MASS TRANSFER AND VOLUME CHANGES IN FRENCH FRIES DURING AIR FRYING

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Abstract

The production of healthier fried foods requires the adaptation of industrial processes. In this context, air frying is an alternative to deep oil frying to obtain French fries with lower fat content. Kinetic analysis of compositional changes and the main fluxes involved in air frying were carried out, and the results were compared to those obtained for deep oil frying. The influence of the type of sample (unpretreated, frozen or blanched potatoes) was also analyzed. The results showed that oil uptake is much lower in air frying although a much longer processing time is required. Also, water loss and thus the loss of volume were much higher in air frying compared to the conventional process.

Keywords: potato; oil intake; deep frying; blanching; freezing

1. Introduction

Frying is one of the oldest and fastest methods of cooking any kind of food such as meat, fish and vegetables by dipping the food, raw or pre-treated, in hot oil or fat over a period of time (Hubbard & Farkas, 2000). Frying can be considered a dehydration operation in which a simultaneous heat and mass transfer occurs giving as a result two counter-fluxes, a water outlet from the food to the hot oil and an oil inlet by the food (Krokida et al., 2000), leading to a series of physical and chemical changes in the final product. Despite the large gain of oil undergoes during processing in the product, frying is a cooking technique widely used both domestic and industrial, because of its ability to generate in the final product a combination of texture, colour and unique flavour that makes it a more palatable and desirable food for the consumer (Mestdagh et al., 2008). Among fried products, the most widely known and consumed are the ones derived from potatoes such as chips and French fries, followed by the batter products and the ones of direct consumption as snacks (Clark, 2003). The processing industry of fries comes in mid-nineteenth century and its sales volume has grown steadily over the years as a result of the popularity of these products among consumers of all ages and also by its easy and fast preparation prior to consumption (Clark, 2003). However, many studies show that excessive consumption of fried products can lead to serious health risks such as cardiovascular diseases, hypertension, diabetes, cancers and obesity (Saguy & Dana, 2003). This fact together with the current trend of society to consume fat-free products have forced the industry in general, and chips industry in particular, to focus its efforts on developing alternative methods of frying that lead to products with low oil content but with the same features of flavour, colour and texture that make them so prized by consumers. In this sense, many strategies have been proposed to reduce oil content in fried products such as low pressure (Troncoso & Pedreschi, 2009; Dueik et al., 2010) or microwave application (Ngadi et al., 2009) or different pre-treatments such as blanching, freezing (Moyano & Pedreschi, 2006) or pre-drying (Debnath et al., 2003). However, these alternatives do not always permit to mimic the sensory features of conventional fried products or the cost is higher than conventional frying. Hot-air frying is a new technique to get fried products through the direct contact between an external emulsion of oil droplets in hot air and the product into a frying chamber. The product is constantly in motion to promote homogeneous contact between both phases. In this way, the product is dehydrated and gradually appears the typical crust of fried products. The amount of oil used is significantly lower than in deep-oil frying giving as a result very low fat products. Today, it is possible to find on the market home equipment designed from this principle to obtain low-fat fried products. However, there are no references or scientific publications that describe the mechanisms and kinetics of mass transfer phenomena and volume change taken place during the hot air-frying. Therefore, a better scientific understanding of this technique is necessary in order to extend its application either to fast food restaurants or industries for instance, due to not only to healthy benefits to consumers but also to the economical and environmental advantages such as the cost saving, the oil volume used and the absence of effluents after frying.

The aim of this study was to analyze the kinetics of mass transfer and volume changes in hot-air frying through a comparative study with the traditional frying or deep frying. The influence of the pre-treatment (blanching and freezing) on the kinetics was also evaluated.

2. Materials and methods

2.1. Raw material and pre-treatments

Fresh potatoes (*Solanum tuberosum L.*, Mona Lisa variety) were purchased from a local supplier in one batch. Potatoes were stored at 6 ºC, and then acclimatized at 20ºC seven days before use. The potatoes were sorted, washed, peeled and cut by means of a manual cutter into strips (0.009 m x 0.009 m x 0.03 m). Frying, either deep-oil or hot-air frying, was carried out using (i) control or unpretreated strips, (ii) strips blanched in hot water at 90 ºC for 1 min, and (iii) commercial frozen pre-fried potato strips with an initial fat content of 2% and similar dimensions. The moisture content (% wet basis) of control, blanched and frozen potato strips was 82.5±0.2, 83.1±0.4 and 79.7±0.5%, respectively. Refined seed oil with 0.2 º acidity was used to fry the potatoes, except for the air-frying experiments on frozen potatoes as these samples already had an initial fat content.

