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

Full Title

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

Name(s) of Author(s)

Maria del Rocio Teruel[a], Michael Gordon[b], Maria Belen Linares[a], Maria Dolores Garrido[a], Araya Ahromrit[c], Keshavan Niranjan[b]

Author Affiliation(s)

[a]Department of Food Technology, Nutrition and Bromatology, Veterinary Faculty, University of Murcia, Espinardo, 30071 Murcia, Spain

[b]Department of Food and Nutritional Sciences, University of Reading, Whiteknights P.O. Box 226, Reading Berkshire RG6 6AP, UK

[c] Department of Food Technology,Faculty of Technology, Khon Kaen University, Khon Kaen, 40002, Thailand

Contact information for Corresponding Author

Keshavan Niranjan, Department of Food and Nutritional Sciences, University of Reading, Whiteknights P.O. Box 226, Reading Berkshire RG6 6AP, UK. Tel.: +44 (0) 118 378 8388. E-mail address: afsniran@reading.ac.uk.

Word count of text 6171

Short version of title Air frying versus deep fat frying

Choice of journal/section Engineering and Physical Sciences

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

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

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

Introduction

Frying is essentially a dehydration process involving rapid heat and mass transfer in food immersed in hot oil, which leads to a succession of physical and chemical changes in the product (Tarmizi and Ismail 2008; Andrés-Bello and others 2011; Dueik and Bouchon 2011). Frying is extensively employed in domestic as well as industrial practice, due to its ability to create unique sensory properties, including texture, flavour and appearance, which make the food more palatable and desirable (Dana and Saguy 2006). Furthermore, its operational simplicity in the context of commercial practice, convenience, and economic viability, has resulted in extensive sales of a large variety of fried products (Mehta and Swinburn 2001). Despite, the many studies correlating fried product consumption with increased health risks (Krokida and others 2001; Mariscal and Bouchon 2008), and increasing consumer awareness of this relationship (Mariscal and Bouchon 2008), there is no sign to suggest that we will give up eating fried products (Dana and Saguy 2006; Tarmizi and Ismail 2008; Sayon-Orea and other 2013). These issues have prompted the fried product industry to search for ways and means to produce healthier products without compromising on the desirable appearance, texture, flavour and taste attributes (Garayo and Moreira 2002; Fan and others 2005; Da Silva and Moreira 2008; Mariscal and Bouchon 2008; Andrés-Bello and others 2011; Andrés and others 2013).

One such process is hot air frying, which aims to produce a “fried product” by sparging, essentially, hot air around the material instead of immersing it in hot oil. A variety of proprietary air fryer designs are currently available in the market, which create the frying effect by bringing direct contact between a fine mist of oil droplets in hot air and the product, inside a chamber. Most designs provide for extremely high heat transfer rates uniformly between air and the product being fried. Some achieve this simply with a built-in air blower, while others also couple high convective rates with radiative heat transfer. A number of manufacturers also claim that the shape of the chamber in which air and product are being contacted is profiled in such a way that air velocities are significantly higher than in typical ovens (Erickson 1989). Moreover, the air is also distributed more uniformly through the product, which minimizes variations in product quality. A schematic of a typical air fryer is shown in Fig. 1. The product gets dehydrated in the process and a crust, typically associated with frying, gradually appears on the product. Oil application could be done before or during the process to lightly coat the food product, in order to provide the taste, texture and appearance typical of fried products. The amount of oil used is significantly lower than in deep oil frying giving, as a result, very low fat products (Andrés and others 2013). To date, there is only a scientific publication about hot air frying. Andrés and others (2013) analyzed the kinetics of mass transfer and volume changes in hot air frying and deep-oil frying at the same temperature (180ºC) and concluded that both are affected by medium type. Heat transfer was slower when the fluid phase is air than when it is oil, due to lower heat transfer coefficient of air. Moreover, they also observed that product mass losses in air frying were higher than in deep frying, because the water lost during air frying was not offset by any significant oil uptake. Unfortunately, this paper makes little or no reference to the quality and sensory parameters of the product, and this is a major knowledge gap. In the present work, we have aimed to draw a comparison between: 1) process parameters of air frying and hot air frying - such as moisture content time profile, product temperature versus time profile and product oil content versus time profile, and 2) product characteristics yielded by the two frying methods, which include starch gelatinization profile, microstructure using SEM as well as sensory characteristics. This detailed comparison has been drawn by holding the same frying medium temperature in both cases, i.e. 180 ^{o}C. Further, the product characteristics mentioned above, including sensory analysis, have been compared after fixing the final product moisture content at a value that consumers normally consume (91.7 ±6.03 g water/ 100g defatted dry matter), which also helps us to evaluate whether air frying can produce a true alternative to traditional frying.

