Assessment of acoustic-mechanical measurements for texture of French fries: Comparison of deep-fat frying and air frying

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25   **Abstract**

26   The aim of this study was to develop an instrumental method for measuring the

27   texture of French fries and correlated it with sensory measurements. For seven samples

28   of French fries with different crispness levels, a cone penetrometer test was conducted

29   simultaneously with microphone recording of sound emissions. A descriptive sensory

30   analysis was also performed on these samples. The results showed that the number of

31   sound peaks, the linear distance of sound peaks, the area under the sound-displacement

32   curve and the mean sound pressure were strongly positively correlated ($r \geq 0.80$; P-

33   value < 0.02) with the crispness of the crust descriptor. The number of force peaks and

34   the linear distance of the force peaks were correlated with all the acoustic parameters.

35   These two mechanical parameters and the maximum force, were not correlated with

36   crispness of the crust ($r = 0.50$; P-value < 0.05) but strongly correlated with product

37   hardness ($r = 0.9$; P-value < 0.01). However, the combination of the acoustic and

38   mechanical parameters appeared suitable for measuring the texture of French fries. An

39   analysis of the variable importance by random forest showed that the main parameters

40   for quantifying the texture differences were the number of sound peaks and the

41   maximum force. The use of this instrumental method and sensory analysis showed that

42   the deep-fat fried products were crispier than the air fried products with the same water

43   loss.

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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.

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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-

99 deformation often do not show clearly a correlation with sensory crispness.

100 Nevertheless, Van Loon (2005) showed a correlation between the number of peaks in

101 the force-deformation and sensory perception of crispness of French fries. Instrumental

102 techniques present some advantages, especially in industrial environments in which

103 quick and easy-to-use methods are in great demand and are economically more

104 profitable (Saeleaw & Schleining, 2011). Other new texture measurement techniques,

105 such as acoustic measurements, have been used on crispy products other than French

106 fries, such as chips, wafer products, and have found high correlations with sensory

107 measurements (L. Duizer, 2001; Marzec, Cacak-Pietrzak, & Gondek, 2011; Saeleaw,

108 Dürrschmid, & Schleining, 2012; Çarşanba, Duerrschmid, & Schleining, 2018). The

109 combination of acoustic and mechanical techniques has been shown to better describe

110 food texture than either of the two techniques alone (L. Piazza & Giovenzana, 2015;

111 Laura Piazza, Gigli, & Ballabio, 2007). The tests, mainly 3-point bending, penetration,

112 and compression methods, predicted the snack crunch (L. Duizer, 2001) and showed

113 good correlations between the acoustic-mechanical and sensory parameters. Other

114 studies have also shown that the sounds produced during food disintegration play an

115 important role in the perception of the texture of food materials (L. Duizer, 2001;

116 Luyten & Vliet, 2006). Sometimes these sounds describe the overall quality of a food

117 product better than any other sensory characteristic (A. marzec, G. cacak-pietrzak & E.

118 Gondek, 2011). The mechanical (penetration test) and acoustic evaluation of crispness

119 was also used to describe the texture of cookies (Chen, Karlsson, & Povey, 2005),

120 extruded bread (Marzec, Lewicki, & Ranachowski, 2007), toasted nuts (Salvador,

121 Varela, Sanz, & Fiszman, 2009) and apples (Zdunek, Cybulska, Konopacka, &

122 Rutkowski, 2011).

123   The aim of this study was to develop an instrumental method for measuring the

124 texture of French fries, and especially the crispness of the crust. A penetration test was

125 conducted simultaneously with microphone recording of sound emissions. A descriptive

126 sensory analysis was performed to evaluate the textural attributes, and the relationships

127 between the sensory parameters and the instrumental measurement parameters were

128 analysed. Finally, this approach was used to compare two products with contrasting

129 texture made using deep fat frying and air frying.

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131 **2.** Materials & Methods

132   **2.1.** Raw materials

133   The experiments were carried out with frozen French fries (Mc-Cain Tradition)

134 purchased at a local supermarket and stored in a cold room at $-18\,°C$. The frozen

135 French fries were resized to 60 mm in length and 10 mm thick (10×10×60 mm) with a

136 specific cutter. Each experiment was conducted with 0.300 kg of sized French fries.

137   **2.2.** Frying equipment

138   Two main fryers were used: a commercial oil bath fryer (Filtra One FF162100

139 Seb) with a power of 1900 W, a chip capacity of 1.20 kg and an oil capacity of 2.10 L,

140 and hot-air frying equipment (Airfryer Philips XL HD9240/90, Avance Collection,

141 Amsterdam, The Netherlands) with a power of 2100 W.

142   **2.3.** Sample preparation

143   French fries with different crispness levels were obtained by adapting the frying

144 equipment type, water loss and frying temperature.. Each experiment was carried out

145 with 0.300 kg of sized French fries. Three French fries samples were fried at $180\,°C$

146 with a conventional deep-fat fryer for final water losses of 60 %, 50 % and 45 %. Four

147 French fries samples were prepared using the hot air fryer. Three of them were fried at

148 $140\,°C$, $180\,°C$ and $200\,°C$ until the water loss reached 50 %. The fourth sample was

149 fried at 180 °C until a water loss of 60 %. The samples were coded according to their

150 frying conditions, as shown in Table 1. All French fries samples were analysed in under

151 5 min. The water loss was defined as the mass of water lost during frying divided by the

152 initial mass (i.m) of the sample before frying.

