LDF and Fmax parameters, the variation ranges were 5.9 N m to 19.8 N m and 1.3 N to 4.3 N, respectively. The relative uncertainty of these two parameters ranged from 4 to 20%. The number of force peaks (NFP; F-value = 32.13) was more discriminating and provides different information compared to Fmax (F-value = 30.71) and LDF (F-value = 19.3).

The analysis of the acoustic parameters showed that the number of sound peaks (NSP) and the linear distance of sound peaks (LDS) followed the same rankings by significantly separating the products into five different groups. The area under the sound displacement curve (AS) and the mean of the sound pressure (MS) parameters also grouped the samples in the same way by classifying them into four product groups. For this reason, the area under the sound displacement curve (AS) was not presented in Table 3. The relative uncertainty of these parameters ranged from 7 to 20 % for NSP (F-value = 60.7) and LDS (F-value = 58.3) and from 7 to 35 % for AS (F-value = 46.6) and MS (F-value = 46.7). The maximum sound pressure (Smax) allowed the separation of the products into four groups with both a low relative uncertainty (< 7 %) and a low variation amplitude (75 to 50) when compared to the other acoustic parameters, such as NSP (87 to 7) and MS (10.5 to 0.5). By comparing the F-value of these acoustic parameters, it can be observed that the Smax has a lower F-value (Smax, F-value = 23) compared to the other parameters. The low F-value and low variation amplitude can lead to a lack of efficiency of this parameter to detect significant differences when the products to compare have a low texture difference.

The various acoustic parameters can be split into three groups (NSP/LDS, Smax and AS/MS), and the mechanical (penetration test) parameters into two groups (NFP and Fmax/LDF). The acoustic parameters separated the products into at least four groups with high F-value, while the mechanical parameters allowed their classification into two and four maximum groups with lower F-value than acoustic parameters. Therefore, the acoustic parameters are more sensitive than the penetration test parameters.

The analysis of the different confidence intervals and different F-values showed that mechanical responses were more repeatable (3 to 18 % relative uncertainty) but were less discriminating (low F-value) than acoustic responses (5 to 25 % relative uncertainty). It is important to point out that the experimental variance was determined with approximately forty-five values (French fries measured). This result shows that this instrumental measurement was not as simple to carry out and required careful implementation conditions to be reproducible.

3.3. Correlation between the results of instrumental and sensory analysis

Figure 3 shows a PCA on correlation, performed to illustrate the relation between some mechanical (penetration test) and acoustic parameters and sensory descriptors of French fries. The PCA showed that 87.60 % of the variability could be explained by the first two main components: 69.76 % by the first component F1 and 17.84 % by the second component F2. Instrumental parameters were projected as supplementary variables and did not influence on the principal components of the analysis. The first dimension (F1 axis) is particularly linked to the variables product hardness (29 %), boiled potato taste (29 %), crispiness of the crust (27 %) and softness of the core (15%). The second axis is more related to the floury of the core (48 %) and the softness of the core (20 %). This bi-plot illustrates that the products DF180_60 and DF180_50 were associated with higher values of the acoustic parameters. These products were the crispiest by sensory analysis. The AY180_60 product, which was considered harder and moderately crispy, was associated with higher values of Fmax and product hardness. The products AY40_50, AY180_50 and AY200_50 were characterized by lower values of most of the acoustic parameters but were associated with higher values of boiled potato taste. These products had the lowest crispness scores and were, therefore, considered less crispy by the sensory analysis. Therefore, it can be concluded that an increase in acoustic parameters reflects a high level of crispness. This is in line with several previous works (Saeleaw & Schleining, 2011; Giacosa et al., 2016; Jakubczyk, Gondek, & Tryzno, 2017; Çarşanba, Duerrschmid, & Schleining, 2018).

Some instrumental parameters were more or less correlated with each other, unlike sensory parameters, which were distinct from each other (Figure 3). Most of the acoustic parameters studied were positively correlated with each other, except for the S_Average which was more closely related to the F2 axis. The acoustic parameters NSP ($r = 0.89$; P-value < 0.01), LDS ($r = 0.90$; P-value < 0.01), Smax ($r = 0.94$; P-value < 0.01) and MS ($r = 0.89$; P-value < 0.01) were strongly positively correlated with the crispness of the crust, with a high level of significance (Table 4). According to this, a small number of acoustic events was considered as an indication of a low crispness of the crust. This conclusion is in line with the work of Salvador, Varela, Sanz, & Fiszman (2009), who obtained the same conclusion with potato chips. Smax, NSP and MS were specifically used to explain the crispness and crunchiness of extruded snacks by Saeleaw and Schleining (2011). In contrast, the sensory descriptor boiled potato taste was negatively correlated to all these parameters (Figure 3). The crispier the products were, the less the products taste like boiled potatoes.

The mechanical (penetration test) parameters were not significantly correlated with the crispness of the crust for P-value < 0.05 (LDF $r = 0.70$, P-value > 0.05; F_max $r = 0.5$, P-value > 0.05), except for the NFP parameter ($r = 0.84$; P-value < 0.05). In contrast, F max was strongly correlated with the product hardness ($r = 0.9$; P-value < 0.01). Obviously, the descriptor product hardness was not only associated with the mechanical parameters. These results are in line with the work carried out by Jakubczyk, Gondek, & Tryzno (2017) on co-extruded snacks. The sensory descriptor softness of the core was negatively correlated to F max ($r = -0.79$; P-value < 0.05) but not significant for the other instrumental parameters. The harder the products were, the less soft the core was.