Materials and Methods

Raw materials

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

Frying equipment used

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

Sample preparation

The samples were prepared following the methodology described by Tarmizi and Niranjan (2010). Potatoes ranging in moisture content between 445.37 ± 107.77 g water/100 g dry matter were selected for this study. The potatoes were taken out from the fridge in which they were stored at least 12 h before being used in experiments, then washed, peeled and manually cut into strips (9 x 9 x 30 mm). The strips were soaked in running water for 1 min to eliminate occluded starch and blotted using tissue paper.

Frying protocol

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

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

Transient analyses of French fries

Proximate composition

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

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

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

Color

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

Texture

Texture measurements were made with Brookfield CT3 Texture fitted with 25kg load cell. Data collection and analysis was accomplished by using electronic Texture Pro CT software. A single cycle puncture test was performed using a cylindrical flat-end punch (2mm diameter probe) by fixing the test speed at 4.6 mm/s; the punch was allowed to travel into the samples for: 2mm (covering the crust region) and 6mm (which covered the core). Six samples were measured and punctured at 2 random positions for each processing time.

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

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

Scanning electron microscopy (SEM)

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

Differential scanning calorimetry (DSC)

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

Sensory analysis

For the sensory analysis, all evaluations were conducted in individual booths which contained the instructions for the evaluation procedure. The tasting room for sensory evaluation was airconditioned and free of disturbing factors. Samples were fried in a commercial deep fat fryer (model: 45470, Morphyrichards) at 180ºC for 9 minutes and in a commercial air fryer (AH-9000 Viva Collection Airfryer HD9220/40, Philips) at 180ºC for 21 minutes. Samples were obtained, and immediately after, were presented to the panelists.

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

Statistical analysis

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

Results and Discussion

Analyses of French fries during the Frying Processes

Temperature profile

The temperature of French fries, measured at a point, more or less, near the centre, under different frying conditions (deep-fat frying and air frying) is presented in Figure 2. The deep-fat fried samples behaved in a manner similar to the one described in earlier work (Budžaki and Seruga 2005; Farinu and Baik 2008; Mir-Bel and others 2012). The initial temperature increased, almost linearly with time, until it reached the boiling point of water (~100ºC). The temperature then increased gradually for a period of time, before increasing more sharply. The air fried samples also showed the same initial trend, i.e. temperature increasing linearly up to the boiling point of water, but at a significantly slower rate than deep-fat frying. The oil fried sample took 1.5 minutes to reach the boiling point of water, whereas the air fried sample took nearly 5.5 minutes. A second difference between oil frying and air frying is that the temperature, in the case of the latter process, remains, more or less, constant at the boiling point of water till the end of the process, and the gradual, but significant, increase in temperature above 100ºC observed in the case of deep oil frying is not evident. Based on the times taken for the product centre to reach the boiling point of water, it can be estimated that the heat flux in the case of oil frying is 3.7 times greater than in the case of air frying, which seems to provide enough energy in the form of latent heat as well as sensible heat. The post boiling heat transfer is accompanied by physicochemical changes occurring such as: gelation of starches, increase in the thickness of superficial crust and reduction in the rate of steam release from the product (Mir-Bel and others 2012).

Moisture and oil content

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

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

Color

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

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

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

Texture

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

Moyano and others (2007) and Pedreschi and Moyano (2005) observed that heating of potato tissue causes drastic physical, chemical, and structural changes, which could be divided into two stages: the tissue softening during the first few minutes of frying followed by crust formation and subsequent hardening. The same trend was observed in the present study for deep fat, as well as, air fried products. Table 1 shows the hardness work to decrease initially. The evaluation of texture parameter (hardness work) at 2 mm and 6 mm allowed studying the crust development and the modifications in product core, respectively. The initial stage of frying resembles a cooking process when a part of the starch gelatinizes and the lamellar media solubilizes at temperatures of around 60 to 70ºC (Moyano and others 2007). The softening phase of the tissue, at the surface as well as core, was much faster in deep fat frying ($p < 0.05$) which required only 3 minutes (105ºC) to be completely softened, compared to 6 minutes (100ºC) required for air fried samples.

The second stage is characterized by the development of a porous dried region and an overheated region which is generically called “crust”. This region is result of a vaporization front located close to the heat exchange surface which progressively moves towards the product center with the frying time. Miranda and Aguilera (2006) showed that the exposure of potato products to temperatures above 100ºC, such as the temperatures encountered during frying, causes starch granules and cells located on the surface to become dehydrated and form an external crust, which makes the product crispy. Both processes showed increase in hardness work values for the crust and core regions with time ($P > 0.05$).