153 **2.4.** Instrumental texture analysis

154 A penetration test was conducted with a conical probe with a 60° angle.

155 Mechanical (penetration test) and acoustic measurements were made using a texture

156 analyser (TA.XT.plus, Stable Micro Systems (SMS), Surrey, U.K) using a 5 kg sensor

157 connected to a microphone (Brüel Kjaer, Type 2671 Naerum, Denmark). This set was

158 placed in the Thermal Cabinet (TC/LN2 for the TA.XTplus Texture Analyser), which

159 was regulated at 50 °C. The microphone included an acoustic envelope detector (AED)

160 to avoid background noise. It was calibrated with a type 4231 acoustic calibrator (1 Hz,

161 Brüel Kjaer) at 94 and 114 dB sound pressure. The acoustic detector included a sound

162 amplification element that was set to level 2. The microphone position was 1.6 cm from

163 the sample at an angle of 50°. Different test speed (0.2 mm.s^{-1}, 0.5 mm.s^{-1}, 1 mm.s^{-1}

164 and 2 mm.s^{-1}) and deformation level (50 % and 80 %) were tried. The thermal cabinet

165 was turned off during the measurement due to the background noise of its fan. It was

166 used as a partition for the external environmental noise and for the sound emitted by the

167 sample. The conical probe was applied at a position of 20 mm from the extremity of the

168 French fry (1/3 of the length of the French fry). Each French fry was penetrated only

169 once. The measurements were carried out in triplicate with approximately fifteen French

170 fries per test.

171 The following parameters—maximum force (Fmax, N), number of force

172 peaks (NFP), linear force peak distance (LDF, Nm), maximum sound pressure level

173 (Smax, dB), mean of sound pressure (MS, dB), area under the sound displacement

174 curve (AS, dB m), number of sound peaks (NSP), linear distance of sound peaks (LDS,

175 dB m) and average drop-off of sound peaks (F_Average, dB)—were evaluated with the

176 software Exponent (Stable Micro Systems) from the force-deformation curves and

177 acoustic displacement (Figure 1) in a range from 0 to 5 mm corresponding to 50%

178 deformation. The definitions of the instrumental parameters are described in detail

179 elsewhere (Varela, Salvador, & Fiszman, 2008; L. Piazza & Giovenzana, 2015; Kirmaci

180 & Singh, 2016). The sound pressure levels and force-deformation curves were recorded

181 with a detection threshold of 5 dB and 0.05 N, respectively. The same threshold values

182 were used for the detection of the number of sound peaks and the number of force

183 peaks.

184 **2.5.** Sensory analysis

185   *2.5.1. Experimental conditions*

186   A quantitative descriptive analysis (QDA) was used to evaluate the sensory

187 characteristics of the samples. The sensory profiles were performed in the sensory

188 analysis laboratory of the QualiSud UMR (CIRAD, Montpellier)). The room is

189 composed of 15 individual boxes including a small sink and an adaptable light. During

190 the tasting sessions, the room temperature and relative humidity were monitored and

191 averaged 22 ± 4 °C and 29 ± 6 %, respectively. Three or four French fries per

192 experimental conditions were presented in monadic form, 1 to 2 minutes after frying, in

193 petri dishes to keep the product warm. The panel consisted of 13 subjects (6 women and

194 7 men) aged 24 to 50 years, who were trained and qualified for sensory analysis

195 (repeatable, homogeneous).

196   *2.5.2. Descriptors*

197   Five descriptors of relevance were selected based on previous studies and

198 considering the purposes of our study. The sensory descriptors studied were crispness of

199 the crust, product hardness, softness of the core, floury of the core and boiled potato

200   taste. The descriptors were evaluated on a continuous scale from the lowest intensity

201   (value 1) to the highest intensity (value 5). The definitions of and evaluation protocols

202   for the sensory descriptors are described in Table 2.

203   *2.5.3. Jury training*

204   Before the tasting started, four training sessions, according to ISO 8586 (2012),

205   were carried out on four types of French fries. These were fried to present the average

206   and extreme intensities of each descriptor. The tasting panel was trained on the different

207   descriptors in the first two training sessions. The last two training sessions were

208   dedicated to assessing the panel's ability to use the descriptors. The scores assigned by

209   the judges were compared to those given by consensus, and judges were asked to

210   comply with the desired benchmark. The jury's training was validated by a statistical

211   analysis, analysing their repeatability. Non-repeatable judges were eliminated for the

212   remainder of the evaluation. Thirteen judges were validated.

213   *2.5.4. Tasting sessions*

214   The seven French fries samples were coded and then submitted to the jury for

215   analysis, giving a score ranging from 1 to 5 for each descriptor out of four tasting

216   sessions. At each tasting session, three to four samples were presented in succession.

217   The order of the samples was determined randomly. The tasting was then carried out in

218   duplicate for each sample.

219   **2.6.** Statistical analysis

220   The statistical analysis of the results was carried out using XLSTAT version 2017

221   (ANOVA and PCA test) and R programs (decision tree test "rpart"). The ANOVA

222   procedure at a significance level at 0.05 and the Tukey test were applied to assess

223   significant differences between the investigated parameters. A correlation analysis

224   (PCA) and a decision tree followed by a random forest were also conducted. An

225 ensemble learner was built on decision trees, in which each decision tree was made with

226 a bagging of observations and instrumental parameters. The mean decrease in accuracy

227 caused by a parameter was determined during the out-of-bag error calculation phase

228 from running the random forest 1000 times (number of trees = 1000, sample size =

229 63%, and no. of variables tried at each split = 2). The parameter importance estimated

230 from the random forest was defined as the percentage of misclassifications.

231   The results of the PCA analysis were presented as a two-dimensional graph: a

232 graph that represents both variables and samples in two dimensions.

233

234 **3.** Results and discussion

235 **3.1.** Sensory analysis

236   The ANOVA's results of the sensory analysis are summarized in Table 3. Seven

237 high-contrast texture samples were generated based on final water loss, frying method

238 and frying temperature. Five sensory descriptors were analysed. The floury of the core

239 was not significantly different for the seven samples. Its value ranged from 1.9 to 3.1.