2.2. Experimental methodology

Experiments were carried at a fixed frying temperature of 180 ºC in commercial deep oil-frying (model: FM 6720 Ideal 2000 Professional, Solac) with a nominal power: 2000W) and hot air-frying equipment (model: AH-9000 Actifry, Tefal) with a nominal power: 1400 W). For deep-oil experiments, samples were immersed in 20 L of oil by kg of potato, i.e. a potato-to-oil ratio of 1:20 (w/v), according to the capacity of the equipment. 1:20 ratio was large enough to avoid important changes in terms of product-to-oil ratio and therefore in the oil composition and temperature. For hot-air frying experiments, 0.003 kg of oil by kg of potatoes was added into the air chamber according to the specifications of the equipment. A constant frying temperature was confirmed by means of two PT-100 temperature sensors (model: TF101K) located at the top and the bottom of each fryer. Samples were immersed in the oil in deep-oil frying and air in hot-air frying when the initial frying temperature of 180ºC was achieved.

Each experiment, e.g. deep oil frying of blanched potatoes, etc., was conducted by triplicate. For analytical determinations, three samples were removed from the frying equipment at 3 min intervals for each hot air-frying experiment (total processing time: 30 min) and at 2 min intervals (total processing time: 16 min) for each deep-oil frying one. Therefore, a total of nine determinations were carried out for each experiment conditions, e.g. deep oil frying of blanched potatoes, etc.

2.3. Analytical determinations

Water content was analyzed by vacuum drying at 60 °C until constant weight was achieved (20.103 AOAC, 1980). The oil content was extracted by chloroform and methanol based on the method proposed by Pedreschi and Moyano (2005). Volume was analyzed by means of a picnometer using distilled water as a reference liquid (Mohsenin, 1986) once samples had achieved 20ºC. Samples achieved this temperature 10 minutes after being taken out of the fryer.

The net mass changes of total weight (ΔM_t), oil (ΔM^{oil}_t), and water (ΔM^{w}_t) during frying were obtained according to the following equations (Eq. 1 to 3):

$$\Delta M_t = \frac{M_t - M_0}{M_0} \qquad (1)$$

$$\Delta M_t^{oil} = \frac{M_t \cdot x_t^{oil} - M_0 \cdot x_0^{oil}}{M_0} \qquad (2)$$

$$\Delta M_t^{w} = \frac{M_t \cdot x_t^{w} - M_0 \cdot x_0^{w}}{M_0} \qquad (3)$$

where M_0 is the mass at initial time (g), M_t is the weight at time t (g), x^w_0 and x^{oil}_0 are the mass fractions of water and oil at initial time (g/g) respectively; and in the same way, x^w_t and x^{oil}_t are the mass fractions of water and fat at time t (g/g).

Additionally, volume change during frying was also quantified as follows (Eq.4):

$$\Delta V_t = \frac{V_t - V_0}{V_0} \qquad (4)$$

V_0 and V_t (m^3) being the volume of the sample at the beginning of frying and time t, respectively.

3. Results and discussion

3.1. Compositional changes during frying processes

During the frying process, mass loss is mainly due to two countercurrent flows, water loss and oil uptake. The analysis of the evolution of moisture and oil content under different frying conditions permits the comparison of the concentration of the two most important components from a sensory and nutritional point of view.

Figure 1 shows the evolution of moisture and fat content in both types of processes, deep and hot-air frying. Both concentrations are expressed in terms of mass ratio (g of component/ g fat-free dry basis) to better establish the adequate comparisons, i.e. the denominator remains throughout the frying time, because of the main changes occur in terms of water and oil content. The results show that the main difference between the two types of frying is the final oil content, this being much lower in hot air frying. The different in terms of mass transfer mechanism are associated with the differences in the external resistance of the type of external fluid surrounding to heat the product. The lower individual heat transfer coefficient for air frying, i.e. value of Biot number, gives as a result higher external rate-control than in deep-oil frying.

Differences between the different samples were also observed, especially in frozen samples as compared to unpretreated and blanched ones.

It is important to note that frozen samples had an initial fat content of 0.019 grams of fat per gram of fat-free dry matter. This is a consequence of the well known pre-crushed industrial process which causes the formation of a fatty sheath. Due to no added oil in air frying in frozen samples, a partial loss of the initial fatty sheath was noticed because of the melting phenomenon of the fat in the frying chamber (figure 1). On the other hand, the frozen samples achieved the highest fat content during deep-oil frying. It could be explained because of the structural changes occurring under frosting which ease the oil intake. For the unpretreated and blanched samples, the evolution of the oil content was very different when comparing the deep frying and air frying processes.