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

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

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

Analyses of the final product deemed to be fit for consumption

Quality control criteria of frying industry stipulate that the moisture content of the final product must be in the range between 38% and 45% on a wet weight basis (Gökmen and others 2006; Romani and others 2008). To meet this criterion the samples used in this study were processed for 9 minutes in the case of deep-fat frying and for 21 minutes in the case of air frying, both at 180ºC. SEM, DSC and sensory analyses were undertaken to compare the two products.

SEM and DSC analyses

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

When we compare the raw potato tissue consisting of cells appearing pentagonal/hexagonal in shape (Figure 6 a-b) with the tissue resulting after "frying" (Figure 6 c-h), irreversible changes can be seen and two particularly clear areas appear: crust and core. Aguilera and others (2001) and Pedreschi and Aguilera (2002) postulated that cells in the crust of fried potato tended to change their shape while shrinking, and their walls became wrinkled and convoluted around dehydrated gelatinised starch; there was however, little or no rupture evident. The crust of air fired samples (Figure 6 f and h) showed higher empty spaces and smaller cells than deep-fat fried samples, because the temperatures and rates of water evaporation were different in the two process; moreover, any empty spaces formed during deep fat frying would be filled with oil. On the other hand, in both products, starch swelling mainly occurred in the core region, which is a result of grain hydration and gelatinisation to form an amylase and amilopectin reticulum which completely fills the cellular lumen (García-Segovia and others 2008), although this process occurred to a greater degree in deep fat fried samples (Figure 6 d) than air fried sample (Figure 6 g). Similar results were noted for the DSC analyses given in Figure 7. Both process showed higher gelatinization temperature and weaker endotherms than raw samples, which indicates the modification of starch structure due to gelatinization process (Garzón 2006; Liu and others 2009). Furthermore, deep-fat fried samples have a lower value of the enthalpy of gelatinization (ΔH) than air fried samples. According to Bello (2009) lower values of enthalpy indicates a higher proportion of gelatinized starch. Thus, a key difference between air fired and deep fat fried products is the higher extent of gelatinization occurring in the latter.

Sensory analyses

A panel evaluated appearance, odor, mouthfeel, taste, flavor and after effects of products obtained by both types processes, based on 31 descriptors (Table 2). There were statistically significant differences found for 22 of the 31 attributes ($P < 0.05$) used, which indicates major difference in the perceived product characteristics. It may be noted that the air fired product was processed for 21 minutes, whereas the deep fat fried product was processed for 9 minutes. Under these conditions, both products had average moisture content about 45%.

In terms of appearance, the extent of brownness and evenness of cooking were not significantly different between air fried and deep fat fried samples, which is also in agreement with instrumental color measurement. However, air fried samples stood out in terms of appearing puffed and dry, when compared with deep-fat fried samples which also highlighted oiliness attributes ($P < 0.05$); the SEM images shown in Figure 6 are consistent with these sensory observations. With regard to odor, the deep-fat fried product gave a fried smell and flavor, while the air fried samples give what was described as “jacket potato smell” ($P < 0.05$).

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

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

Key appearance differences between air fried and deep fat fried products

The external appearance of the samples is shown in Figure 8. The color of air fried and deep fat fried products may not be significantly different, however, the visual presence of fat in deep-fat fried product is amply evident. Another major difference between samples fried in air and oil is the structure of the products formed. Visual observations indicate that deep-fat fried samples have a surface crust structure which is dry, crisp and thick. This is the result of the high temperatures being reached rapidly at the product surface which causes intense local water evaporation that impedes gelatinization of the starch in the region. In the case of air fried product, the water evaporates much more slowly causing the surface crust to be thinner, homogeneous and without irregularities, which gives a perceptible difference in mouth feel. The visual observations of the crust also showed that air-fried samples expanded to a greater extent and contained regular pore distribution in core region in contrast to deep fat fried samples. During cooling too, the air-fried samples showed crust shrinkage, which was not observed in the deep fat fried product. Higher crust shrinkage during cooling is indeed a feature of air fried product, which does not seem to happen to the same extent in the case of deep fat fried product. This is most probably because crust cooling of air fried product occurs with concomitant steam condensation that leaves voids in the crust causing it to collapse. In contrast, the presence of oil in the crust of deep fried products minimizes crust collapse. As far as the core is concerned, both products showed gelatinized appearance, although the extent of gelatinization was higher in the deep fat fried product.