The relation between the parameters highly correlated with some evaluated sensory texture descriptors was established by analysing the linear regression coefficients (Figure 5). The coefficient of determination (R^2) shows how the instrumental parameters such as NSP and Fmax explain sensory descriptors (crispness of the crust, product hardness, softness of the core or floury of the core) by a linear model. The parameters NSP ($R^2 = 0.80$) shows a high and positive regression coefficient for the sensory crispness of the crust. This instrumental parameter allowed the prediction of the sensory crispness of French fries correctly with high robustness. The coefficient of determination of Fmax relative to hardness was high and reflects a strong correlation between hardness and F max ($R^2 = 0.80$). No parameter can significantly predict the soft and floury of the core. This confirms that the two parameters (NSP and Fmax) reflect the crispness and the product hardness. These results confirm that the two methods provide different and complementary information. The mechanical parameters had better explain the hardness of the product and the softness of the core, and the acoustic parameters better explain the crispness of the crust. The combination of the acoustic and mechanical (penetration test) methods seems appropriate to describe the texture of French fries. Several other previous studies have reported the same conclusion for other crispy food such as dutch crisbakes, wafers, crispy bakery products (Mohamed, Jowitt, & Brennan, 1982; Laura Piazza, Gigli, & Ballabio, 2007; L. Piazza & Giovenzana, 2015).

A random forest classification was carried out by comparing 45 deep-fat fries (DF180_50) and 45 hot-air fries (AY180_50). The purpose was to detect the importance of the variables in predicting the class of the French fries (between deep-fat and hot-air). The products were made at the same frying temperature (180 °C) and with the same water loss (50%). Figure 4 a) presents the classification tree relating the frying process groups (deep-fat frying; air frying) to the instrumental parameters. The parameter importance estimated from the random forest was defined as the percentage of misclassifications. The more the accuracy of the random forest decreased due to the exclusion (or permutation) of a single parameter, the more important that parameter was deemed, and therefore, parameters with a large mean decrease in accuracy were more important for the classification of the data. The acoustic parameters were more important, especially the number of sound peaks (NSP) and the linear distance of sound peaks (LDS), followed by the mean sound pressure (MS) and the area under the sound displacement curve (AS). The parameters that have less weight were S_max and NFP. Figure 4 b) shows a good discrimination of the products due to the parameters NSP and Fmax and with an out-of-bag error of just 8.04 %. This confirms the relevance of combining the acoustic parameters with NSP and the mechanical parameters with Fmax with a performance error of 6.6 %. Other important instrumental parameters, such as LDS, MS and AS, did not appear in the classification because they were highly correlated with NSP and with each other. The combination of NSP and Fmax provides a better classification of products. These results confirm also that a minimum hardness (F max) was required to detect the crispness of French fries.

3.4. Impact of frying process on the texture

The analysis of Figure 1 showed that more acoustic and mechanical (penetration test) events were observed for the deep-fat fried products curve (Figure 1 a) than for the air-fried products (Figure 1 b). Teruel et al. (2015) also showed previously that the deep-fat fried fries are crispier than the air-fried fries.

3.4.1. Effect of water loss

Three groups of French fries were generated according to their final water loss, ranging from 45 % to 60 %. An analysis of the sensory parameters did not make it possible to distinguish these three groups according to water loss. Only the Fmax, which reflects the hardness of the product, separated the samples into two groups. In the first group, all samples have a water loss of 60 %, and in the second group, the samples have a final water loss of 45 % and 50 %. The more water was lost, the harder the product became. For the other instrumental parameters, the effect of water loss was more difficult to detect because of the combination of effects of process, temperature and water loss. Indeed, it was possible to obtain the same water loss with different operating conditions, and it was the rate of water transfer that was probably more important for the texture of the product (Vitrac, Trystram, & Raoult-Wack, 2000; Bouchon & Aguilera, 2001; Botero-Uribe, Fitzgerald, Gilbert, & Midgley, 2017). However, the analysis of samples performed with deep-fat frying at 180 °C showed that an increase in water loss increased the crispness of the crust and the product hardness. In contrast, the softness of the core decreased with the water loss. In the instrumental parameters, there was also an increase in mechanical and acoustic events as a function of water loss. For comparing crispy products, it could be especially important to consider the water content of the product (Seymour & Ann, 1988; Saeleaw, Dürrschmid, & Schleining, 2012)

3.4.2. Effect of air temperature

An analysis of the air-fried samples with the same water loss of 50 % showed that an increase in frying temperature from 140 °C to 180 °C or 200 °C increased the values of the crispness of the crust and product hardness. This is in line with several previous works (Kita, Lisińska, & Gołubowska, 2007; van Koerten et al., 2015). The acoustic parameter values also increased as the frying temperature increased. From 180 °C to 200 °C, the increase in the values of the various instrumental parameters analysed was not significant. These results confirm the conclusions of van Koerten, Schutyser, Somsen, & Boom (2015) that state that increased frying temperatures will improve the crispy properties of the fries due to the formation of more and larger pores, but this improvement only occurs until the temperature reaches a certain maximum, which was between 180 and 195 °C. The sample (AY140_50) obtained by air frying at 140 °C has the lowest values of crispness of the crust and product hardness but has the highest value of softness at the core. The low air frying temperature (140 °C) was not sufficient to develop a crispy crust, such as that developed at temperatures of 180 °C and 200 °C. This difference is due to the low heat and mass transfer rates, which are responsible for the development of the particular texture of fried products. (Loon, 2005; Kita, Lisińska, & Gołubowska, 2007; Thussu & Datta, 2012; Zeb, 2019).