Although in both cases the oil uptake occurred in the early stages of the process, it was much higher in the case of deep frying. When frozen potatoes were subjected to deep frying the oil content was hardly modified from the original content, though a small loss occurs due to melting at the beginning of the process and a later retrieval by oil uptake from the medium. In the case of the air frying of frozen potatoes, a reduction of oil concentration to values of about half the initial content is observed as a result of the melting of the fatty sheath.

3.2. Net mass Fluxes during frying processes

The analysis of compositional changes during the frying process is important for their relationship with the sensory and nutritional quality of the product but is also very useful to analyze the net fluxes of mass, water and oil since the process yield is directly related to them, and as they provide information additional to the concentration curves previously discussed.

The heat and mass transport phenomena involved in the frying processes are much faster for deep frying than air frying. It is important to note that although the temperature of the medium is the same in both cases (180 º C) the heat transfer is much faster when the fluid phase is oil than when it is air, therefore water transport is affected by this difference. The end result is shorter processing times. Since the net mass loss is the result of water loss and oil uptake, it is necessary to analyze these two fluxes separately to better understand the kinetics and the extent of transport of these compounds.

In general terms it is observed that mass losses in air-frying were higher than in deep frying reaching a loss of 70% in all cases at the end of the process (Fig. 2). This is because there was almost no oil gain during air frying and the mass loss corresponded almost exclusively to the water loss. The water loss in deep frying was affected by the type of pre-treatment to which the unpretreated material was subjected (freezing or blanching) while in air frying no important differences were found (Fig. 2). In deep oil frying, blanched samples had the highest water loss, though very similar to the unpretreated samples, while the frozen samples were the ones with the lowest water loss. Water loss is limited by the characteristic crust on these products, which is formed more rapidly in the deep frying process. This could explain the lower water loss of the frozen potato fried in deep oil, as previous studies show that frozen potato chips completely form the crust during the first 4 minutes of deep frying and that its thickness increases and becomes more consistent (Du Pont et al., 1992). Losses of part of the fatty sheath during air frying of frozen samples seem result in a less consistent crust, which offers less resistance to water loss, which is why in this type of frying differences between samples are not appreciated. Some studies confirm that blanching promotes the starch gelatinization of potatoes resulting in a different microstructure from that of unpretreated potatoes. These changes in the starch structure and consequently in potato tissue may explain the differences found in these samples which exhibit a trend toward greater water loss and less oil intake, which would confirm what other authors have found, that blanching is a suitable pre-treatment to reduce the oil content of fried products (Califano & Calvelo, 1987; Aguilar et al., 1997). In general it can be observed that oil uptake takes place in the first few minutes of the process, being more marked in the unpretreated potatoes than in the rest (Fig. 2). Tissue shrinkage at the beginning of frying promotes oil penetration, though only superficially. Blanched samples experience this contraction in the blanching step which could justify the lower ingress of oil through this mechanism. When comparing the two types of frying processes for each type of sample, it could be said that for the same frying time, oil uptake in unpretreated and blanched samples is about ten times higher in deep frying than in hot air frying.

Frozen samples were the ones that gained least oil during deep frying, while in the air-frying process they did not gain any oil, in fact their initial fat content was reduced.

Frying processes can be described according to the plot of the ratio $R = (\Delta M_t / \Delta M^{w}_{t})$ versus time (Fig.3). In figure 3, two stages can be distinguished in all cases:

Stage I: very short, between 3 and 6 minutes, during which the ingress ($R<1$) or egress ($R>1$) of oil occurs, while water loss is induced by an increase in temperature.

Stage II: in which R remains constant indicating that only the net flux of water contributes to the loss in weight.

It can be noted that in deep oil frying of frozen samples the value of R remains almost constant indicating that the entry of oil takes place in the first moments of the process while in the first stage of hot-air frying a value of $R > 1$ is obtained, reflecting the loss of fat mentioned above. However, in the first stage of both types of frying R values were <1 for blanched samples reflecting the entry of oil; while for unpretreated samples, the value of R is roughly equal to 1 during all the frying processes noticing the low oil uptake.

3.3. Volume changes during frying processes

Figure 4 shows the results of the net volume changes observed throughout the experiments with both frying processes using unpretreated, frozen or blanched potatoes. Volume changes are the result of several phenomena that can occur in a coupled way such as: water loss, collapse of the porous structure, viscoelastic deformation of the matrix as a result of the expansion of entrapped gas, etc. Different steps that are related to these phenomena can be identified from the results of volume changes during the frying process:

(I) *Volume loss Stage*. During this stage the volume loss is related to tissue shrinkage due to thermal shock at the beginning, but it is mainly associated with water loss.

