

A comparative study of the characteristics of French Fries produced by deep fat frying and air frying

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1 **Full Title**

2 A comparative study of the characteristics of French Fries produced by deep fat frying and air
3 frying.

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28 **ABSTRACT:** Air frying is being projected as an alternative to deep fat frying for producing
29 snacks such as French Fries. In air frying, the raw potato sections are essentially heated in hot
30 air containing fine oil droplets, which dehydrates the potato and attempts to impart the
31 characteristics of traditionally produced French fries, but with a substantially lower level of fat
32 absorbed in the product. The aim of this research is to compare: 1) the process dynamics of air
33 frying with conventional deep fat frying under otherwise similar operating conditions, and 2)
34 the products formed by the two processes in terms of color, texture, microstructure,
35 calorimetric properties and sensory characteristics. Although, air frying produced products with
36 a substantially lower fat content but with similar moisture contents and color characteristics, it
37 required much longer processing times, typically 21 minutes in relation to 9 minutes in the case
38 of deep fat frying. The slower evolution of temperature also resulted in lower rates of moisture
39 loss and color development reactions. DSC studies revealed that the extent of starch
40 gelatinization was also lower in the case of air fried product. In addition, the two types of frying
41 also resulted in products having significantly different texture and sensory characteristics.

42 **Keywords:** Air frying, deep fat frying, French fries, oil uptake, sensory evaluation;

43 **Practical Application:** Despite air fryers being available in our markets, systematic comparisons
44 of the quality and sensory characteristics of products such as French fries produced by air
45 frying and deep fat frying are not available. This study shows that the colour of air fried
46 products can be similar to deep fat fried product, but the texture is harder, and mouth feel and
47 appearance are dryer - more akin to puffed/baked products. This study will advance our quest
48 to develop truly competing alternatives to deep fat frying which yield products having the
49 same mouth-feel and eating experience.

50 **Introduction**

51 Frying is essentially a dehydration process involving rapid heat and mass transfer in food
52 immersed in hot oil, which leads to a succession of physical and chemical changes in the
53 product (Tarmizi and Ismail 2008; Andrés-Bello and others 2011; Dueik and Bouchon 2011).

54 Frying is extensively employed in domestic as well as industrial practice, due to its ability to
55 create unique sensory properties, including texture, flavour and appearance, which make the
56 food more palatable and desirable (Dana and Saguy 2006). Furthermore, its operational
57 simplicity in the context of commercial practice, convenience, and economic viability, has
58 resulted in extensive sales of a large variety of fried products (Mehta and Swinburn 2001).

59 Despite, the many studies correlating fried product consumption with increased health risks
60 (Krokida and others 2001; Mariscal and Bouchon 2008), and increasing consumer awareness of
61 this relationship (Mariscal and Bouchon 2008), there is no sign to suggest that we will give up
62 eating fried products (Dana and Saguy 2006; Tarmizi and Ismail 2008; Sayon-Orea and other
63 2013). These issues have prompted the fried product industry to search for ways and means to
64 produce healthier products without compromising on the desirable appearance, texture,
65 flavour and taste attributes (Garayo and Moreira 2002; Fan and others 2005; Da Silva and
66 Moreira 2008; Mariscal and Bouchon 2008; Andrés-Bello and others 2011; Andrés and others
67 2013).

68 One such process is hot air frying, which aims to produce a “fried product” by sparging,
69 essentially, hot air around the material instead of immersing it in hot oil. A variety of
70 proprietary air fryer designs are currently available in the market, which create the frying effect
71 by bringing direct contact between a fine mist of oil droplets in hot air and the product, inside

72 a chamber. Most designs provide for extremely high heat transfer rates uniformly between air
73 and the product being fried. Some achieve this simply with a built-in air blower, while others
74 also couple high convective rates with radiative heat transfer. A number of manufacturers also
75 claim that the shape of the chamber in which air and product are being contacted is profiled in
76 such a way that air velocities are significantly higher than in typical ovens (Erickson 1989).
77 Moreover, the air is also distributed more uniformly through the product, which minimizes
78 variations in product quality. A schematic of a typical air fryer is shown in Fig. 1. The product
79 gets dehydrated in the process and a crust, typically associated with frying, gradually appears
80 on the product. Oil application could be done before or during the process to lightly coat the
81 food product, in order to provide the taste, texture and appearance typical of fried products.
82 The amount of oil used is significantly lower than in deep oil frying giving, as a result, very low
83 fat products (Andrés and others 2013). To date, there is only a scientific publication about hot
84 air frying. Andrés and others (2013) analyzed the kinetics of mass transfer and volume changes
85 in hot air frying and deep-oil frying at the same temperature (180°C) and concluded that both
86 are affected by medium type. Heat transfer was slower when the fluid phase is air than when it
87 is oil, due to lower heat transfer coefficient of air. Moreover, they also observed that product
88 mass losses in air frying were higher than in deep frying, because the water lost during air
89 frying was not offset by any significant oil uptake. Unfortunately, this paper makes little or no
90 reference to the quality and sensory parameters of the product, and this is a major knowledge
91 gap. In the present work, we have aimed to draw a comparison between: 1) process
92 parameters of air frying and hot air frying - such as moisture content time profile, product
93 temperature versus time profile and product oil content versus time profile, and 2) product

94 characteristics yielded by the two frying methods, which include starch gelatinization profile,
95 microstructure using SEM as well as sensory characteristics. This detailed comparison has been
96 drawn by holding the same frying medium temperature in both cases, i.e. 180 °C. Further, the
97 product characteristics mentioned above, including sensory analysis, have been compared
98 after fixing the final product moisture content at a value that consumers normally consume
99 (91.7 ± 6.03 g water/ 100g defatted dry matter), which also helps us to evaluate whether air
100 frying can produce a true alternative to traditional frying.

101

102 **Materials and Methods**

103 ***Raw materials***

104 Maris Piper potatoes packaged in polyethylene bags and sunflower oil were purchased from a
105 local supermarket (Morrisons, Reading, UK), and stored in a refrigerator at 4 °C.

106 ***Frying equipment used***

107 Commercial deep oil frying (model: 45470, Morphyrichards) with a nominal power: 2,000 W)
108 and hot air frying equipment (model: AH-9000 Viva Collection Airfryer HD9220/40, Philips) with
109 a nominal power: 1,300 W.

110 ***Sample preparation***

111 The samples were prepared following the methodology described by Tarmizi and Niranjana
112 (2010). Potatoes ranging in moisture content between 445.37 ± 107.77 g water/100 g dry
113 matter were selected for this study. The potatoes were taken out from the fridge in which they
114 were stored at least 12 h before being used in experiments, then washed, peeled and manually

115 cut into strips (9 x 9 x 30 mm). The strips were soaked in running water for 1 min to eliminate
116 occluded starch and blotted using tissue paper.