Conclusion

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

The final product evaluation by SEM and DSC analyses showed that air fried samples had a lower degree of gelatinization than deep-fat fried samples, which may explain the differences found between texture and sensorial characteristics of the two products.

Overall, air frying process permits the manufacture of lower fat content products, though these products have different sensory characteristics.

Author Contributions

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

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

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Table 1- Compression test results (Hardness Work, mJ) of products air fried and deep fat fried at 180ºC, as a function of 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^{bc,z}
Air	16,84±0,55^{d}	10,18±3,80^{bc,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}

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

Table 2- Quantitative descriptive analysis of French fries in both types processes: Deep-fat (9 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}	***

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

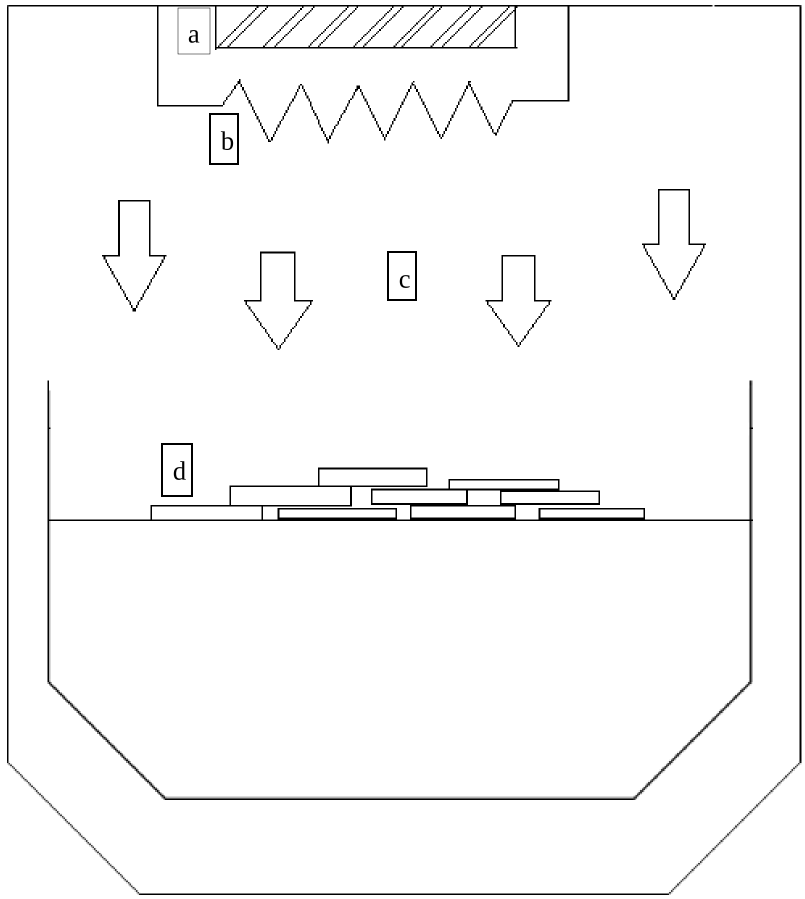

Figure 1- Schematic representation of air fryer: (a) fan, (b) electrical resistance heater, (c) hot air and (d) samples. It may be noted that there are a variety of proprietary hardware designs available each claiming heat and mass transport advantages as well as improved product quality, for instance,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

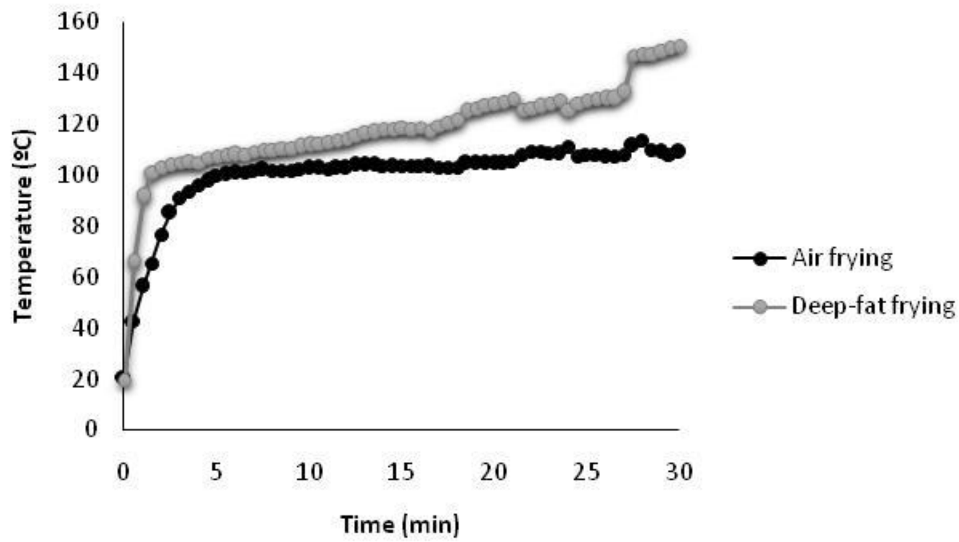

Figure 2- Evolution of Temperature inside French fries in both types processes at 180ºC, deep-fat and air frying. Both sets of experiments were performed in triplicate and the temperatures shown are mean values.