(II) *Volume recovery Stage*. This stage is observed only in deep oil frying of unpretreated and blanched samples where the high heat transfer coefficient compared to air frying, causes a quick vaporization of the water inside the potato tissue. Vapour expansion causes an increase in porosity resulting in an increase of the apparent volume of these samples. This stage is not observed in frozen potatoes which miss this stage going directly to stage III. This fact could be associated to the fact that frozen potatoes required more time to evaporate water in comparison with unpretreated and blanched samples.

(III) *Constant volume Stage.* In this stage the process of water loss progresses without volume changes due to crusting or formation of a vitreous cortex, increasing the internal porosity without changes in the apparent volume.

Since water loss plays an important role in the deformation of the samples the existence of the previously described stages are confirmed by plotting the volume loss versus water loss (Fig. 5).

4. Conclusions

The results from this study permit the description and the better understanding of the mass transfer and the associated volume changes during the hot air frying process. Besides, it is shown that the air frying process permits the production of fried products with lower fat content and similar moisture levels to those obtained by conventional frying. On the other hand, the influence of pretreatments, blanching or freezing, on the kinetics and on the extent of transport of water and oil is highlighted and must be considered in further optimization studies.

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Figure captions:

Figure 1. Evolution of moisture (X^{w}_{t}/X^{w}_{0}) and oil (X^{oil}_{t}) contents in both types of processes, deep-oil and air frying.

Figure 2. Evolution of net mass fluxes of total mass (ΔM_t), oil (ΔM^{oil}_{t}) and water (ΔM^{w}_{t}) in both types of processes, deep and air frying

Figure 3. Evolution of the ratio between mass and water losses ($R = \Delta M_t/\Delta M^{w}_{t}$) of unpretreated, blanched and frozen French fries throughout the experiments with both frying processes using raw, frozen or blanched potatoes. Vertical dotted lines separate stages I and II.

Figure 4. Net volume changes (ΔV_t) throughout the experiments with both frying processes using unpretreated, frozen or blanched potatoes. Vertical dotted lines separate stages I, II and III.

Figure 5. Correlation between volume change (ΔV_t) and water loss (ΔM^{w}_{t}) in both types of processes, deep and air frying. I: Volume loss Stage. II Volume recovery Stage. III. Constant volume Stage.