240 This descriptor is not presented in Table 3. The crispness of the crust, product hardness,

241 softness of the core descriptors and boiled potato taste made it possible to classify the

242 seven samples into 4, 4, 2 and 3 groups, respectively. The variation coefficient of these

243 descriptors in the range from 4 and 10% was satisfactory. It was mainly the crispness of

244 the crust (F-value = 44) and product hardness that differentiate the samples (F-

245 value = 20). This is demonstrated in Figure 2, which presents the bi-plot PCA on

246 covariance, regarding the sensory descriptors data set for the seven French fries

247 samples. The average jury scores for the two tasting sessions are represented in

248 Figure 2. The first two dimensions explain 91.2 % of the variability (56.8 % F1,

249 34.4 % F2). The crispness of the crust and boiled potato taste descriptors contribute

250 highly to the F1 axis respectively 62% and 20%. The product DF180_60 and

251 AY140_50 strongly drives the F1 axis. The axis F2 was more explained by the

252 descriptors softness of the core (39.5 %), floury of the core (32.7 %) and product

253 hardness (23.3 %). There was no correlation between the product hardness and the

254 crispness of the crust ($r = 0.47$; P-value < 0.05). Çarşanba, Duerrschmid, & Schleining

255 (2018) also showed on wafer products that hardness and crispness were also slightly

256 correlated. In addition, the product hardness was strongly negatively correlated with the

257 softness of the core ($r = -0.83$; p-value < 0.02). The crispness of the crust was strongly

258 negatively correlated with only the boiled potato taste ($r = -0.88$; P-value < 0.01). The

259 PCA (Figure 2) shows that the seven French fries samples were repeatable quite varied

260 and well dispersed, thus explaining the different sensory descriptors. Afterwards, these

261 seven samples with contrasting textures were used to characterize the performance of

262 the instrumental measurements of texture.

263 **3.2.** Instrumental analysis: acoustics and force-deformation test

264   Four different test speeds were used (0.2 mm.s^{-1}, 0.5 mm.s^{-1}, 1 mm.s^{-1} and

265 2 mm.s^{-1}), and two deformation levels (50 % and 80 %). The results showed that the

266 use of a high test speed (2 mm.s^{-1}) dit not allow a significant difference between

267 products, but a too low test speed (0.2 mm.s^{-1}) produces high significant differences but

268 with a high variation coefficient (55 %). A moderate test speed of 0.5 mm.s^{-1}was used

269 to make a successful compromise to minimize the variation coefficient. The

270 deformation levels has no significant effect. The deformation level 50 % was used.

271   Figure 1 shows typical force-distance and acoustic amplitude-distance curves for

272 two products: one very crispy and the other slightly crispy. In Figure 1 a), more acoustic

273 and mechanical events were observed than in Figure 1 b). In Figure 1 b), when the force

274 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).

301   The analysis of the acoustic parameters showed that the number of sound

302   peaks (NSP) and the linear distance of sound peaks (LDS) followed the same rankings

303   by significantly separating the products into five different groups. The area under the

304   sound displacement curve (AS) and the mean of the sound pressure (MS) parameters

305   also grouped the samples in the same way by classifying them into four product groups.

306   For this reason, the area under the sound displacement curve (AS) was not presented in

307   Table 3. The relative uncertainty of these parameters ranged from 7 to 20 % for NSP (F-

308   value = 60.7) and LDS (F-value = 58.3) and from 7 to 35 % for AS (F-value = 46.6) and

309   MS (F-value = 46.7). The maximum sound pressure (Smax) allowed the separation of

310   the products into four groups with both a low relative uncertainty (< 7 %) and a low

311   variation amplitude (75 to 50) when compared to the other acoustic parameters, such as

312   NSP (87 to 7) and MS (10.5 to 0.5). By comparing the F-value of these acoustic

313   parameters, it can be observed that the Smax has a lower F-value (Smax, F-value = 23)

314   compared to the other parameters. The low F-value and low variation amplitude can

315   lead to a lack of efficiency of this parameter to detect significant differences when the

316   products to compare have a low texture difference.

317   The various acoustic parameters can be split into three groups (NSP/LDS, Smax

318   and AS/MS), and the mechanical (penetration test) parameters into two groups (NFP

319   and Fmax/LDF). The acoustic parameters separated the products into at least four

320   groups with high F-value, while the mechanical parameters allowed their classification

321   into two and four maximum groups with lower F-value than acoustic parameters.

322   Therefore, the acoustic parameters are more sensitive than the penetration test

323   parameters.

324   The analysis of the different confidence intervals and different F-values showed

325   that mechanical responses were more repeatable (3 to 18 % relative uncertainty) but

326   were less discriminating (low F-value) than acoustic responses (5 to 25 % relative

327   uncertainty). It is important to point out that the experimental variance was determined

328   with approximately forty-five values (French fries measured). This result shows that

329   this instrumental measurement was not as simple to carry out and required careful

330   implementation conditions to be reproducible.

331   **3.3.** Correlation between the results of instrumental and sensory analysis

332   Figure 3 shows a PCA on correlation, performed to illustrate the relation between

333   some mechanical (penetration test) and acoustic parameters and sensory descriptors of

334   French fries. The PCA showed that 87.60 % of the variability could be explained by the

335   first two main components: 69.76 % by the first component F1 and 17.84 % by the

336   second component F2. Instrumental parameters were projected as supplementary

337   variables and did not influence on the principal components of the analysis. The first

338   dimension (F1 axis) is particularly linked to the variables product hardness (29 %),

339   boiled potato taste (29 %), crispiness of the crust (27 %) and softness of the core (15%).