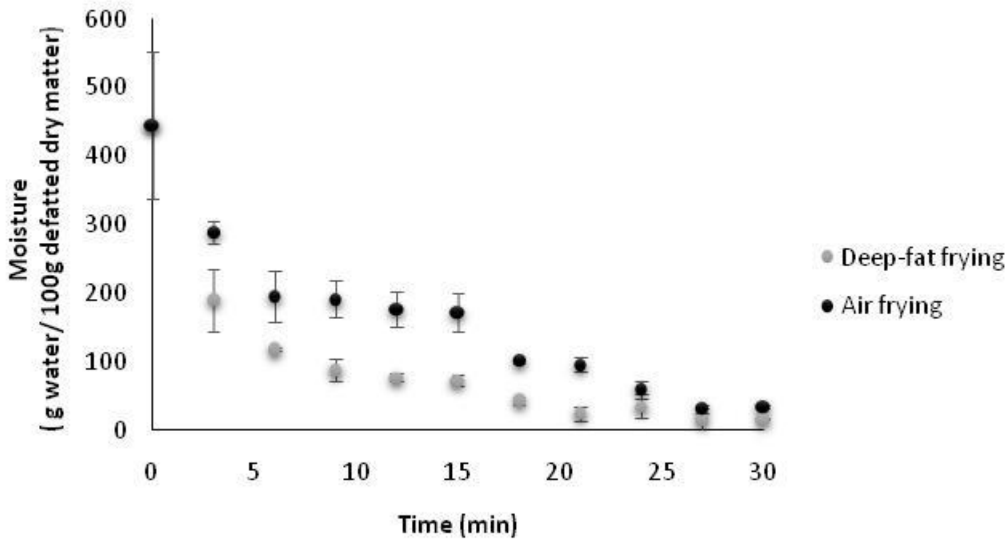

Figure 3- Evolution of moisture values of French fries in both types processes at 180ºC, deep-fat and air frying. Data shown in the figure are based on experiments performed in triplicates.

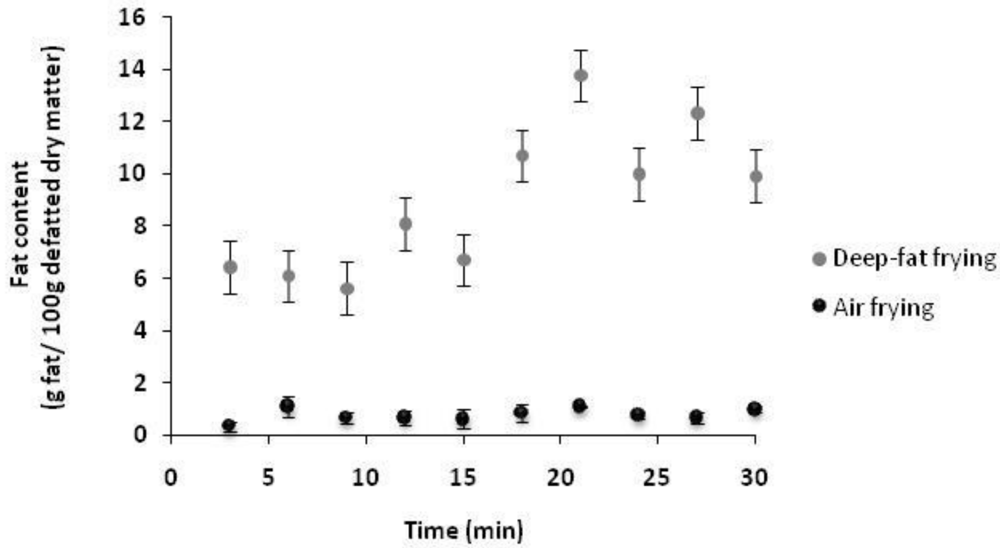

Figure 4- Evolution of fat values of French fries in both types processes at 180ºC, deep-fat and air frying. Data shown in the figure are based on experiments performed in triplicates.