4. Conclusion

This study allowed the development of an instrumental method for measuring the texture of French fries. The penetration test and acoustic signals provide different and complementary information. Acoustic signals are very sensitive to the crispness of the crust of French fries. Acoustic parameters, such as the number of sound peaks (NPS), the linear distance of sound peaks (LDS), the maximum sound pressure (Smax), the mean sound pressure (MS) and the area under the sound displacement curve (AS), are highly correlated with the sensory crispness of the crust. The instrumental parameters NSP, Smax and the maximum force (Fmax) are suitable for good characterization of the texture of French fries, especially the crispness of the crust and the product hardness. By using a combination of mechanical (penetration test) and acoustic approaches, it was possible to better estimate the texture of French fries than by using one of the other technique alone.

However, this method requires a large number of repetitions (about thirty French fries) and requires careful implementation conditions to be reproducible. The instrumental tests were able to evaluate, discriminate and reasonably predict the sensory crispness of the crust of French fries, with an R^2 close to 0.8. In addition, the following specific advantages make this approach suitable for industrial application.

The use of this instrumental method and sensory analysis showed that the deep-fat fried products are crispier than the air fried products and that water loss has an effect on the crispness and hardness of the fries. It is important to take into account the moisture content when comparing the crispness or hardness of fried products.

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Table 1: French fries samples condition obtained by deep fat frying (DF) or air frying (AY) at three different temperatures (for oil bath or air) and three different water loss level.

Sample's code	Frying equipment	T (°C)	Water loss (% i.m.)
DF180_60	Deep-fat fryer	180	60
DF180_50	Deep-fat fryer	180	50
DF180_45	Deep-fat fryer	180	45
AY180_60	Air fryer	180	60
AY200_50	Air fryer	200	50
AY180_50	Air fryer	180	50
AY140_50	Air fryer	140	50

Table 2: Definition and evaluation protocol of sensory descriptors

Sensory descriptors	Definition	Evaluation protocol	scoring scale
Crispness of the crust	Mechanical property related to the force required for the surface of the French fries to crumble or break during mastication	Put a French fry in the mouth and evaluate the force required to break the crust	1: Cardboardy 5: Crispy
Product hardness	Ability of the product to resist mechanical strain	Put a French fry in the mouth and evaluate the force required to break the whole French fry.	1: Soft 5: Hard
Softness of the core	Mechanical property related to the force required to obtain a deformation of the core of the French fries during mastication	Evaluate the force required to deform the product by compressing the core of the French fries between the teeth or between the tongue and the palate.	1: Hard 5: Soft
Floury of the core	Mechanical property related to the cohesion and presence of fine particles in the core of French fries during mastication	Put a French fry in the mouth and evaluate the presence of floury particles during mastication	1: Smooth 5: Floury
Boiled potato taste	Aroma of potato cooked in boiling water	Evaluate the intensity of the boiled potato aroma when tasting the French fries	1: Low 5: High

Table 3: Results of sensory analysis and instrumental tests for French fries samples obtained by deep fat frying (DF) or air frying (AY) at three different temperatures (140, 180 and 200 °C) and three different water loss level 45, 50 and 60 (% i.m).

Sample's code	Sensory descriptors				Mechanical test*			Acoustic test**			
	Crispness of the crust	Product hardness	Softness of the core	Boiled potato taste	NFP	LDF (10^{-3} N m)	Fmax (N)	NSP	LDS (10^{-3} dB m)	Smax (dB)	MS (dB)
DF180_60	4.9 ± 0.2 ^{a}	3.5 ± 0.3 ^{b}	3.3 ± 0.3 ^{b}	1.9 ± 0.2 ^{c}	13.3 ± 3.5 ^{a}	19.8 ± 3.7 ^{a}	3.4 ± 0.6 ^{a}	87.1 ± 10.4 ^{a}	6.9 ± 1.3 ^{a}	75.3 ± 3.5 ^{a}	10.4 ± 2.3 ^{a}
DF180_50	4.7 ± 0.3 ^{a}	2.9 ± 0.3 ^{c}	4.5 ± 0.2 ^{a}	2.6 ± 0.3 ^{b}	7.5 ± 1.0 ^{c}	9.2 ± 0.5 ^{b}	1.8 ± 0.2 ^{b}	54.0 ± 4.5 ^{bc}	4.4 ± 0.7 ^{bc}	69.2 ± 2.5 ^{a}	5.6 ± 0.5 ^{bc}
DF180_45	3.9 ± 0.3 ^{b}	3.0 ± 0.2 ^{c}	4.5 ± 0.2 ^{a}	2.4 ± 0.5 ^{b}	4.7 ± 0.7 ^{cd}	7.0 ± 0.3 ^{b}	1.4 ± 0.2 ^{b}	39.7 ± 3.1 ^{c}	3.3 ± 0.3 ^{c}	67.4 ± 3.8 ^{b}	3.8 ± 0.3 ^{c}
AY180_60	3.8 ± 0.4 ^{b}	4.2 ± 0.2 ^{a}	3.0 ± 0.3 ^{b}	2.7 ± 0.5 ^{b}	9.9 ± 1.3 ^{bc}	15.0 ± 4.5 ^{a}	4.3 ± 0.6 ^{a}	66.4 ± 9.3 ^{b}	5.3 ± 1.2 ^{b}	70.8 ± 3.3 ^{b}	6.5 ± 1.8 ^{b}
AY200_50	3.1 ± 0.3 ^{c}	3.2 ± 0.2 ^{bc}	3.5 ± 0.3 ^{b}	2.6 ± 0.3 ^{b}	2.9 ± 0.7 ^{d}	6.3 ± 0.4 ^{b}	1.4 ± 0.2 ^{b}	20.7 ± 4.1 ^{d}	1.6 ± 0.2 ^{d}	59.0 ± 3.2 ^{c}	1.6 ± 0.5 ^{d}
AY180_50	3.2 ± 0.2 ^{c}	3.0 ± 0.2 ^{c}	4.1 ± 0.2 ^{a}	2.8 ± 0.3 ^{b}	2.9 ± 0.7 ^{d}	6.2 ± 1.2 ^{b}	1.3 ± 0.2 ^{b}	16.7 ± 3.5 ^{d}	1.3 ± 0.2 ^{d}	57.4 ± 2.6 ^{cd}	1.2 ± 0.3 ^{d}
AY140_50	2.4 ± 0.3 ^{d}	2.4 ± 0.3 ^{d}	4.3 ± 0.2 ^{a}	3.6 ± 0.2 ^{a}	1.9 ± 0.4 ^{d}	5.9 ± 0.2 ^{b}	1.3 ± 0.3 ^{b}	6.9 ± 1.7 ^{e}	0.5 ± 0.1 ^{e}	50.8 ± 3.5 ^{d}	0.5 ± 0.2 ^{d}