340   The second axis is more related to the floury of the core (48 %) and the softness of the

341   core (20 %). This bi-plot illustrates that the products DF180_60 and DF180_50 were

342   associated with higher values of the acoustic parameters. These products were the

343   crispiest by sensory analysis. The AY180_60 product, which was considered harder and

344   moderately crispy, was associated with higher values of Fmax and product hardness.

345   The products AY40_50, AY180_50 and AY200_50 were characterized by lower values

346   of most of the acoustic parameters but were associated with higher values of boiled

347   potato taste. These products had the lowest crispness scores and were, therefore,

348   considered less crispy by the sensory analysis. Therefore, it can be concluded that an

349   increase in acoustic parameters reflects a high level of crispness. This is in line with

350   several previous works (Saeleaw & Schleining, 2011; Giacosa et al., 2016; Jakubczyk,

351   Gondek, & Tryzno, 2017; Çarşanba, Duerrschmid, & Schleining, 2018).

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352   Some instrumental parameters were more or less correlated with each other, unlike

353   sensory parameters, which were distinct from each other (Figure 3). Most of the

354   acoustic parameters studied were positively correlated with each other, except for

355   the S_Average which was more closely related to the F2 axis. The acoustic parameters

356   NSP ($r = 0.89$;   P-value < 0.01),   LDS ($r = 0.90$; P-value < 0.01),   Smax ($r = 0.94$; P-

357   value < 0.01) and MS ($r = 0.89$; P-value < 0.01) were strongly positively correlated with

358   the crispness of the crust, with a high level of significance (Table 4). According to this,

359   a small number of acoustic events was considered as an indication of a low crispness of

360   the crust. This conclusion is in line with the work of Salvador, Varela, Sanz, & Fiszman

361   (2009), who obtained the same conclusion with potato chips. Smax, NSP and MS were

362   specifically used to explain the crispness and crunchiness of extruded snacks by

363   Saeleaw and Schleining (2011). In contrast, the sensory descriptor boiled potato taste

364   was negatively correlated to all these parameters (Figure 3). The crispier the products

365   were, the less the products taste like boiled potatoes.

366   The mechanical (penetration test) parameters were not significantly correlated with

367   the   crispness   of   the   crust   for   P-value < 0.05 (LDF $r = 0.70$, P-value > 0.05;

368   F_max $r = 0.5$, P-value > 0.05),   except   for   the   NFP   parameter   ($r = 0.84$; P-

369   value < 0.05). In   contrast,   F max   was   strongly   correlated   with   the   product

370   hardness ($r = 0.9$; P-value < 0.01). Obviously, the descriptor product hardness was not

371   only associated with the mechanical parameters. These results are in line with the work

372   carried out by Jakubczyk, Gondek, & Tryzno (2017) on co-extruded snacks. The

373   sensory   descriptor   softness of   the   core   was   negatively   correlated   to

374   F max ($r = -0.79$; P-value < 0.05) but   not   significant   for   the   other   instrumental

375   parameters. The harder the products were, the less soft the core was.

376   The relation between the parameters highly correlated with some evaluated sensory

377   texture   descriptors   was   established   by   analysing   the   linear   regression

378   coefficients (Figure 5). The coefficient of determination (R^2) shows how the

379   instrumental parameters such as NSP and Fmax explain sensory descriptors (crispness

380   of the crust, product hardness, softness of the core or floury of the core) by a linear

381   model. The parameters NSP ($R^2 = 0.80$) shows a high and positive regression coefficient

382   for the sensory crispness of the crust. This instrumental parameter allowed the

383   prediction of the sensory crispness of French fries correctly with high robustness. The

384   coefficient of determination of Fmax relative to hardness was high and reflects a strong

385   correlation between hardness and F max ($R^2 = 0.80$). No parameter can significantly

386   predict the soft and floury of the core. This confirms that the two parameters (NSP and

387   Fmax) reflect the crispness and the product hardness. These results confirm that the two

388   methods provide different and complementary information. The mechanical parameters

389   had better explain the hardness of the product and the softness of the core, and the

390   acoustic parameters better explain the crispness of the crust. The combination of the

391   acoustic and mechanical (penetration test) methods seems appropriate to describe the

392   texture of French fries. Several other previous studies have reported the same

393   conclusion for other crispy food such as dutch crisbakes, wafers, crispy bakery products

394   (Mohamed, Jowitt, & Brennan, 1982; Laura Piazza, Gigli, & Ballabio, 2007; L. Piazza

395   & Giovenzana, 2015).

396   A random forest classification was carried out by comparing 45 deep-fat

397   fries (DF180_50) and 45 hot-air fries (AY180_50). The purpose was to detect the

398   importance of the variables in predicting the class of the French fries (between deep-fat

399   and hot-air). The products were made at the same frying temperature (180 °C) and with

400   the same water loss (50%). Figure 4 a) presents the classification tree relating the frying

401   process groups (deep-fat frying; air frying) to the instrumental parameters. The

402   parameter importance estimated from the random forest was defined as the percentage

403   of misclassifications. The more the accuracy of the random forest decreased due to the

404 exclusion (or permutation) of a single parameter, the more important that parameter was

405 deemed, and therefore, parameters with a large mean decrease in accuracy were more

406 important for the classification of the data. The acoustic parameters were more

407 important, especially the number of sound peaks (NSP) and the linear distance of sound

408 peaks (LDS), followed by the mean sound pressure (MS) and the area under the sound

409 displacement curve (AS). The parameters that have less weight were S_max and NFP.