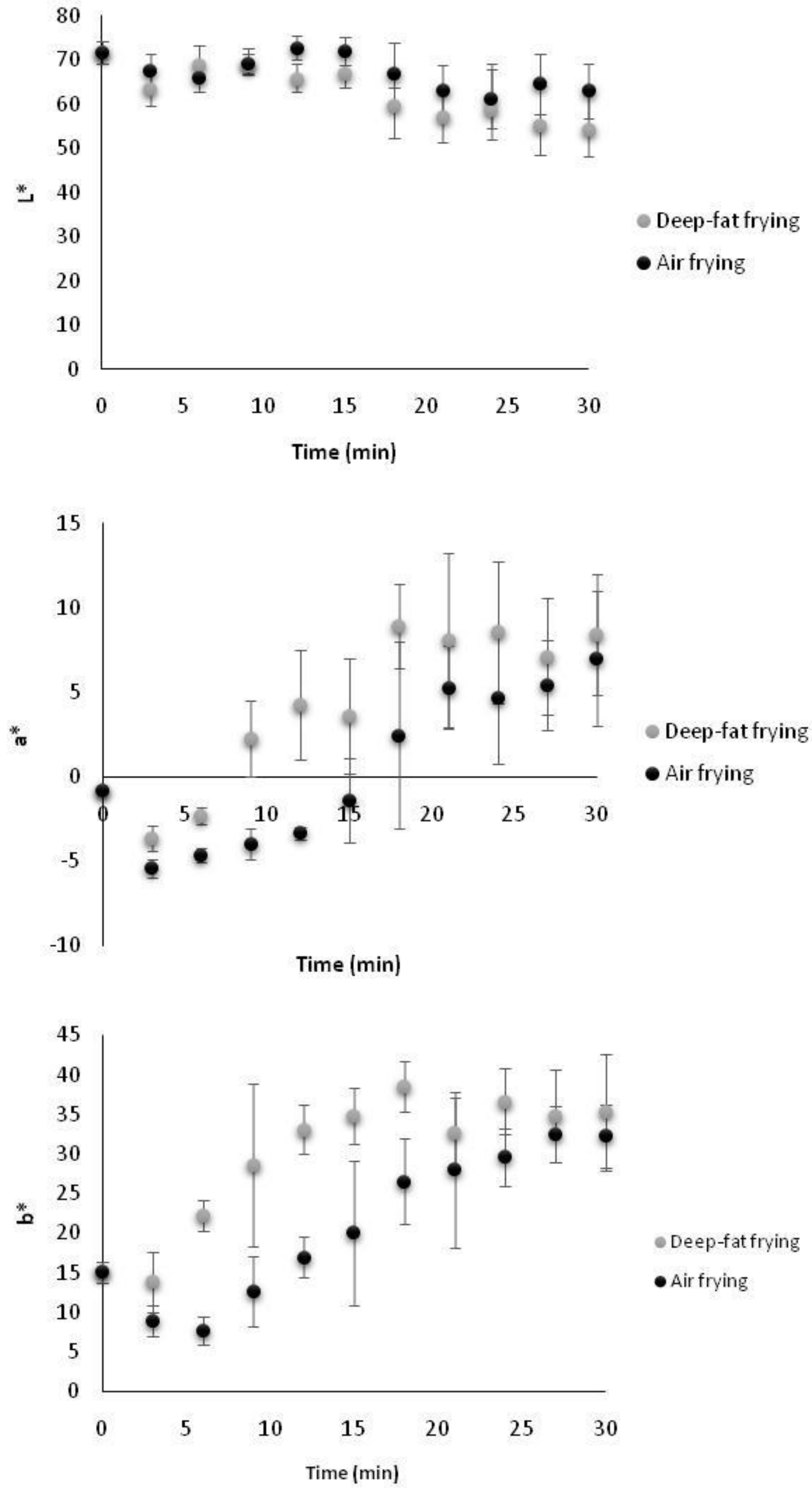

Figure 5- Evolution of L*a*b* values of French fries in both types processes at 180ºC, deep-fat and air frying: L* values, a* values, and b*values.