Values are the mean ± 95% confidence interval (n = 26 (2 tasting sessions × 13 judges) for sensory analysis; $35 \leq n \leq 45$ for acoustical and mechanical analysis).
Means with the same superscript (a–e) within the same column do not differ significantly (Tukey test, p-value ≤ 0.05).
*   NFP: number of force peaks; LDF: linear distance of force peaks; Fmax : maximum force
** NSP number of sound peaks; LDS: linear distance of sound peaks; Smax : maximum sound pressure level; MS: mean of sound pressure level

Table 4: Matrix of correlation coefficients (*r*) between investigated variables.

	Variables	Sensory descriptors					Mechanical parameters			Acoustic parameters				
		Crispness of the crust	Product hardness	Softness of the core	Floury of the core	boiled potato taste	NFP	LDF	F max	NSP	LDS	Smax	SAire	MS
Sensory descriptors	Crispness of the crust	1*												
	Product hardness	0.47	1*											
	Softness of the core	-0.12	-0.83*	1*										
	Floury of the core	-0.46	0.43	-0.51	1*									
	boiled potato taste	-0.88*	-0.54	0.35	0.43	1*								
Mechanical parameters	NFP	0.84*	0.70	-0.54	-0.09	-0.76	1*							
	LDF	0.70	0.72	-0.66	0.04	-0.68	0.97*	1*						
	F max	0.50	0.89*	-0.79	0.39	-0.44	0.85*	0.89*	1*					
Acoustic parameters	NSP	0.89*	0.71	-0.49	-0.10	-0.81*	0.99*	0.93*	0.81*	1*				
	LDS	0.90*	0.70	-0.47	-0.11	-0.81*	0.99*	0.92*	0.80*	1 *	1*			
	Smax	0.94*	0.69	-0.37	-0.16	-0.87*	0.91*	0.81*	0.70	0.96*	0.97*	1*		
	SAire	0.89*	0.64	-0.46	-0.16	-0.81*	0.99*	0.95*	0.77	0.99*	0.99*	0.94*	1*	
	MS	0.89*	0.64	-0.46	-0.16	-0.81*	0.99*	0.95*	0.77	0.99*	0.99*	0.94*	1*	1*

The values of the correlation coefficients are different from 0 with a significance level alpha = 0.95
Values marked with an asterisk (*) correspond to correlation coefficients ≥ 0.8 indicating a high correlation.
NFP: number of force peaks; LDF: linear distance of force peaks; Fmax: maximum force
NSP number of sound peaks; LDS: linear distance of sound peaks; Smax: maximum sound pressure level; MS: mean of sound pressure level