410 Figure 4 b) shows a good discrimination of the products due to the parameters NSP and

411 Fmax and with an out-of-bag error of just 8.04 %. This confirms the relevance of

412 combining the acoustic parameters with NSP and the mechanical parameters with Fmax

413 with a performance error of 6.6 %. Other important instrumental parameters, such as

414 LDS, MS and AS, did not appear in the classification because they were highly

415 correlated with NSP and with each other. The combination of NSP and Fmax provides a

416 better classification of products. These results confirm also that a minimum hardness

417 (F max) was required to detect the crispness of French fries.

418 **3.4.** Impact of frying process on the texture

419 The analysis of Figure 1 showed that more acoustic and mechanical (penetration

420 test) events were observed for the deep-fat fried products curve (Figure 1 a) than for the

421 air-fried products (Figure 1 b). Teruel et al. (2015) also showed previously that the

422 deep-fat fried fries are crispier than the air-fried fries.

423 *3.4.1. Effect of water loss*

424 Three groups of French fries were generated according to their final water loss,

425 ranging from 45 % to 60 %. An analysis of the sensory parameters did not make it

426 possible to distinguish these three groups according to water loss. Only the Fmax, which

427 reflects the hardness of the product, separated the samples into two groups. In the first

428 group, all samples have a water loss of 60 %, and in the second group, the samples have

429   a final water loss of 45 % and 50 %. The more water was lost, the harder the product

430   became. For the other instrumental parameters, the effect of water loss was more

431   difficult to detect because of the combination of effects of process, temperature and

432   water loss. Indeed, it was possible to obtain the same water loss with different operating

433   conditions, and it was the rate of water transfer that was probably more important for

434   the texture of the product (Vitrac, Trystram, & Raoult-Wack, 2000; Bouchon &

435   Aguilera, 2001; Botero-Uribe, Fitzgerald, Gilbert, & Midgley, 2017). However, the

436   analysis of samples performed with deep-fat frying at 180 °C showed that an increase in

437   water loss increased the crispness of the crust and the product hardness. In contrast, the

438   softness of the core decreased with the water loss. In the instrumental parameters, there

439   was also an increase in mechanical and acoustic events as a function of water loss. For

440   comparing crispy products, it could be especially important to consider the water

441   content of the product (Seymour & Ann, 1988; Saeleaw, Dürrschmid, & Schleining,

442   2012)

443   ### 3.4.2. *Effect of air temperature*

444   An analysis of the air-fried samples with the same water loss of 50 % showed that

445   an increase in frying temperature from 140 °C to 180 °C or 200 °C increased the values

446   of the crispness of the crust and product hardness. This is in line with several previous

447   works (Kita, Lisińska, & Gołubowska, 2007; van Koerten et al., 2015). The acoustic

448   parameter values also increased as the frying temperature increased. From 180 °C to

449   200 °C, the increase in the values of the various instrumental parameters analysed was

450   not significant. These results confirm the conclusions of van Koerten, Schutyser,

451   Somsen, & Boom (2015) that state that increased frying temperatures will improve the

452   crispy properties of the fries due to the formation of more and larger pores, but this

453   improvement only occurs until the temperature reaches a certain maximum, which was

454   between 180 and 195 °C. The sample (AY140_50) obtained by air frying at 140 °C has

455   the lowest values of crispness of the crust and product hardness but has the highest

456   value of softness at the core. The low air frying temperature (140 °C) was not sufficient

457   to develop a crispy crust, such as that developed at temperatures of 180 °C and 200 °C.

458   This difference is due to the low heat and mass transfer rates, which are responsible for

459   the development of the particular texture of fried products. (Loon, 2005; Kita, Lisińska,

460   & Gołubowska, 2007; Thussu & Datta, 2012; Zeb, 2019).

461

462

463   **4.** Conclusion

464   This study allowed the development of an instrumental method for measuring the

465   texture of French fries. The penetration test and acoustic signals provide different and

466   complementary information. Acoustic signals are very sensitive to the crispness of the

467   crust of French fries. Acoustic parameters, such as the number of sound peaks (NPS),

468   the linear distance of sound peaks (LDS), the maximum sound pressure (Smax), the

469   mean sound pressure (MS) and the area under the sound displacement curve (AS), are

470   highly correlated with the sensory crispness of the crust. The instrumental parameters

471   NSP, Smax and the maximum force (Fmax) are suitable for good characterization of the

472   texture of French fries, especially the crispness of the crust and the product hardness.

473   By using a combination of mechanical (penetration test) and acoustic approaches, it was

474   possible to better estimate the texture of French fries than by using one of the other

475   technique alone.

476   However, this method requires a large number of repetitions (about thirty French

477   fries) and requires careful implementation conditions to be reproducible. The

478   instrumental tests were able to evaluate, discriminate and reasonably predict the sensory

479   crispness of the crust of French fries, with an R^2 close to 0.8. In addition, the following

480   specific advantages make this approach suitable for industrial application.

481   The use of this instrumental method and sensory analysis showed that the deep-fat

482   fried products are crispier than the air fried products and that water loss has an effect on

483   the crispness and hardness of the fries. It is important to take into account the moisture

484   content when comparing the crispness or hardness of fried products.