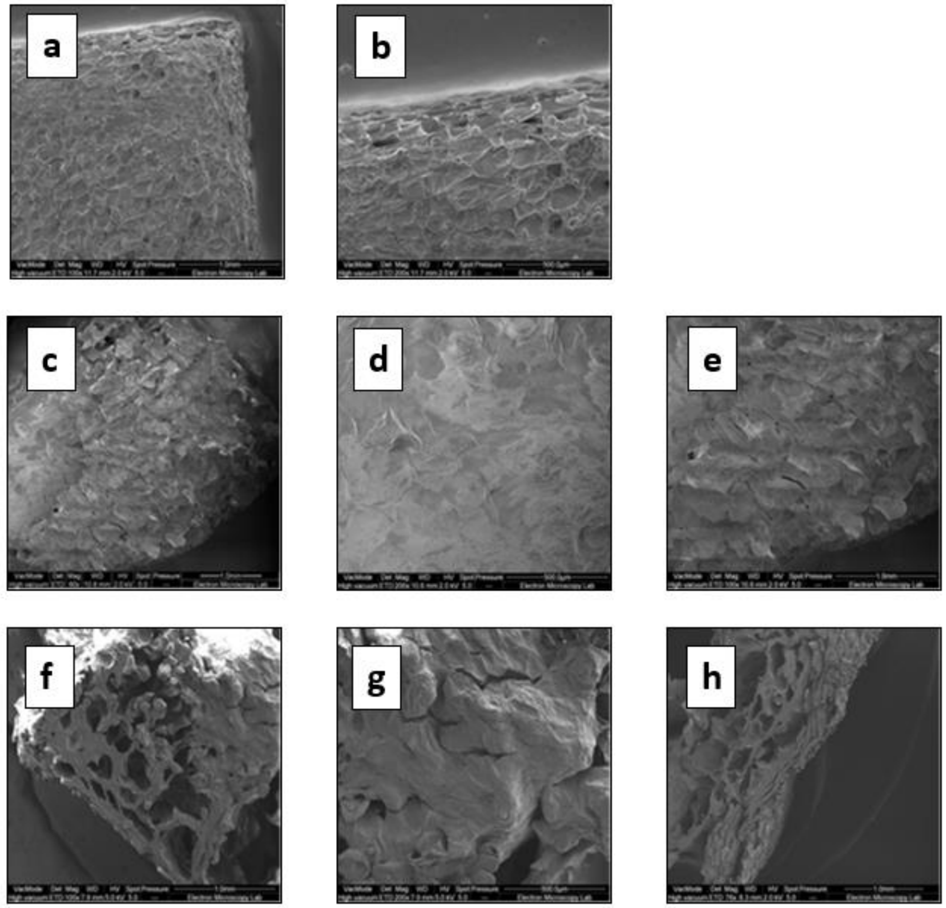

Figure 6- SEM of French fries raw, deep-fat fried (9 minutes) and air fried (21 minutes); moisture content of both samples 91.7 ±6.03 g water/ 100g defatted dry matter: (a-b) raw, (c-d-e) deep-fat fried samples, and (f-g-h) air fried samples. Figures a-c-f: sample size = 1mm; Figures b-d-g: sample size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