117 ***Frying protocol***

118 The frying methodology, described by Andrés and others (2013), was used in this study. In the
119 case of deep fat frying, about 100 g of potato strips were immersed in 2 L of oil to give a
120 product to oil ratio of 1:20 (w/v) which was deemed by Andrés and others (2013) to be
121 sufficient to avoid major changes occurring in terms of product-to-oil ratio, oil composition and
122 temperature. In the case of hot air frying experiments, 0.45 g of oil per 100 g of potatoes strips,
123 was added into the air chamber.

124 The potato strips were only introduced into the oil in the case of deep fat frying or into the hot
125 air frying chamber in the case of air frying, after an operating temperature of 180°C was
126 reached, the temperature being confirmed by thermocouples located at the bottom of both
127 frying equipment. Samples were removed from the frying equipment at 3 min intervals, for up
128 to a maximum of 30 mins, and subjected to physico-chemical analysis.

129 ***Transient analyses of French fries***

130 *Proximate composition*

131 Samples were analysed according to American Oil Chemists' Society official methods, also
132 described by Tarmizi and Niranjana (2010).

133 *Moisture content:* The moisture content was determined by taking three homogenized samples
134 of 10 g collected at each processing time, and drying these for 48 hours at 105 °C in the
135 convection oven (Weiss-Gallenkamp, Loughborough, U.K.) to obtain a constant weight.

136 *Oil content determination:* The total fat content of three dried samples (5 g) collected at a given
137 processing time was measured. The dried samples were ground using a mortar and transferred
138 to a single-thickness cellulose extraction thimble (Fisher Scientific UK Ltd, Loughboroug, UK). A
139 dried and weighed 250-mL round-bottom flask (Quickfit-BDH, Poole, U.K.) was filled with 150
140 mL of petroleum ether (Fisher Scientific UK Ltd, Loughboroug, UK), and oil was extracted
141 gravimetrically using a Soxhlet extraction system (Quickfit-BDH) for 4 h. The solvent was then
142 removed by rotary evaporation (Rotavapor RE 111, Büchi Labortechnik AG, Flawil, Switzerland)
143 under vacuum of 380 to 510 mmHg at 50°C. The flask containing oil was dried to constant
144 weight at 105°C using the same convection oven described above (Weiss-Gallenkamp,
145 Loughborough, U.K.). The oil content was expressed as g oil/100 g defatted dry matter.

146 *Color*

147 The color of the potato French fries was measured using a reflectance colorimeter (HunterLab
148 CT-1100 ColorQUEST, Reston, VA). According to the CIE LAB system, Lightness (L^*), green-red
149 chromacity (a^*), and blue-yellow chromacity (b^*) were measured. The illuminant used was D
150 65 and the colorimeter was standardized using a cylindrical light trap (black), followed by
151 standard white and grey calibration plates. All measurements were undertaken in triplicate.

152 *Texture*

153 Texture measurements were made with Brookfield CT3 Texture fitted with 25kg load cell. Data
154 collection and analysis was accomplished by using electronic Texture Pro CT software. A single
155 cycle puncture test was performed using a cylindrical flat-end punch (2mm diameter probe) by
156 fixing the test speed at 4.6 mm/s; the punch was allowed to travel into the samples for: 2mm

157 (covering the crust region) and 6mm (which covered the core). Six samples were measured and
158 punctured at 2 random positions for each processing time.

159 ***Analyses of the final product (i.e. ready to consume)***

160 Although the above analyses were carried out over an extended time scale, which was much
161 longer than what will be used in practice, the final product was defined in accordance with the
162 quality control criteria set by frying industry, which stipulates that the moisture content of the
163 ideal product must be in the range between 38% and 45% on a wet weight basis (Matthäus and
164 others 2004). The moisture and oil contents, color and texture of the final product were
165 determined as above. In addition, SEM, DSC and sensory analyses were also carried out on the
166 final product.

167 *Scanning electron microscopy (SEM)*

168 Sections taken from the core and crust regions of the product were freeze-dried and their
169 fractured surface was examined and photographed using a scanning electron microscope (FEI
170 Quanta FEG 600 with a Quorum PP2000T Cryo Stage, Eindhoven, Netherlands) at different
171 magnifications, and representative images were chosen.

172 *Differential scanning calorimetry (DSC)*

173 The method of Steeneken and Woortman (2009) was used. Heating scans were performed on
174 core samples of French fries by employing a Perkin Elmer DSC 200, by heating from 20 to 210°C
175 at 10°C/min followed by cooling to 20°C at 200°C/min.

176 *Sensory analysis*

177 For the sensory analysis, all evaluations were conducted in individual booths which contained
178 the instructions for the evaluation procedure. The tasting room for sensory evaluation was air-

179 conditioned and free of disturbing factors. Samples were fried in a commercial deep fat fryer
180 (model: 45470, Morphyrichards) at 180°C for 9 minutes and in a commercial air fryer (AH-9000
181 Viva Collection Airfryer HD9220/40, Philips) at 180°C for 21 minutes. Samples were obtained,
182 and immediately after, were presented to the panelists.

183 The panelists were trained according to ISO 8586 (2012). The training program consisted of
184 three sessions aiming to develop sensory descriptors and ensure competent usage of these by
185 the panel. For each sample the panelists registered the perceived intensities of each of the
186 attributes. These attributes were individually recorded using an unstructured scale of 100 mm,
187 and the data sets checked by ANOVA. Mineral water and bread were provided for mouth
188 rinsing between samples.

189 ***Statistical analysis***

190 The statistical analysis of the data was conducted using statistical package SPSS 15.0 (Statistical
191 Package for the Social Science for Windows). Statistical significance was expressed at $p < 0.05$
192 level.

193 **Results and Discussion**

194 ***Analyses of French fries during the Frying Processes***

195 *Temperature profile*

196 The temperature of French fries, measured at a point, more or less, near the centre, under
197 different frying conditions (deep-fat frying and air frying) is presented in Figure 2. The deep-fat
198 fried samples behaved in a manner similar to the one described in earlier work (Budžaki and
199 Seruga 2005; Farinu and Baik 2008; Mir-Bel and others 2012). The initial temperature
200 increased, almost linearly with time, until it reached the boiling point of water (~100°C). The

201 temperature then increased gradually for a period of time, before increasing more sharply. The
202 air fried samples also showed the same initial trend, i.e. temperature increasing linearly up to
203 the boiling point of water, but at a significantly slower rate than deep-fat frying. The oil fried
204 sample took 1.5 minutes to reach the boiling point of water, whereas the air fried sample took
205 nearly 5.5 minutes. A second difference between oil frying and air frying is that the
206 temperature, in the case of the latter process, remains, more or less, constant at the boiling
207 point of water till the end of the process, and the gradual, but significant, increase in
208 temperature above 100°C observed in the case of deep oil frying is not evident. Based on the
209 times taken for the product centre to reach the boiling point of water, it can be estimated that
210 the heat flux in the case of oil frying is 3.7 times greater than in the case of air frying, which
211 seems to provide enough energy in the form of latent heat as well as sensible heat. The post
212 boiling heat transfer is accompanied by physicochemical changes occurring such as: gelation of
213 starches, increase in the thickness of superficial crust and reduction in the rate of steam
214 release from the product (Mir-Bel and others 2012).