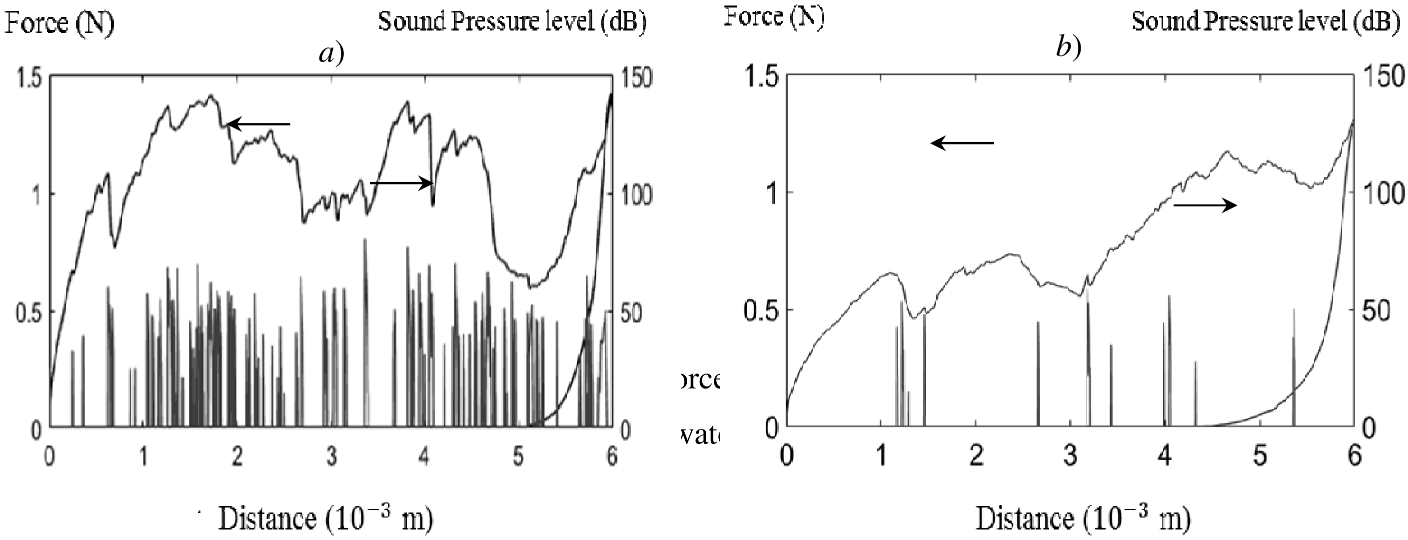

Force (N)
Sound Pressure level (dB)
a)
b)
1.5
1
0.5
0
150
100
50
0
0
1
2
3
4
5
6
Distance (10^{-3} m)

Figure 1.

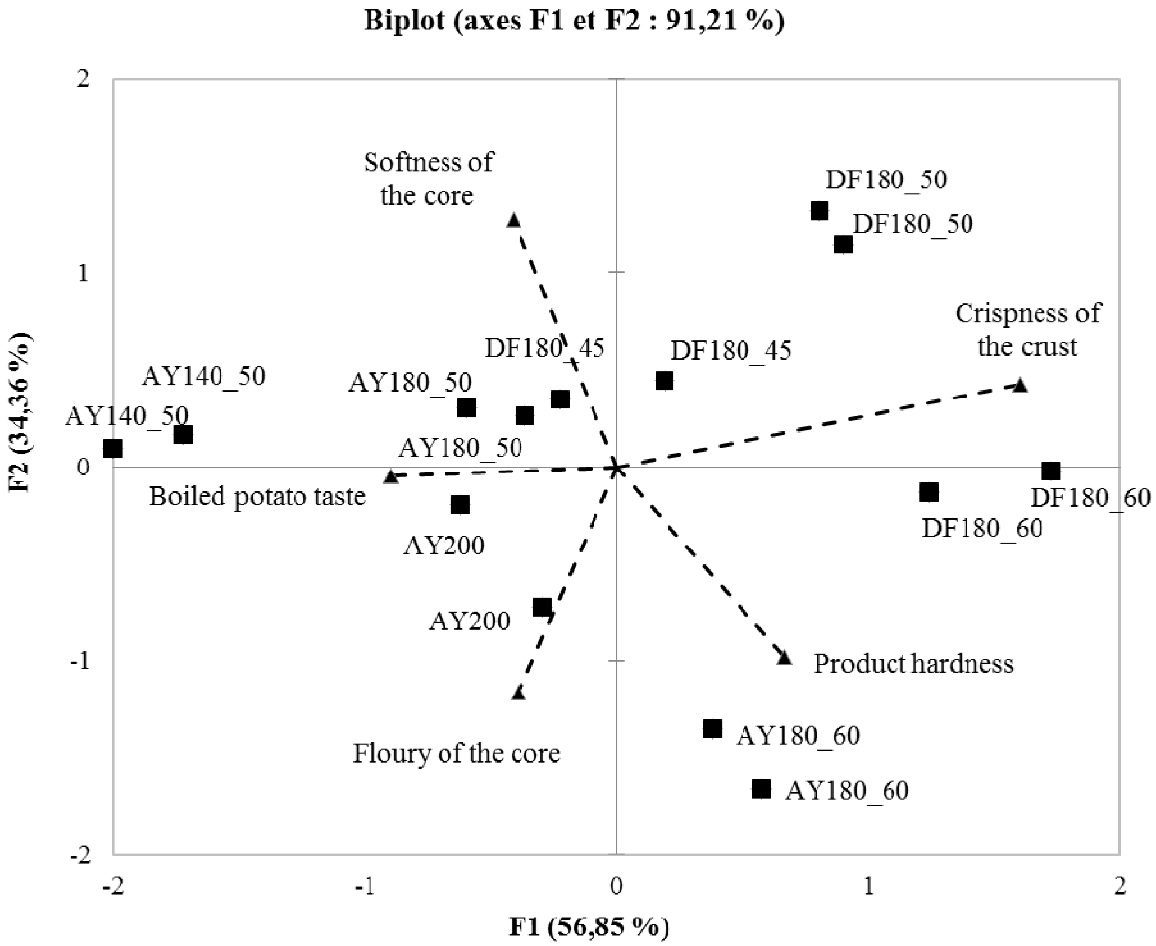

Biplot (axes F1 et F2 : 91,21 %)
Softness of the core
DF180_50
DF180_50
Crispness of the crust
DF180_45
DF180_45
AY140_50
AY140_50
AY180_50
AY180_50
Boiled potato taste
AY200
AY200
DF180_60
DF180_60
Product hardness
Floury of the core
AY180_60
AY180_60
F2 (34,36 %)
F1 (56,85 %)
2
1
0
-1
-2
-2
-1
0
1
2

Figure 2.