485

486   **5.** Acknowledgements

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494   **6.** References

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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
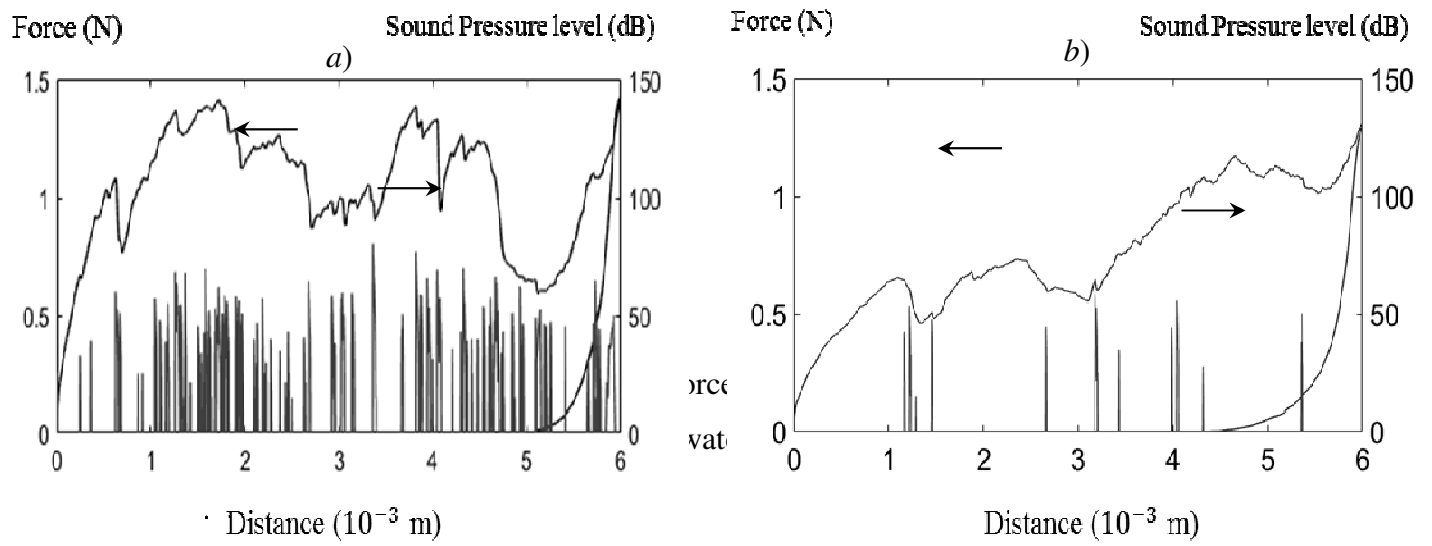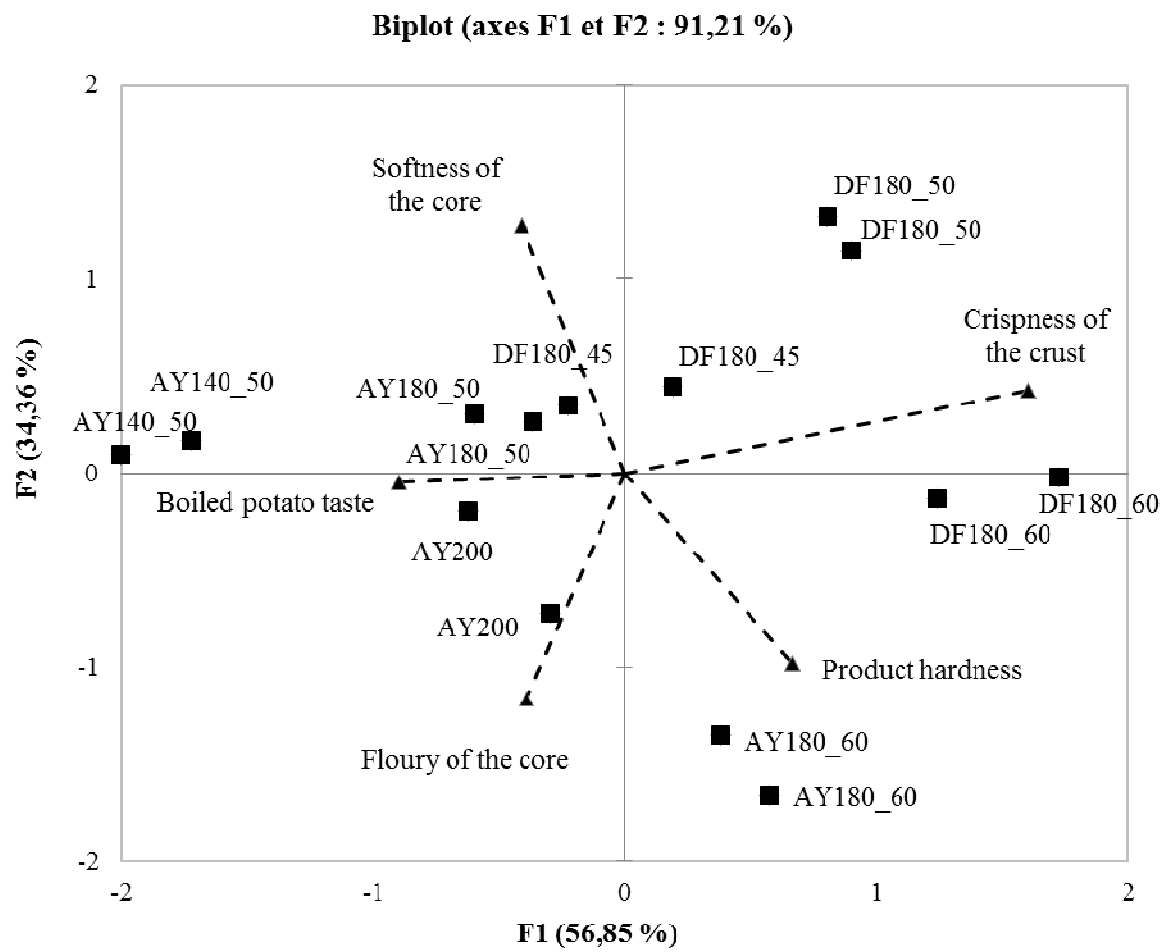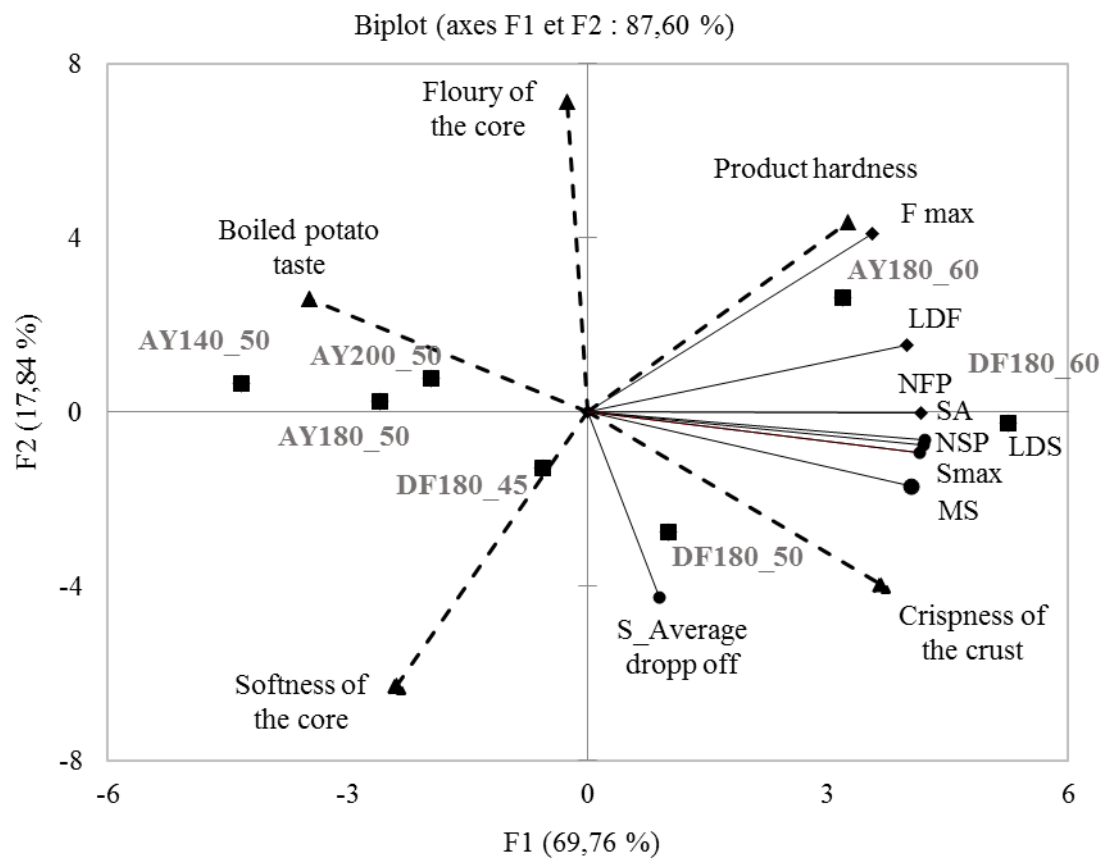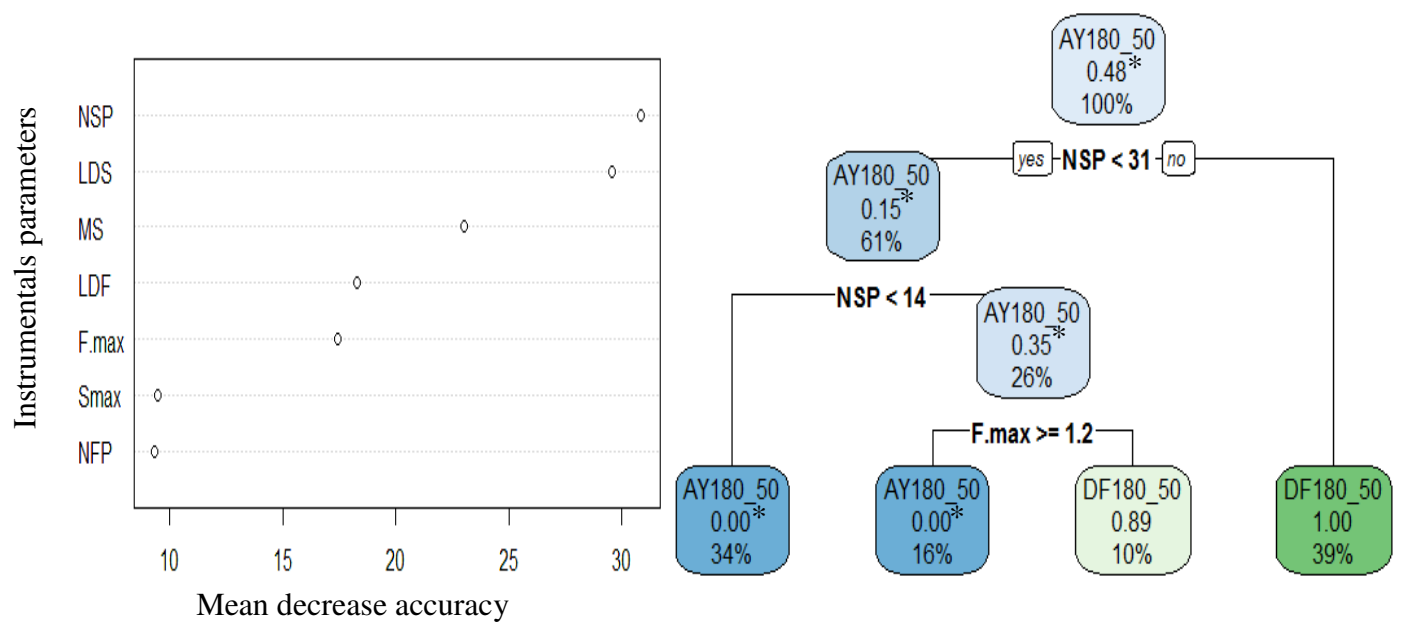
Figure 1.