215 *Moisture and oil content*

216 Frying process normally implies a series of complex mass transfer processes between the food
217 and fluid phase giving, as a result, two counter current-fluxes: a water/steam flow from the
218 food to the hot oil and an oil inlet into the food (Ziaifar and other 2008; Krotida and others
219 2000; Andrés 2013; Kalogianni and Popastergiadis 2014), although such simplistic explanations
220 have been questioned (Bouchon and Pyle 2005).

221 The variation of moisture content (expressed as g/100g defatted dry matter) with time for
222 different frying conditions is shown in Figure 3. As expected, the moisture decreases with

223 frying time ($P < 0.05$) for both deep-fat as well as air frying. The mechanism of water loss
224 during frying has been interpreted previously as a dehydration process (Mir-Bel and others
225 2012; Bingol and others 2014). It is clear from Figure 3 that the moisture content decreases
226 more rapidly in deep-fat frying than air frying ($P < 0.05$). These results are consistent with
227 higher heat flux observed in the case of deep-fat frying and are also in agreement with Andrés
228 and others (2013) who compared moisture loss kinetics between the two frying methods.
229 Figure 4 shows fat content variation with time in of the two frying process. The values varied
230 between 0.37-1.12 g/100g defatted dry matter for samples processed by air frying, and
231 between 5.63-13.77 g/100g defatted dry matter for deep fat fried samples. The differences
232 between the oil contents may be attributed to the "frying medium" surrounding the products:
233 hot oil in the case of deep fat frying, and a mist of oil droplet in air in the case of deep fat
234 frying. This observation is also in agreement with the findings of Andrés and others (2013) who
235 showed that the main difference between the two types of frying is the final fat content and
236 these differences are due to the type of frying medium employed. In the case of deep fat
237 frying, it is known that the oil absorption (64-90% of the total oil absorbed) predominantly
238 occurs at the end of frying, due to the condensation of water vapor inside product caused by
239 the fall in temperature below the boiling point of water, which creates a suction pressure
240 gradient between the surface and the inner structure of the product (Mellema 2003; Saguy and
241 Dana 2003; Dana and Saguy 2006; Ziaifar and others 2008; Mir-Bel and others 2009; Tarmizi
242 and Niranjani 2010). Deep-fat frying is undertaken in oil (20 g of oil per gram of potatoes),
243 whereas air-frying samples are mixed with a small oil amount before "frying" (0.003 g of oil by

244 gram of potatoes). This implies that, in the case of the latter process, a limited amount of oil is
245 in contact with the sample surface and therefore oil absorption is limited.

246 *Color*

247 The color of the fried potatoes is one of the most significant quality factors determining
248 acceptance (Korkida and others 2001). Instrumental color coordinates (CIELab) for both types
249 of French fries are shown in Figure 5.

250 As expected, L* decreased with frying time in the two processes whereas a* and b* increased
251 ($P < 0.05$). This is consistent with the potatoes turning darker and more red-yellow as described
252 by Nourian and Ramaswamy (2003) and Romani and others (2009a, b). The characteristic color
253 of French fried potatoes essentially result from the Maillard reaction (non-enzymatic browning)
254 involving reducing sugars and amino acids (Nouiuian and Ramaswamy 2003; Pathare and others
255 2013).

256 It is also clear from Figures 5 that a* and b* drop initially, attain a minimum value,-and then
257 increase progressively before leveling off around the same values for both types of products. A
258 closer analysis of the figures also shows that the minimum values of a* and b* are attained
259 much more rapidly in the case of deep fat frying ($P < 0.05$) The rapid evolution of colour is
260 consistent with the higher rates of temperature rise observed in the case of deep fat frying
261 (Figure 2). Baik and Mittal (2003), Pedreschi and others (2005) and Ngadi and others (2007)
262 and Pathare and others (2013) reported that the non-enzymatic browning reactions are highly
263 temperature dependant. Thus, air frying process can potentially achieve the characteristic
264 color of deep fat fried French fries but requires significantly longer processing time.

265 *Texture*

266 The kinetics of textural changes occurring in the two types of products was studied using a
267 compression test. Table 1 shows hardness work (mJ) for the probe to penetrate the surface (2
268 mm) and core (6mm) of samples.

269 Moyano and others (2007) and Pedreschi and Moyano (2005) observed that heating of potato
270 tissue causes drastic physical, chemical, and structural changes, which could be divided into
271 two stages: the tissue softening during the first few minutes of frying followed by crust
272 formation and subsequent hardening. The same trend was observed in the present study for
273 deep fat, as well as, air fried products. Table 1 shows the hardness work to decrease initially.

274 The evaluation of texture parameter (hardness work) at 2 mm and 6 mm allowed studying the
275 crust development and the modifications in product core, respectively. The initial stage of
276 frying resembles a cooking process when a part of the starch gelatinizes and the lamellar media
277 solubilizes at temperatures of around 60 to 70°C (Moyano and others 2007). The softening
278 phase of the tissue, at the surface as well as core, was much faster in deep fat frying ($p < 0.05$)
279 which required only 3 minutes (105°C) to be completely softened, compared to 6 minutes
280 (100°C) required for air fried samples.

281 The second stage is characterized by the development of a porous dried region and an
282 overheated region which is generically called "crust". This region is result of a vaporization
283 front located close to the heat exchange surface which progressively moves towards the
284 product center with the frying time. Miranda and Aguilera (2006) showed that the exposure of
285 potato products to temperatures above 100°C, such as the temperatures encountered during
286 frying, causes starch granules and cells located on the surface to become dehydrated and form

287 an external crust, which makes the product crispy. Both processes showed increase in hardness
288 work values for the crust and core regions with time ($P > 0.05$).

289 With regard to the effect of frying methods, in general no differences were observed between
290 the two frying methods for crust region at different frying times. However in the case of the
291 core region, the air fried samples showed higher hardness work values ($P < 0.05$) than the deep
292 fat fried samples. These differences in core texture may be due to a smaller degree of
293 gelatinization occurring in air fried samples, associated with the prevalence of lower
294 temperatures inside the product.

295 As evident in Table 1, with time, the evaporation continues until the products are completely
296 dry, in both processes, and the hardness work converge to more or less identical values at very
297 long process times. In practice, however, it is necessary to note that this final stage is never
298 reached since the products are removed much earlier at process end-points defined by
299 consumer acceptability of the product.

300 The quality parameters of the final product, withdrawn at this end point, i.e. the products
301 which are meant to be consumed, are discussed below. In terms of texture data shown in Table
302 1, it is clear that both products have different texture characteristics in both the regions: crust
303 and core. Air fried samples (21minutes) had hardness work values about 1.38 and 7.29 mJ for
304 crust and core respectively, while that deep fat fried samples (9 minutes) were about 4.23 and
305 11.49 mJ ($P < 0.05$; $P < 0.001$).