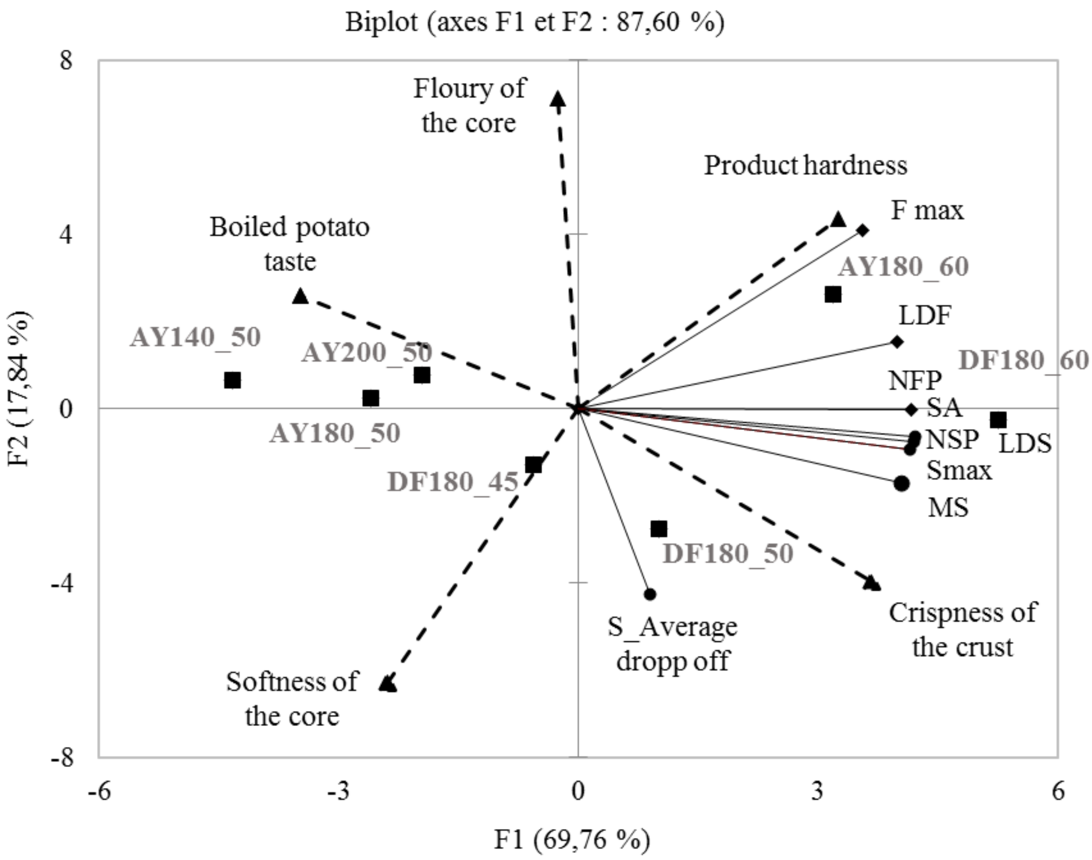

Biplot (axes F1 et F2 : 87,60 %)
Floury of the core
Product hardness
F max
Boiled potato taste
AY180_60
LDF
DF180_60
AY140_50
AY200_50
NFP
SA
NSP
LDS
AY180_50
Smax
DF180_45
MS
DF180_50
S_Average dropp off
Crispness of the crust
Softness of the core
F1 (69,76 %)
F2 (17,84 %)
8
4
0
-4
-8
-6
-3
0
3
6

Figure 3.