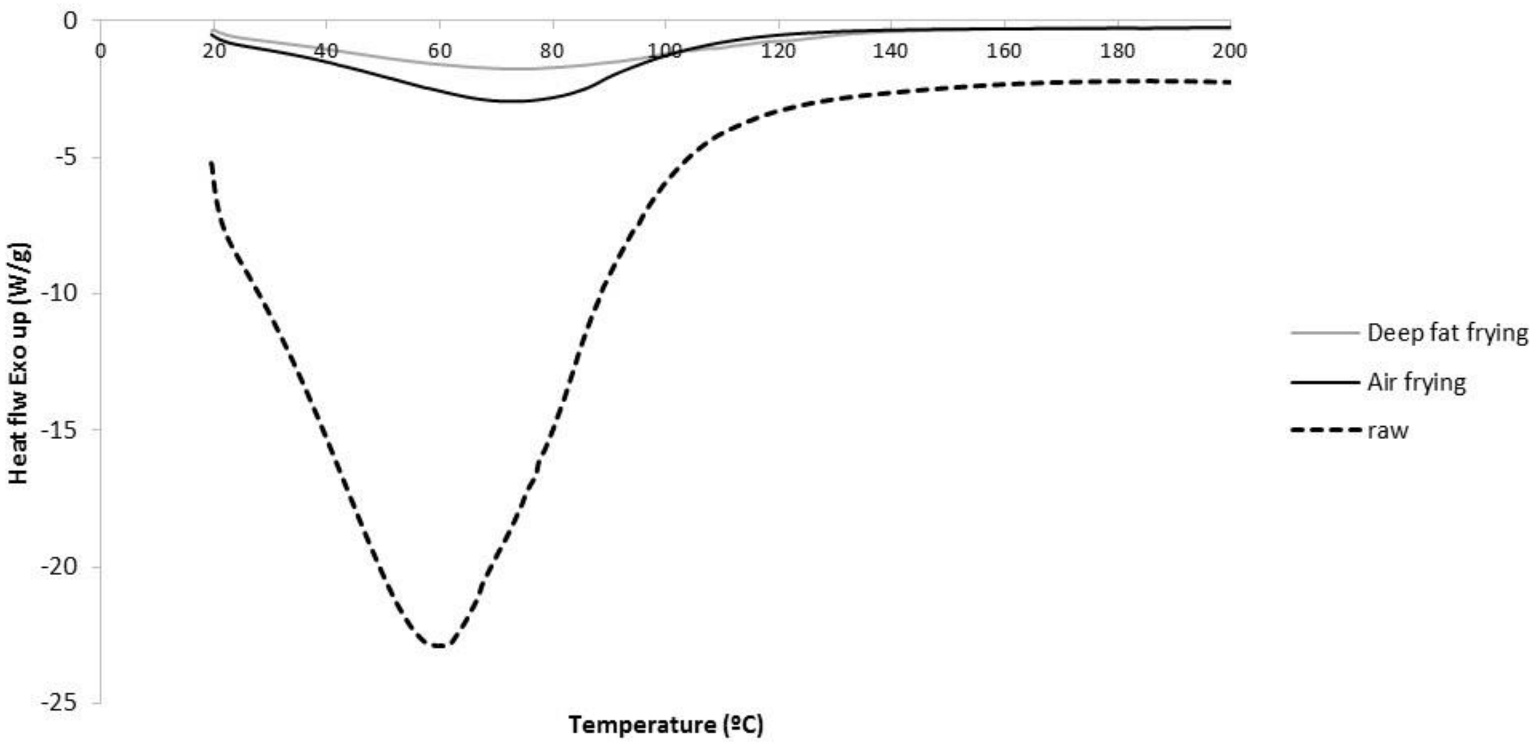

Figure 7- Gelatinization endotherms of French fries: raw samples, deep-fat frying samples (9 minutes) and air frying samples (21 minutes)); moisture content of both samples 91.7 ±6.03 g water/ 100g defatted dry matter.

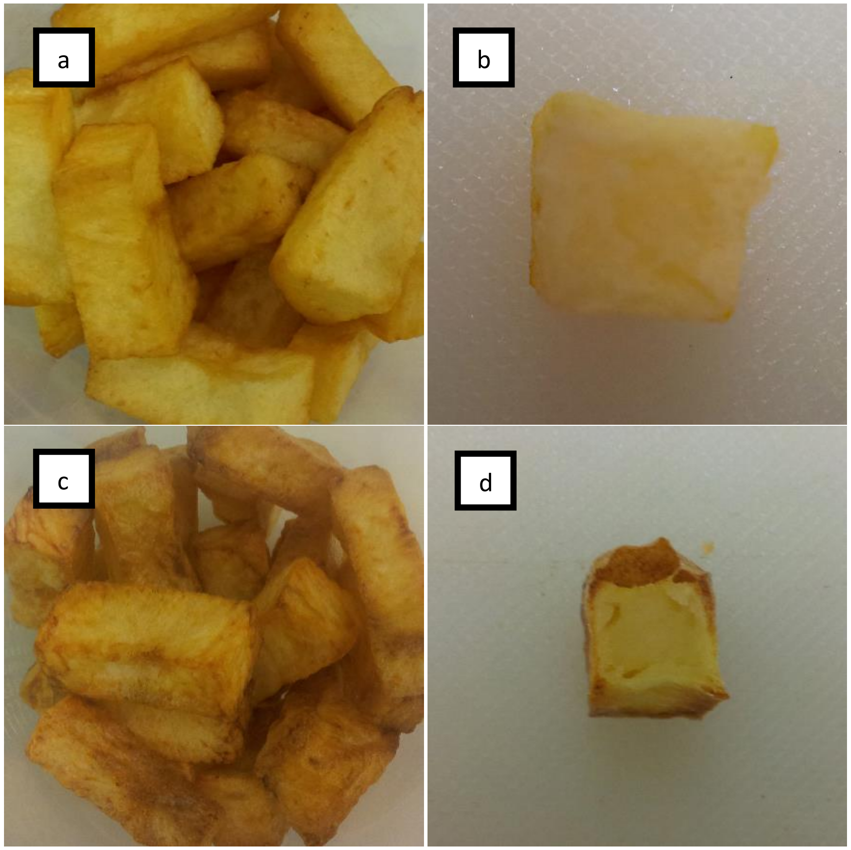

Figure 8- Pictures of French fries samples: deep-fat for 9 minutes (a-b) and air for 21 minutes (b-c)); moisture content of both samples 91.7 ±6.03 g water/ 100g defatted dry matter.