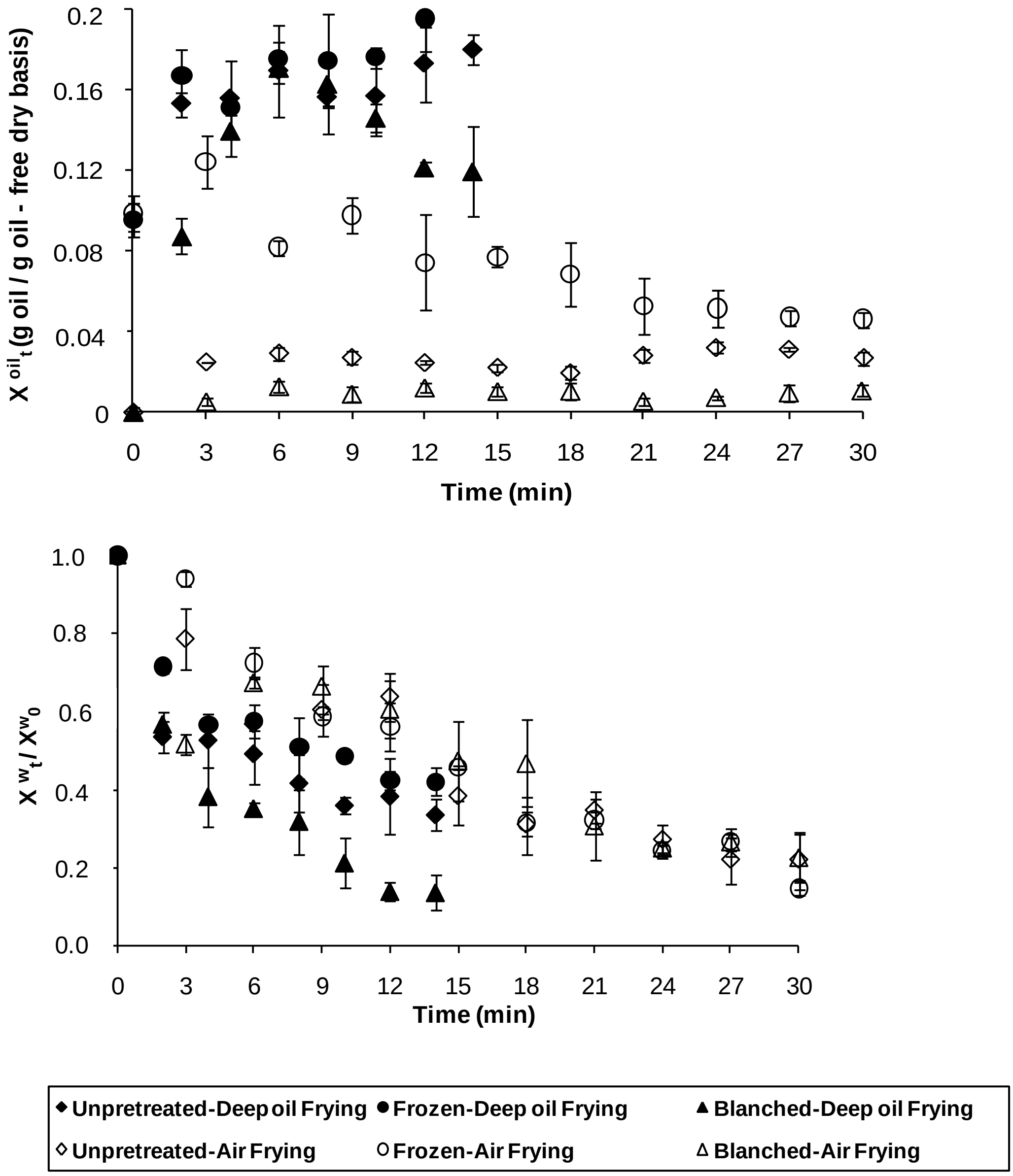

X oil t (g oil / g oil - free dry basis)
0.2
0.16
0.12
0.08
0.04
0
0 3 6 9 12 15 18 21 24 27 30
Time (min)
X w t / X w 0
1.0
0.8
0.6
0.4
0.2
0.0
0 3 6 9 12 15 18 21 24 27 30
Time (min)
Unpretreated-Deep oil Frying
Frozen-Deep oil Frying
Blanched-Deep oil Frying
Unpretreated-Air Frying
Frozen-Air Frying
Blanched-Air Frying

Figure 1.