306 ***Analyses of the final product deemed to be fit for consumption***

307 Quality control criteria of frying industry stipulate that the moisture content of the final
308 product must be in the range between 38% and 45% on a wet weight basis (Gökmen and

309 others 2006; Romani and others 2008). To meet this criterion the samples used in this study
310 were processed for 9 minutes in the case of deep-fat frying and for 21 minutes in the case of
311 air frying, both at 180°C. SEM, DSC and sensory analyses were undertaken to compare the two
312 products.

313 *SEM and DSC analyses*

314 Figure 6 show the microstructure of the raw and fried potato chips. Figure 6 (a-b) shows the
315 cross section of raw potato chips. The core of the chips contain non-deformed flesh cells with
316 starch granules, while the outer surface reveals mechanical damage of cells caused by the
317 cutting process; these results are similar to the ones described by Lisińska and Golubowska
318 (2005).

319 When we compare the raw potato tissue consisting of cells appearing pentagonal/hexagonal in
320 shape (Figure 6 a-b) with the tissue resulting after “frying” (Figure 6 c-h), irreversible changes
321 can be seen and two particularly clear areas appear: crust and core. Aguilera and others (2001)
322 and Pedreschi and Aguilera (2002) postulated that cells in the crust of fried potato tended to
323 change their shape while shrinking, and their walls became wrinkled and convoluted around
324 dehydrated gelatinised starch; there was however, little or no rupture evident. The crust of air
325 fired samples (Figure 6 f and h) showed higher empty spaces and smaller cells than deep-fat
326 fried samples, because the temperatures and rates of water evaporation were different in the
327 two process; moreover, any empty spaces formed during deep fat frying would be filled with
328 oil. On the other hand, in both products, starch swelling mainly occurred in the core region,
329 which is a result of grain hydration and gelatinisation to form an amylose and amilopectin
330 reticulum which completely fills the cellular lumen (García-Segovia and others 2008), although

331 this process occurred to a greater degree in deep fat fried samples (Figure 6 d) than air fried
332 sample (Figure 6 g). Similar results were noted for the DSC analyses given in Figure 7. Both
333 process showed higher gelatinization temperature and weaker endotherms than raw samples,
334 which indicates the modification of starch structure due to gelatinization process (Garzón
335 2006; Liu and others 2009). Furthermore, deep-fat fried samples have a lower value of the
336 enthalpy of gelatinization (ΔH) than air fried samples. According to Bello (2009) lower values of
337 enthalpy indicates a higher proportion of gelatinized starch. Thus, a key difference between air
338 fired and deep fat fried products is the higher extent of gelatinization occurring in the latter.

339 *Sensory analyses*

340 A panel evaluated appearance, odor, mouthfeel, taste, flavor and after effects of products
341 obtained by both types processes, based on 31 descriptors (Table 2). There were statistically
342 significant differences found for 22 of the 31 attributes ($P < 0.05$) used, which indicates major
343 difference in the perceived product characteristics. It may be noted that the air fired product
344 was processed for 21 minutes, whereas the deep fat fried product was processed for 9
345 minutes. Under these conditions, both products had average moisture content about 45%.
346 In terms of appearance, the extent of brownness and evenness of cooking were not
347 significantly different between air fried and deep fat fried samples, which is also in agreement
348 with instrumental color measurement. However, air fried samples stood out in terms of
349 appearing puffed and dry, when compared with deep-fat fried samples which also highlighted
350 oiliness attributes ($P < 0.05$); the SEM images shown in Figure 6 are consistent with these
351 sensory observations. With regard to odor, the deep-fat fried product gave a fried smell and
352 flavor, while the air fried samples give what was described as “jacket potato smell” ($P < 0.05$).

353 In the same way, the after effects attributes only show differences in terms of the deep fat
354 fried product giving a oily mouth coating and greasy fingers. The skin mouth feel was smoother
355 and it felt tough in the case of air fried samples ($P < 0.05$) which is also consistent with the
356 texture test that showed higher values of hardness work for air fried samples than deep-fat
357 fried samples . However, the crispness was similar ($P > 0.05$). In traditional deep-fat frying, oil
358 migrates to intracellular spaces formed by cell wall shrinkage and water evaporation (Costa Rui
359 and others 2001), resulting in a more oily mouth feel ($P < 0.001$). On the other hand, in air fried
360 samples, these spaces remain void and gave a desiccated mouth feel. The floury mouthfeel and
361 earthy flavor were significantly higher in deep-fat fried samples. The mealiness sensation in
362 potatoes is associated with a greater volume of the gelatinized starch filled up in their cells
363 (Bordoloi and others 2012). These observations are also supported by DSC and SEM
364 measurement (Figure 6 and 7).

365 In general, the QDA results indicate that sensory characteristics of the products obtained from
366 the two processes are significantly different, and the key differences will be summarized
367 below.

368 ***Key appearance differences between air fried and deep fat fried products***

369 The external appearance of the samples is shown in Figure 8. The color of air fried and deep fat
370 fried products may not be significantly different, however, the visual presence of fat in deep-
371 fat fried product is amply evident. Another major difference between samples fried in air and
372 oil is the structure of the products formed. Visual observations indicate that deep-fat fried
373 samples have a surface crust structure which is dry, crisp and thick. This is the result of the high
374 temperatures being reached rapidly at the product surface which causes intense local water

375 evaporation that impedes gelatinization of the starch in the region. In the case of air fried
376 product, the water evaporates much more slowly causing the surface crust to be thinner,
377 homogeneous and without irregularities, which gives a perceptible difference in mouth feel.
378 The visual observations of the crust also showed that air-fried samples expanded to a greater
379 extent and contained regular pore distribution in core region in contrast to deep fat fried
380 samples. During cooling too, the air-fried samples showed crust shrinkage, which was not
381 observed in the deep fat fried product. Higher crust shrinkage during cooling is indeed a
382 feature of air fried product, which does not seem to happen to the same extent in the case of
383 deep fat fried product. This is most probably because crust cooling of air fried product occurs
384 with concomitant steam condensation that leaves voids in the crust causing it to collapse. In
385 contrast, the presence of oil in the crust of deep fried products minimizes crust collapse. As far
386 as the core is concerned, both products showed gelatinized appearance, although the extent of
387 gelatinization was higher in the deep fat fried product.

388 **Conclusion**

389 The present study shows that the oil content of French fries having similar moisture content
390 and color was significantly lower when the product is air fried: the values were 5.63 g oil/100 g
391 defatted dry matter for deep-oil frying and 1.12 g oil/100 g defatted dry matter for air frying.
392 On the other hand, the evolution of temperature, moisture content, and color were
393 significantly slower in the case of air frying than deep-fat frying. As a consequence, longer
394 cooking times are required in the case of air frying.

395 The final product evaluation by SEM and DSC analyses showed that air fried samples had a
396 lower degree of gelatinization than deep-fat fried samples, which may explain the differences
397 found between texture and sensorial characteristics of the two products.
398 Overall, air frying process permits the manufacture of lower fat content products, though these
399 products have different sensory characteristics.