Biplot (axes F1 et F2 : 91,21 %)

Figure 2.

Biplot (axes F1 et F2 : 87,60 %)
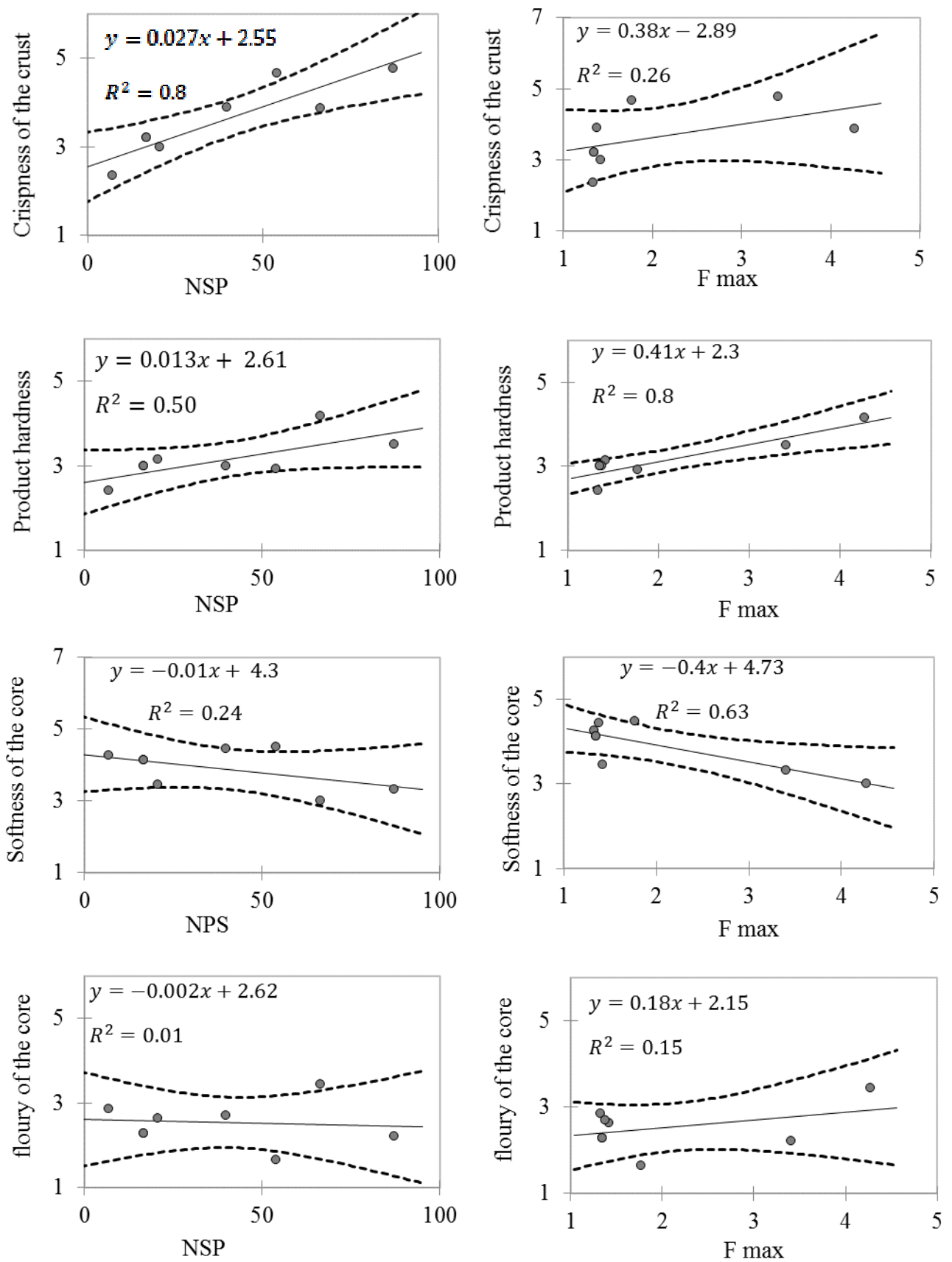
Figure 3.

Figure 4:

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
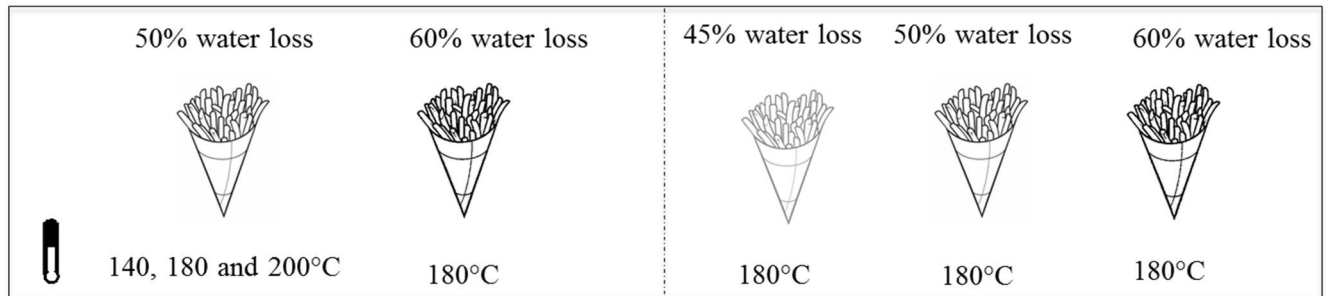
Instrumental texture analysis

- 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)