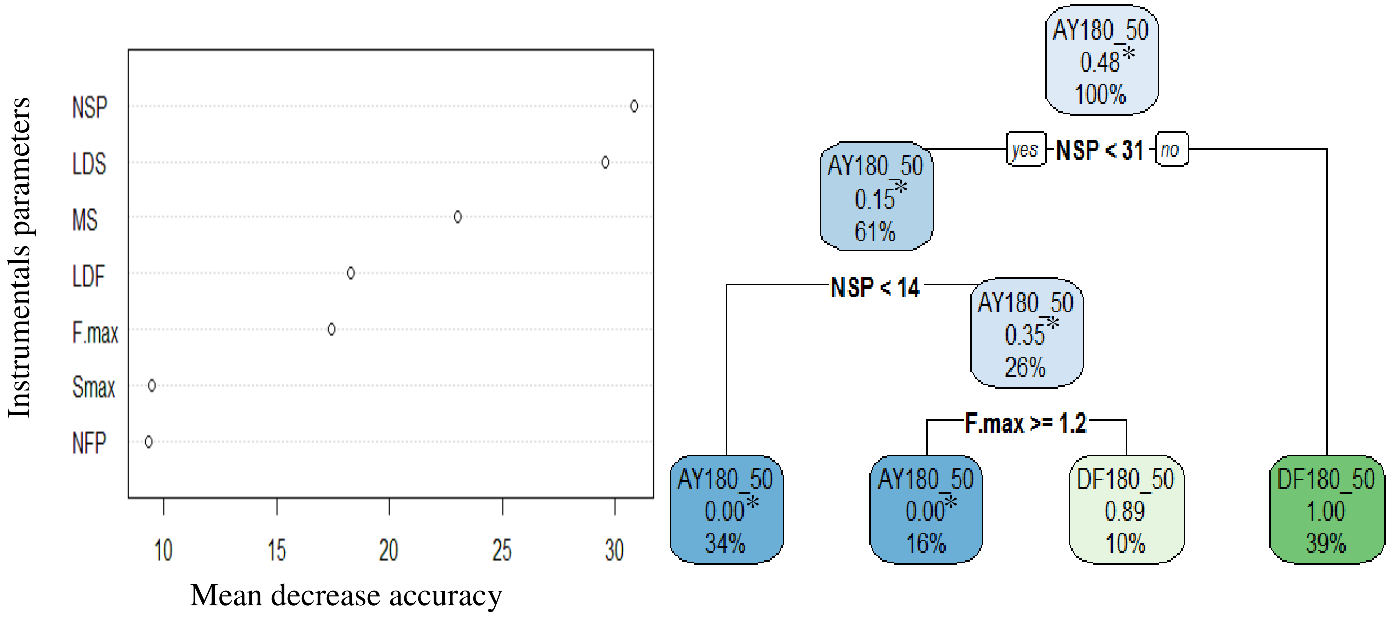
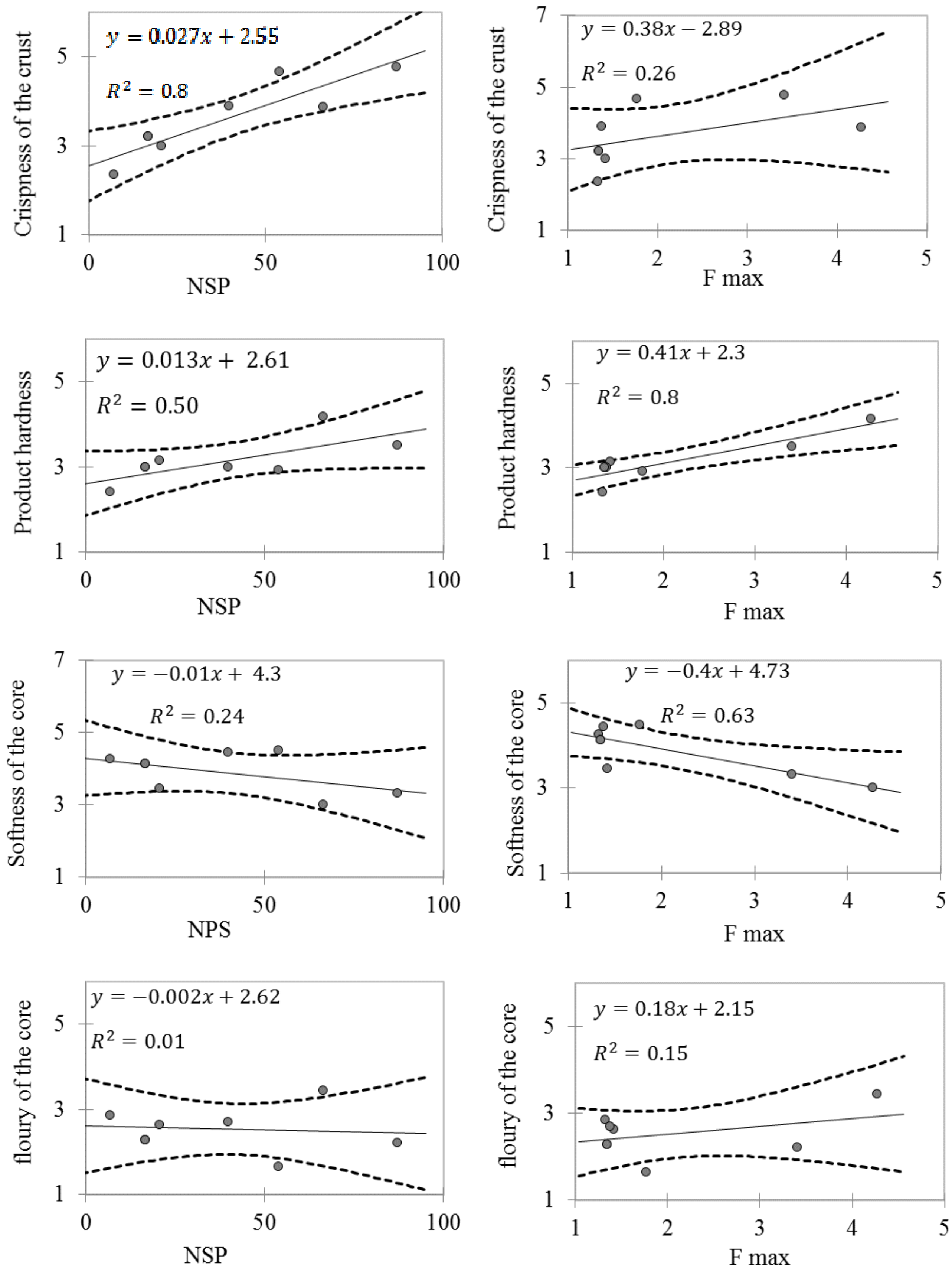
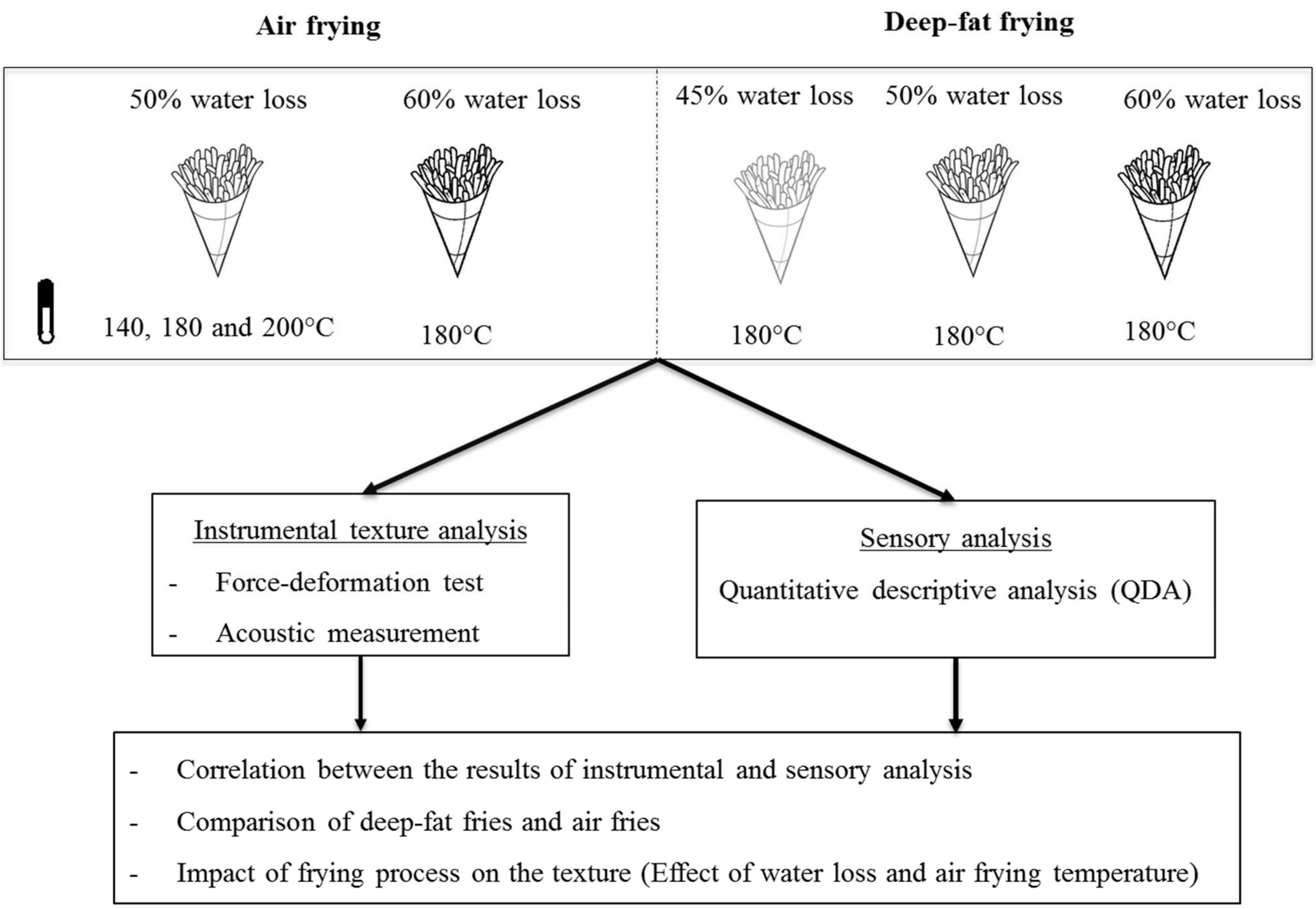