400 **Author Contributions**

401 MR. Teruel undertook most of the experimental work presented in this paper, compiled the
402 data and did the statistical analysis. Initial problem identification and some of the experimental
403 procedures were set up by Araya Ahromrit. K. Niranjana, M. Gordon, MB. Linares, MD. Garrido
404 supervised and organized the study.

405 K. Niranjana and MR. Teruel predominantly interpreted the results and drafted the manuscript
406 with help from other authors.

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510 conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying
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516 **Table 1- Compression test results (Hardness Work, mJ) of products air fried and deep fat fried at 180°C, as a function of**
 517 **processing time.**

	Time (minutes)										
	0	3	6	9	12	15	18	21	24	27	30
	2mm										
Deep-fat	16,84±0,55 ^c	1,26±0,52 ^{a,y}	1,28±0,92 ^a	1,38±1,26 ^a	2,26±1,41 ^a	2,49±1,19 ^a	1,84±1,77 ^a	5,41±3,56 ^a	3,10±2,53 ^a	10,32±6,95 ^b	14,93±6,11 ^{b,c,z}
Air	16,84±0,55 ^d	10,18±3,80 ^{b,c,z}	2,03±0,71 ^a	1,61±1,03 ^a	2,06±0,99 ^a	1,44±0,52 ^a	1,83±1,78 ^a	2,84±1,40 ^a	3,49±1,86 ^a	8,84±8,06 ^b	5,52±7,98 ^{c,y}
	6mm										
Deep-fat	75,74±8,23 ^d	4,51±2,32 ^{a,y}	4,44±1,95 ^{a,y}	4,23±1,32 ^{a,y}	3,84±2,30 ^{a,y}	4,76±1,77 ^{a,y}	7,48±3,93 ^a	5,51±3,61 ^{a,y}	5,71±2,05 ^a	30,92±22,56 ^b	50,83±26,76 ^c
Air	75,74±8,23 ^c	29,24±11,95 ^{b,z}	7,46±1,70 ^{a,z}	7,29±3,20 ^{a,z}	8,27±3,67 ^{a,z}	8,95±3,47 ^{a,z}	8,07±4,09 ^a	11,49±3,04 ^{a,z}	10,59±5,85 ^a	27,73±16,19 ^b	29,72±16,46 ^b

518 Represent averages of three independent repeat ± standard deviations. a, b, c, d: indicate statistically significant differences (P <
 519 0.05) among frying time; x, y: indicate statistically significant differences (P < 0.05) among treatments.

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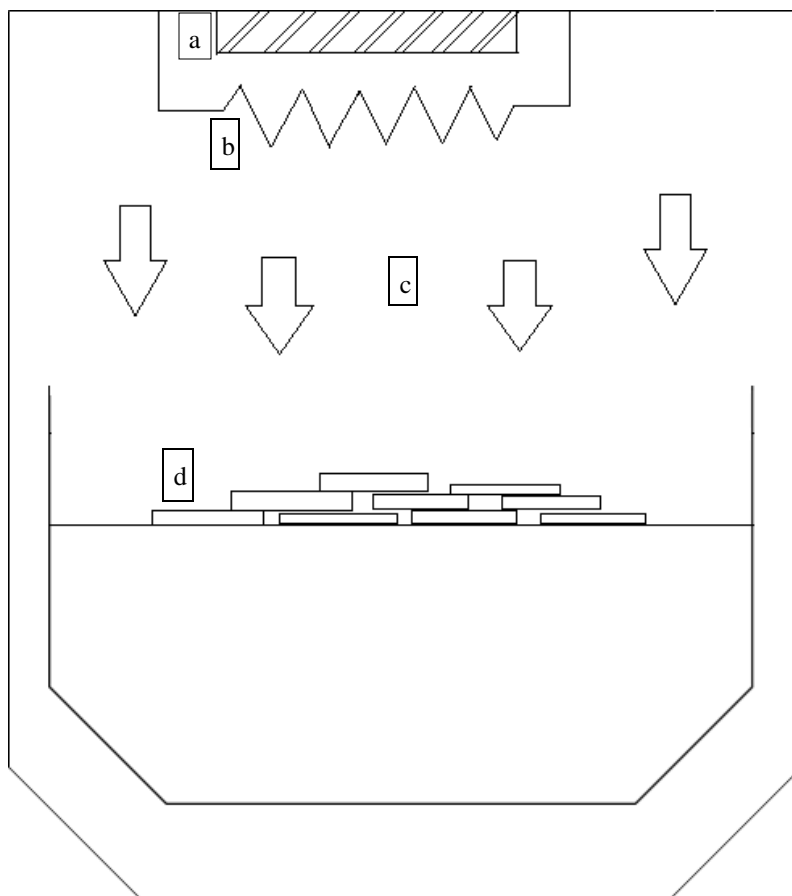
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525 **Table 2- Quantitative descriptive analysis of French fries in both types processes: Deep-fat (9**
 526 **minutes) and Air (21 minutes) frying.**

	Deep-fat frying	Air frying	
Appearance			
Brown	10,85±6,33 ^a	8,33±7,83 ^a	ns
Puffed	42,45±15,84 ^a	1,00±3,16 ^b	***
Dryness	62,95±15,21 ^a	29,08±17,74 ^b	***
Evenness of Cook	48,93±16,83 ^a	54,45±15,15 ^a	ns
Oil release to fingers	0,50±0,99 ^b	41,55±16,38 ^a	***
Odor			
Jacket Potato	43,10±12,66 ^a	1,08±3,40 ^b	***
Boiled Potato	5,33±7,70 ^b	18,83±5,72 ^a	**
Fried Odour	2,55±8,06 ^b	40,63±11,84 ^a	***
Old Fat	2,00±6,32 ^a	1,38±3,36 ^a	ns
Mouthfeel			
Smoothness of Outer Skin	55,73±18,40 ^a	31,80±18,39 ^b	**
Toughness of Outer Skin	48,40±16,70 ^a	22,73±11,00 ^b	***
Crispness of Outer Skin	39,58±23,68 ^a	36,55±14,11 ^a	ns
Dessicated	58,70±14,31 ^a	20,75±16,92 ^b	***
Oily mouthfeel	1,80±4,65 ^b	26,83±11,09 ^a	***
Hollow Gap 1/2	1,05±0,16 ^b	2,00±0,00 ^a	***
Moistness of Core Potato	15,93±8,53 ^b	28,88±11,65 ^a	*
Chewy	42,30±14,42 ^a	21,58±13,23 ^b	***
Dense	22,98±12,28 ^a	31,63±14,52 ^a	ns
Amount of potato inside	24,20±13,72 ^b	54,60±20,04 ^a	***
Floury	9,15±8,14 ^b	34,05±19,44 ^a	**
Taste			
Sweet	11,68±11,04 ^b	19,33±6,60 ^a	*
Acidic	4,60±7,04 ^a	3,75±5,58 ^a	ns
Flavour			
Oily Flavour	2,10±5,59 ^b	26,38±8,38 ^a	***
Jacket Potato Flavour	40,55±19,07 ^a	0,63±1,98 ^b	***
Boiled Potato	6,80±10,52 ^b	21,28±7,65 ^a	*
Earthy	7,35±8,69 ^a	0,60±1,90 ^b	*
After Effects			
Bitter	9,05±8,12 ^a	3,70±4,11 ^a	ns
Metallic	0,25±0,79 ^a	0,00±0,00 ^a	ns
Acidic	3,78±7,67 ^a	2,60±3,51 ^a	ns
Oily film coating mouth	1,20±3,71 ^b	17,73±7,17 ^a	***
Greasy Fingers	0,53±1,11 ^b	33,88±16,53 ^a	***

527 Represent averages of three independent repeat ± standard deviations. a, b: indicate
 528 statistically significant differences among treatments.