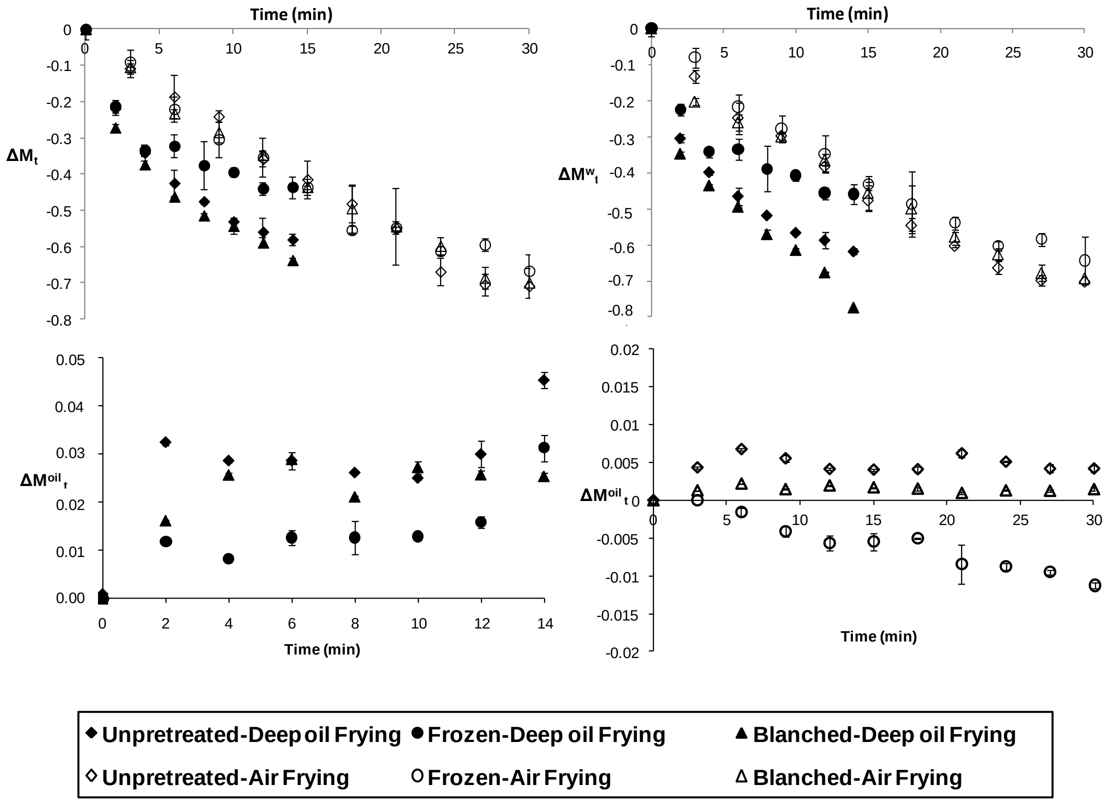
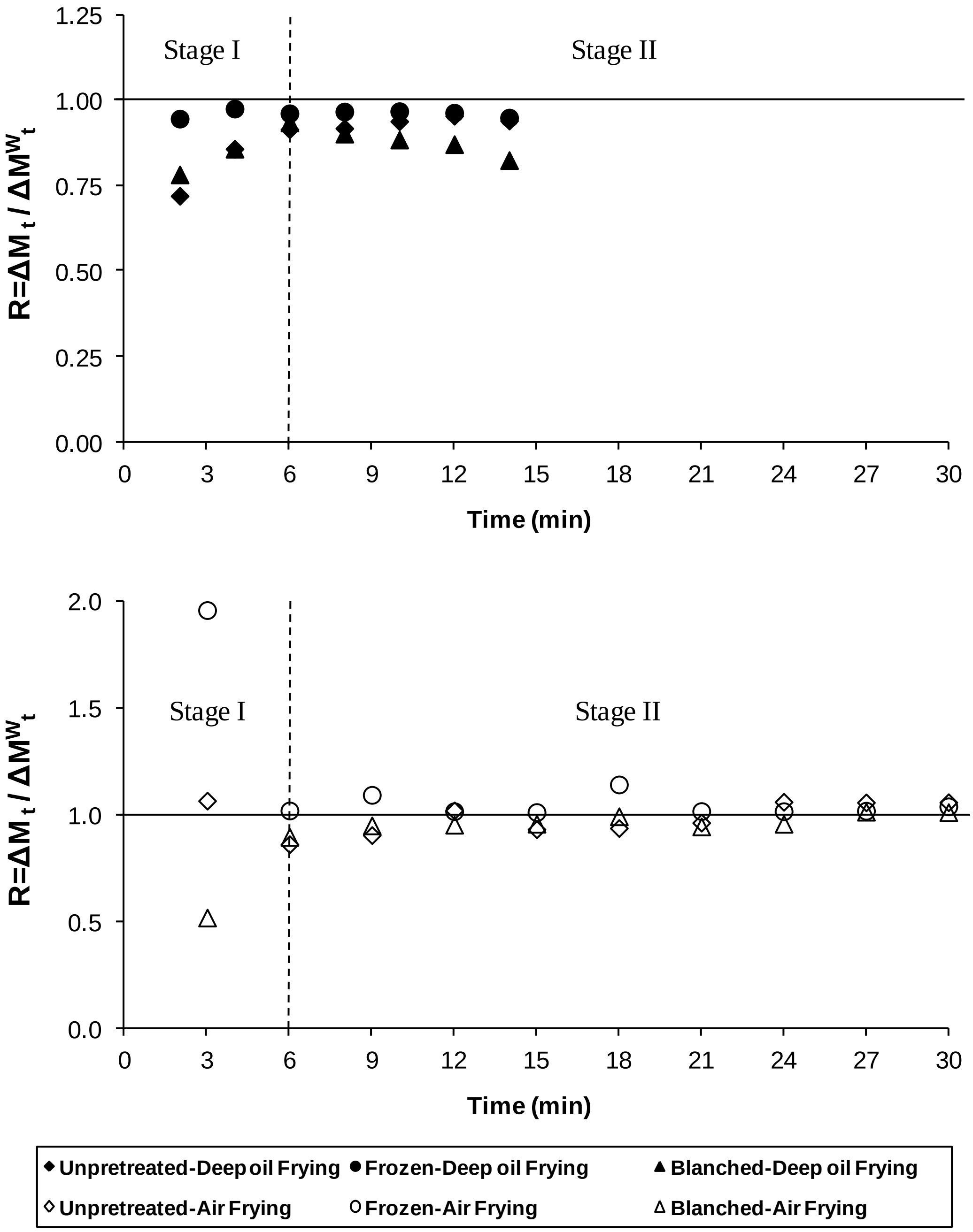

Time (min)
ΔMt
Time (min)
ΔMwt
ΔMoilt
Time (min)
ΔMoil t
Time (min)
Unpretreated-Deep oil Frying
Frozen-Deep oil Frying
Blanched-Deep oil Frying
Unpretreated-Air Frying
Frozen-Air Frying
Blanched-Air Frying

Figure 2.