Instrumentals parameters
NSP
LDS
MS
LDF
F.max
Smax
NFP
10
15
20
25
30
Mean decrease accuracy
AY180_50
0.48*
100%
yes
NSP < 31
no
AY180_50
0.15*
61%
NSP < 14
AY180_50
0.35*
26%
F.max >= 1.2
AY180_50
0.00*
34%
AY180_50
0.00*
16%
DF180_50
0.89
10%
DF180_50
1.00
39%

Figure 4:



$y = 0.027x + 2.55$
$R^2 = 0.8$
Crispness of the crust
NSP
$y = 0.38x - 2.89$
$R^2 = 0.26$
Crispness of the crust
F max
$y = 0.013x + 2.61$
$R^2 = 0.50$
Product hardness
NSP
$y = 0.41x + 2.3$
$R^2 = 0.8$
Product hardness
F max
$y = -0.01x + 4.3$
$R^2 = 0.24$
Softness of the core
NPS
$y = -0.4x + 4.73$
$R^2 = 0.63$
Softness of the core
F max
$y = -0.002x + 2.62$
$R^2 = 0.01$
floury of the core
NSP
$y = 0.18x + 2.15$
$R^2 = 0.15$
floury of the core
F max

Figure 5.


Air frying
Deep-fat frying
50% water loss
60% water loss
45% water loss
50% water loss
60% water loss
140, 180 and 200°C
180°C
180°C
180°C
180°C
Instrumental texture analysis
- Force-deformation test
- Acoustic measurement
Sensory analysis
Quantitative descriptive analysis (QDA)
- Correlation between the results of instrumental and sensory analysis
- Comparison of deep-fat fries and air fries
- Impact of frying process on the texture (Effect of water loss and air frying temperature)