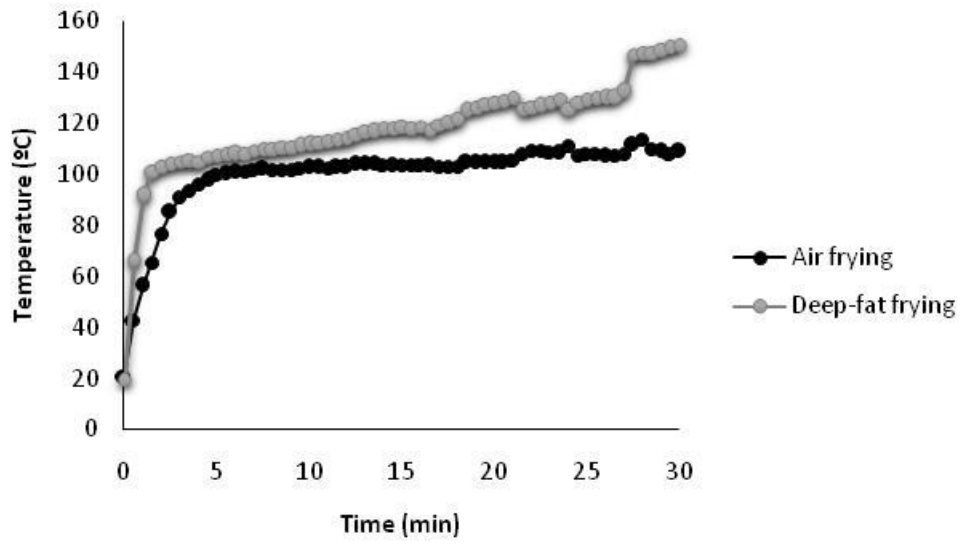
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532 **Figure 1- Schematic representation of air fryer: (a) fan, (b) electrical resistance heater, (c) hot**
533 **air and (d) samples. It may be noted that there are a variety of proprietary hardware designs**
534 **available each claiming heat and mass transport advantages as well as improved product**
535 **quality, for instance, see Erickson (1989).**

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551 **Figure 2- Evolution of Temperature inside French fries in both types processes at 180°C,**
552 **deep-fat and air frying. Both sets of experiments were performed in triplicate and the**
553 **temperatures shown are mean values.**

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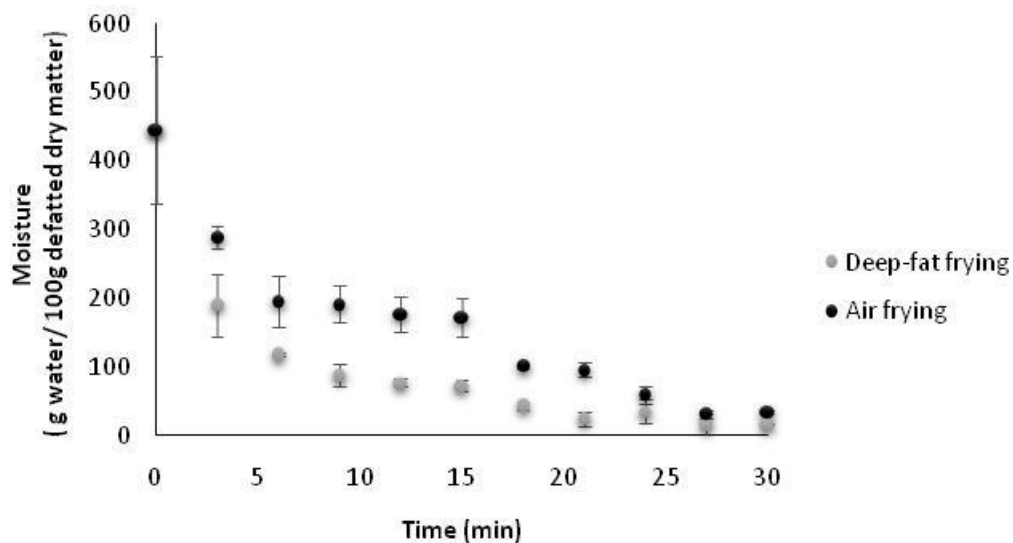
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569 **Figure 3- Evolution of moisture values of French fries in both types processes at 180°C, deep-**
570 **fat and air frying. Data shown in the figure are based on experiments performed in**
571 **triplicates.**

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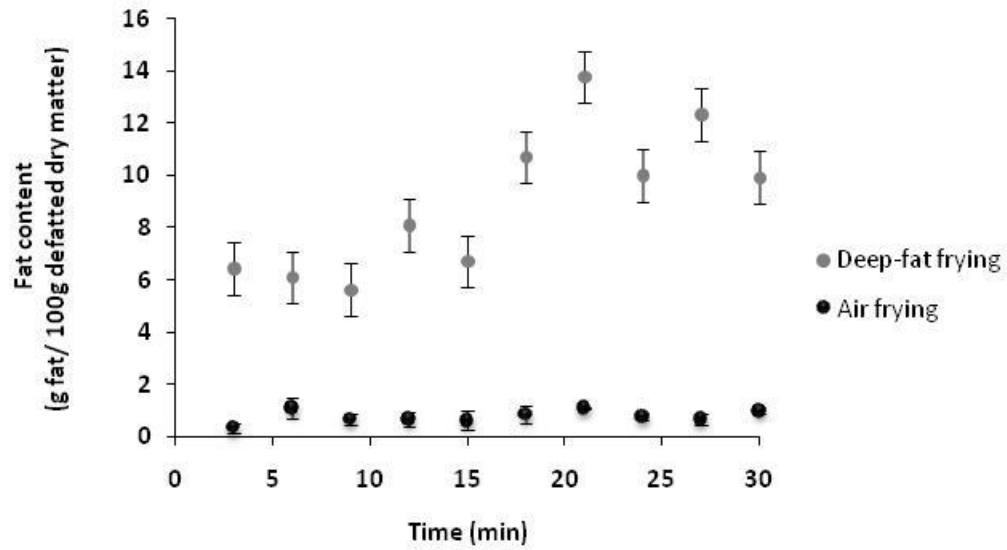
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582 **Figure 4- Evolution of fat values of French fries in both types processes at 180°C, deep-fat**
 583 **and air frying. Data shown in the figure are based on experiments performed in triplicates.**