Stage I
Stage II
R=ΔMt / ΔMWt
Time (min)
Stage I
Stage II
R=ΔMt / ΔMWt
Time (min)
Unpretreated-Deep oil Frying
Frozen-Deep oil Frying
Blanched-Deep oil Frying
Unpretreated-Air Frying
Frozen-Air Frying
Blanched-Air Frying

Figure 3.

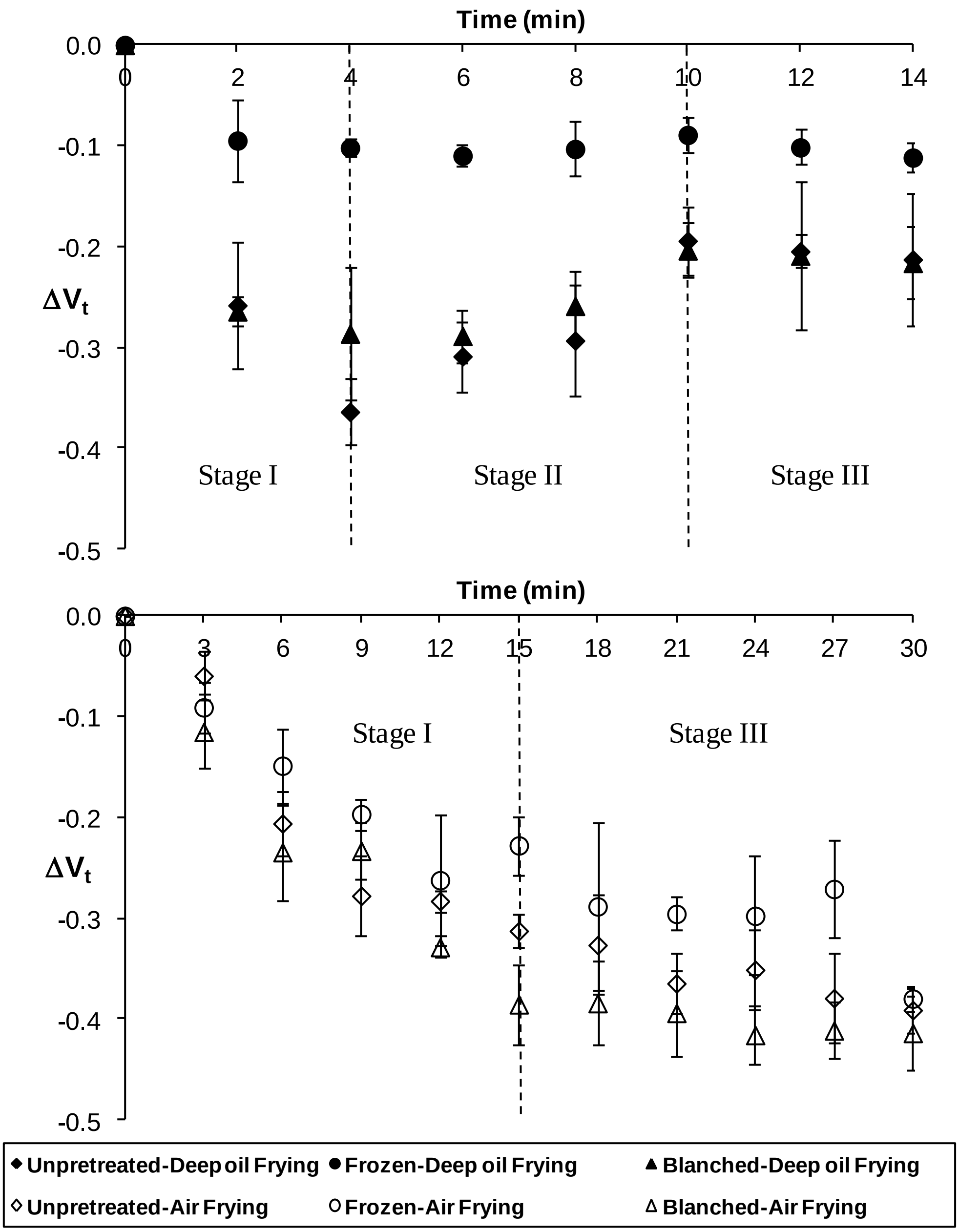
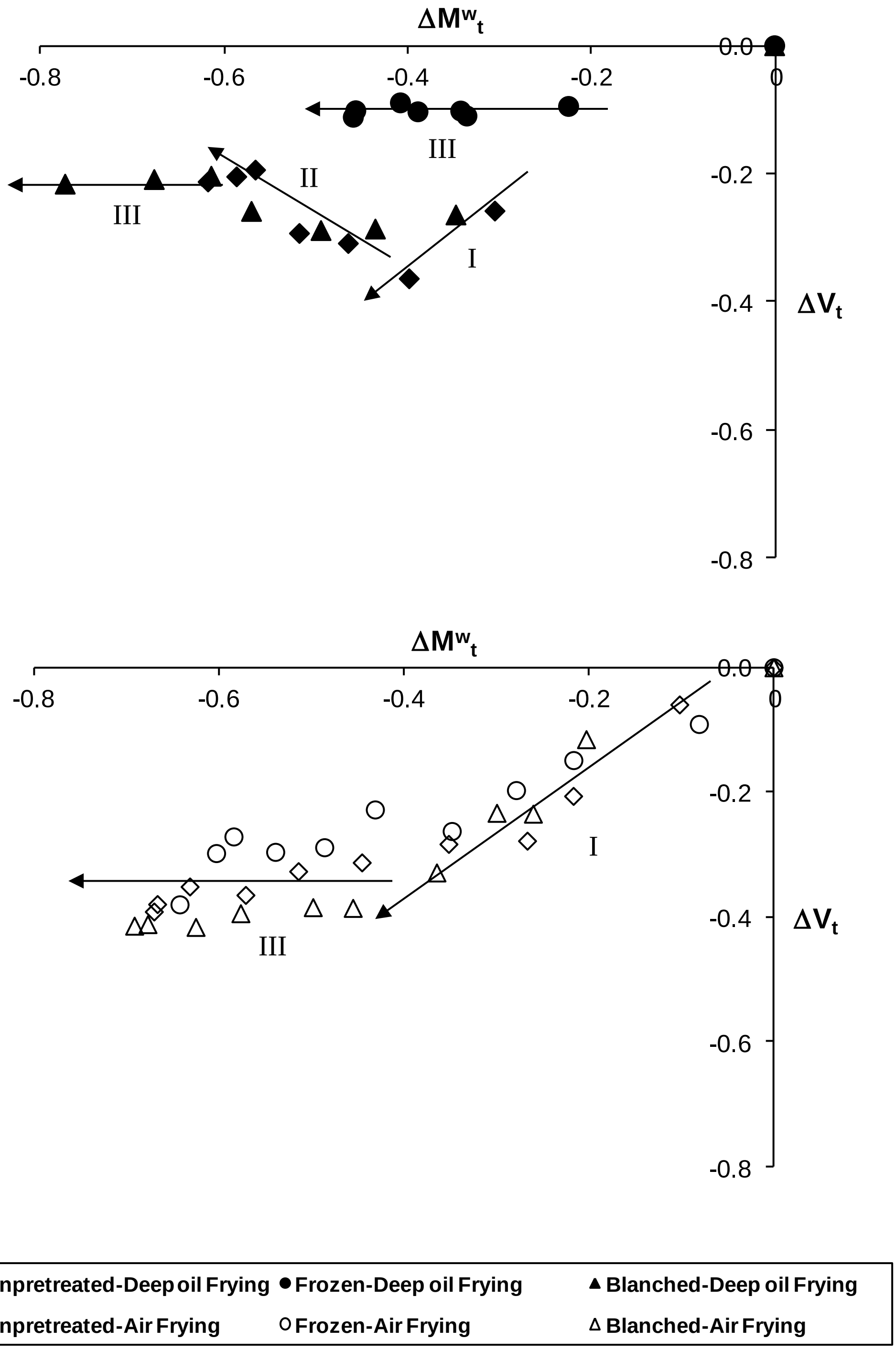

Time (min)
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
2
4
6
8
10
12
14
ΔVt
Stage I
Stage II
Stage III
Time (min)
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
3
6
9
12
15
18
21
24
27
30
ΔVt
Stage I
Stage III
Unpretreated-Deep oil Frying
Frozen-Deep oil Frying
Blanched-Deep oil Frying
Unpretreated-Air Frying
Frozen-Air Frying
Blanched-Air Frying

Figure 4.



ΔM^w_t
-0.8
-0.6
-0.4
-0.2
0
0.0
-0.2
-0.4
-0.6
-0.8
ΔV_t
I
II
III
III
ΔM^w_t
-0.8
-0.6
-0.4
-0.2
0
0.0
-0.2
-0.4
-0.6
-0.8
ΔV_t
I
III
Unpretreated-Deep oil Frying
Frozen-Deep oil Frying
Blanched-Deep oil Frying
Unpretreated-Air Frying
Frozen-Air Frying
Blanched-Air Frying

Figure 5.