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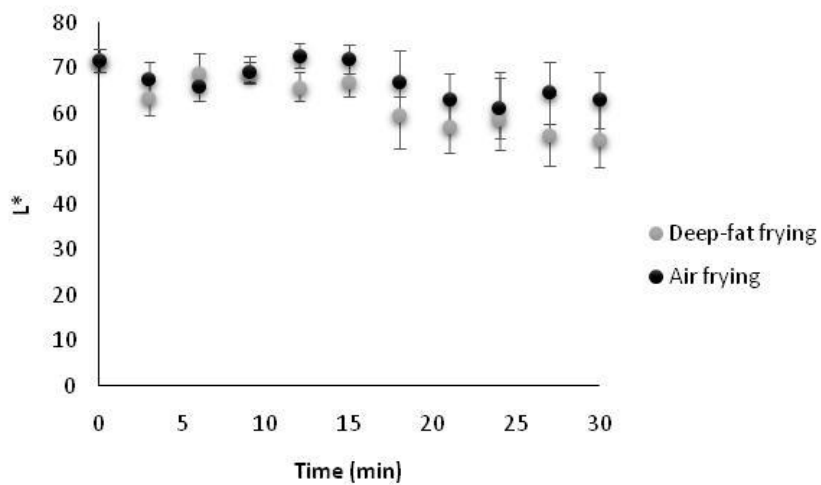
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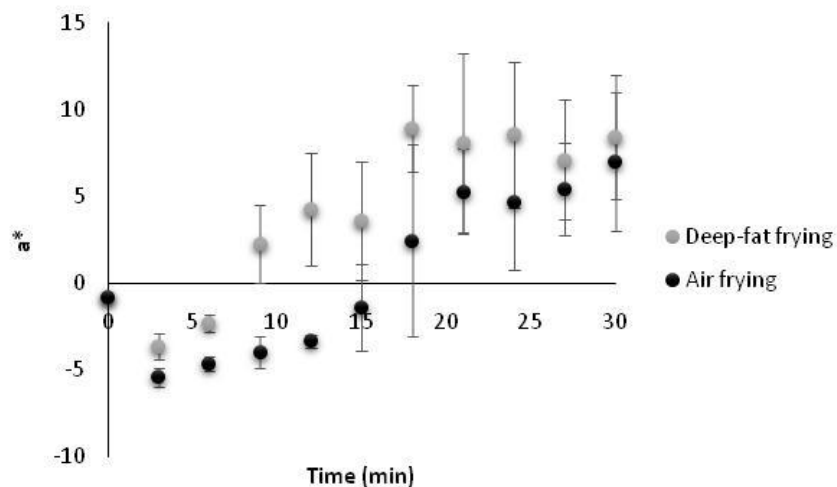
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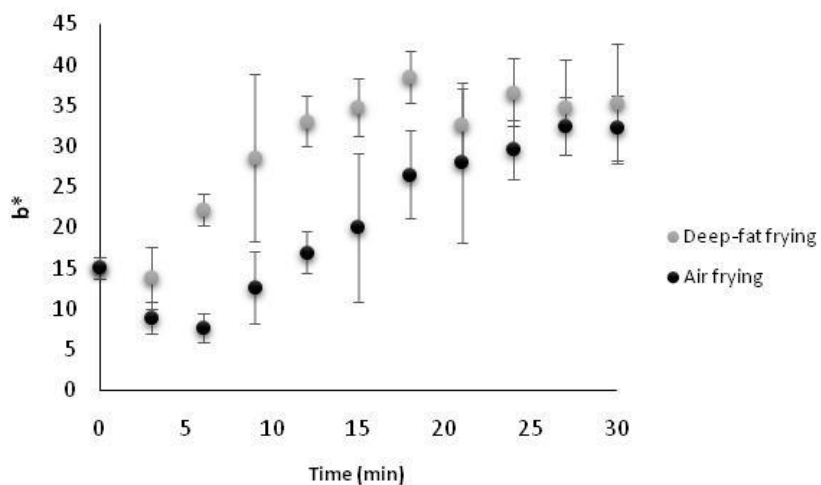
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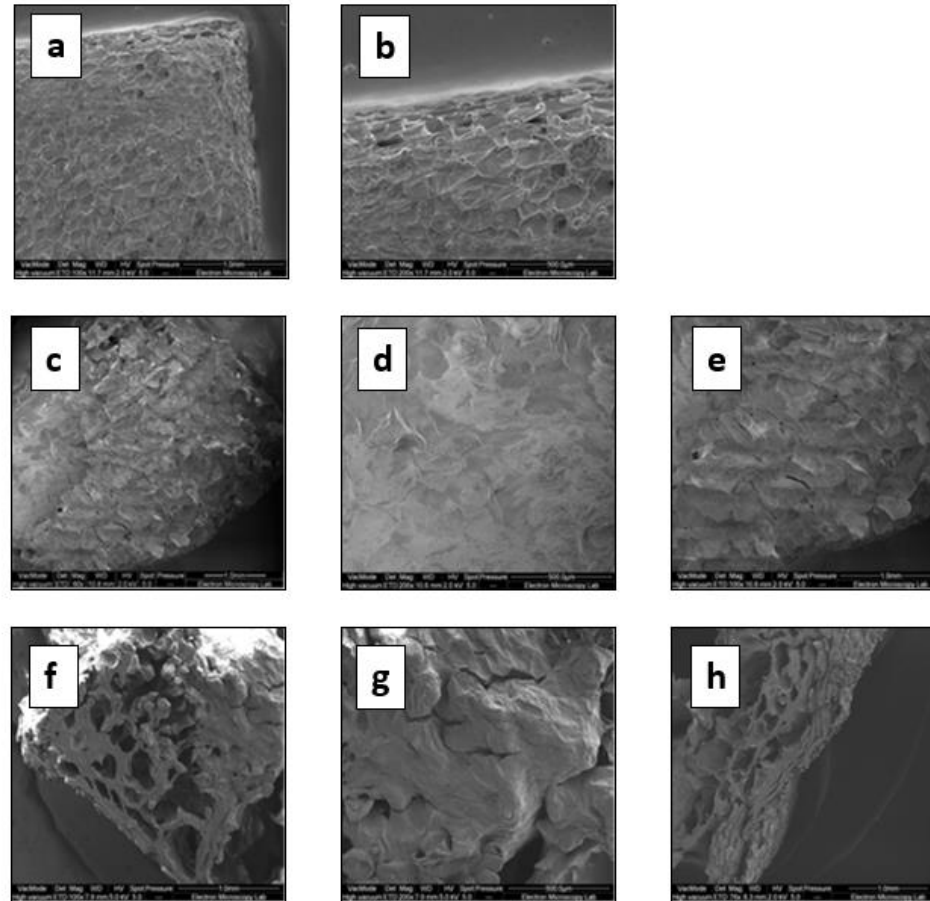


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Figure 5- Evolution of L*a*b* values of French fries in both types processes at 180°C, deep-fat and air frying: L* values, a* values, and b* values.



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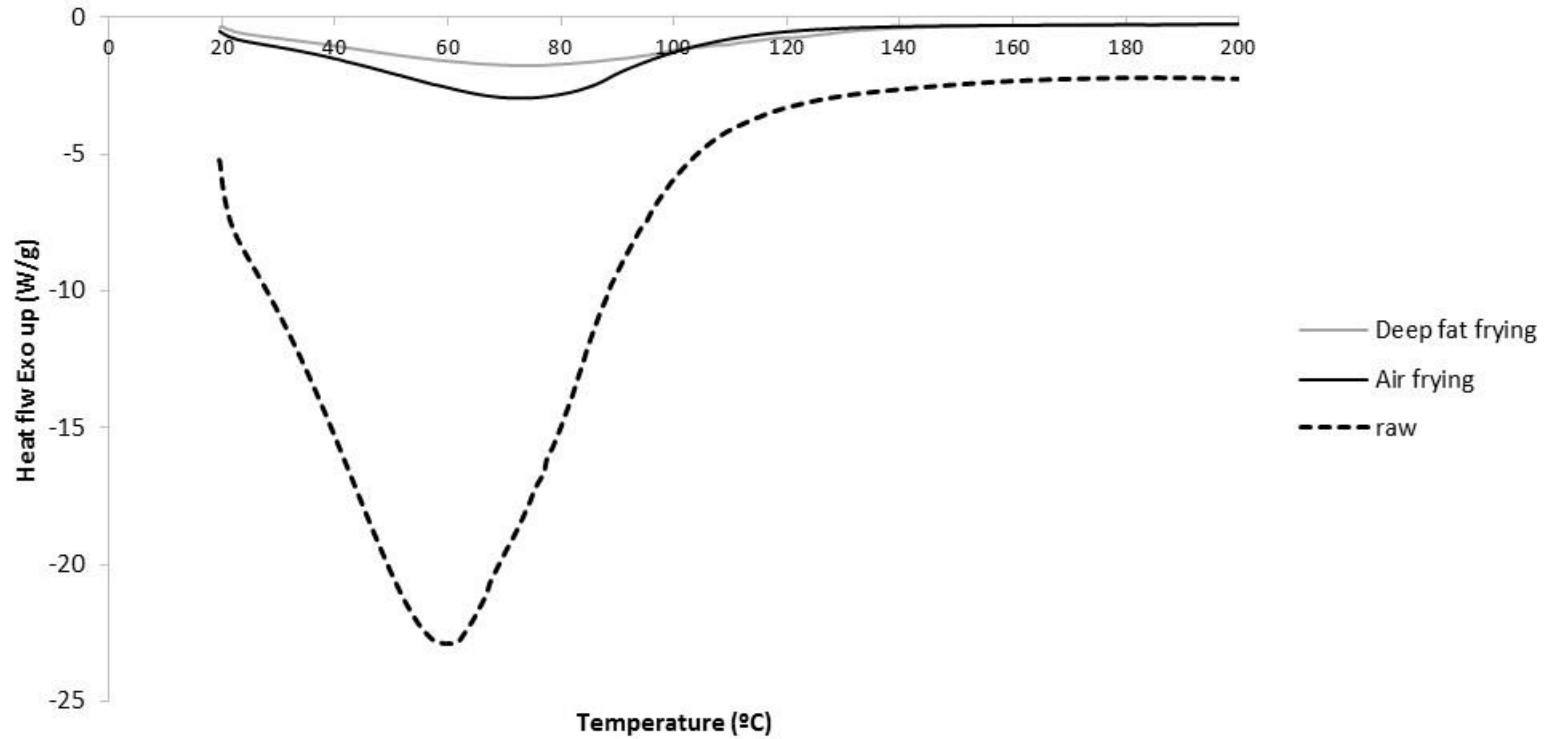
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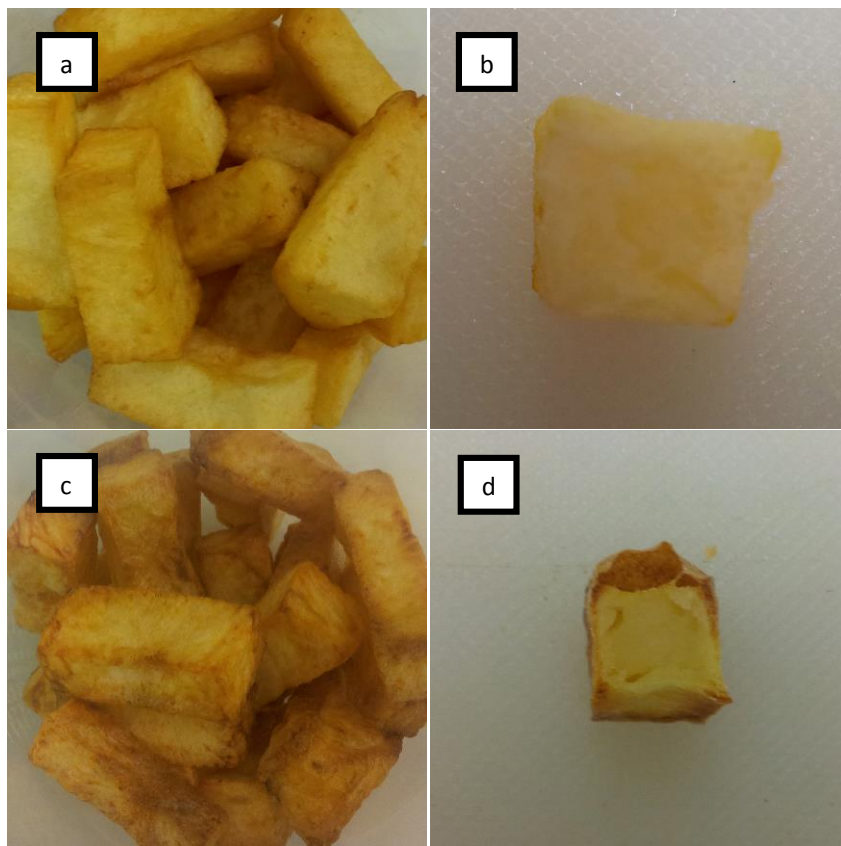
Figure 6- SEM of French fries raw, deep-fat fried (9 minutes) and air fried (21 minutes); moisture content of both samples 91.7 ± 6.03 g water/ 100g defatted dry matter: (a-b) raw, (c-d-e) deep-fat fried samples, and (f-g-h) air fried samples. Figures a-c-f: sample size = 1mm; Figures b-d-g: sample size 500 μ m; Figures e-h: sample size 1mm.



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 611 **Figure 7- Gelatinization endotherms of French fries: raw samples, deep-fat frying samples (9 minutes) and air frying samples (21**
 612 **minutes)); moisture content of both samples 91.7 ± 6.03 g water/ 100g defatted dry matter.**
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Figure 8- Pictures of French fries samples: deep-fat for 9 minutes (a-b) and air for 21 minutes (b-c)); moisture content of both samples 91.7 ± 6.03 g water/ 100g defatted dry matter.