IMPROVED VACUUM FRYING PROCESS FOR HIGH QUALITY SWEET POTATO CHIPS

A Thesis

By

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ABSTRACT

Vacuum frying is a promising method for preserving the desired color, texture, and flavor of products with high sugar content. Since most vegetables and fruits degrade when processed with traditional frying, vacuum frying is an excellent alternative to high temperature processing. However, in vacuum frying the product should be pre-treated before frying to obtain a better texture.

The kinetics of oil absorption and oil distribution in sweet potato chips (total, internal, and surface oil content) was studied so that effectiveness of the de-oiling system could be established. An analysis of product quality attributes (PQA) such as moisture content, oil content, microstructure, diameter shrinkage, and thickness expansion, as well as, color, texture, bulk density, true density, and porosity of chips fried at different temperatures (120, 130, and 140°C) was performed to evaluate the effect of process temperature on the product.

The final oil content of the sweet potato chips was 0.178±0.007, 0.178±0.011, and 0.172±0.002 g/g solid for frying temperatures of 120, 130, and 140ºC, respectively. These values were lower (~60% less) than those found in traditionally fried sweet potato chip, which indicates that the de-oiling mechanism is crucial in vacuum frying processing.

It was found that the rate of change in PQAs is greatly affected by temperature; however, the final values of bulk density, true density, porosity, diameter shrinkage, and thickness expansion were not affected by temperature. The texture of the samples was

affected by temperature, with the chips fried at 140°C being crispier. In terms of color, the $L*$ and color $b*$ values decreased as temperature increased. While color $a*$ was not affected by temperature.

In this study, a two-stage frying process was also evaluated to improve the flavor and texture of sweet potato chips. First, a basket filled with the sweet potato slices was submerged into the oil under atmospheric conditions. As soon as the potato slices were partially cooked (1 min), the pressure was lowered to1.33 kPa (vacuum frying stage) and the product fried for 2 more min. The products were fried at 130°C for different interval of times. Starch gelatinization, texture, moisture content, and oil content were evaluated at each time interval. Sensory analysis was accomplished by using a consumer panel with 50 members. The samples were compared with the on-stage frying and atmospheric frying processes.

The two-stage fried chips had better appearance and texture compared to the ones that were only fried under vacuum or atmospheric conditions. The samples were lighter and more yellow than the chips fried under the single-stage process. In vacuum frying, the temperature of the chips does not reach the gelatinization temperature until most of the water is evaporated. Therefore, there is not sufficient moisture content in the product for gelatinization to occur completely. As a result, the product has a glassy texture. In the two stage frying, the atmospheric frying prior to vacuum frying helps the starch to gelatinize thus producing a better product in terms of texture, oil content, and flavor. The atmospheric fried samples were darker in color and had a scorch taste. The degree of

starch gelatinization was 21% higher for the two-stage fried samples than the single-stage fried ones.

The application of the dual stage enhances the quality of sweet potato chips, improves consumer satisfaction, and reduces the need for space, cost, and any other needs of blanching pre-treatment to the sweet potato manufacturers.

DEDICATION

To my parents, Mujgan & Ismail Hakki

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Deep-fat frying is one of the oldest processes used for food preparation. The food industry is trying to find new methods to reduce oil content of food products while preserving the desired color, texture, and flavor.

Vacuum frying can be an alternative method to produce fried foods with lower oil content and desired quality characteristics (Garayo and Moreira, 2002).

Some studies have demonstrated that less oil adsorption occurred in vacuum fried products by the application of pre-treatments and de-oiling process. De-oiling is an essential step in vacuum frying, which is applied before the pressurization step to reduce the total oil content of fried chips (Da Silva et al. 2008). Da Silva et al. (2008) showed that the quality attributes, such as color, flavor, texture, and oil content, of mango chips fried under vacuum were superior to those fried under atmospheric pressure.

Another advantage of vacuum frying is the reduction of acrylamide formation during frying of starch reach products such as potato chips. Granda et. al. (2005) showed that potatoes fried under vacuum had 94% less acrylamide content compared to those fried under atmospheric conditions.

Sweet potato (*Ipomoea batatas L.*) is an important food crop around the world (Wu et al., 2008). Orange-fleshed cultivars are recognized as healthy foods because of their significant content of β-carotene, phenolic acids, anthocyanin, and dietary fiber

(Turner and Burri, 2001). The crop is widely cooked by deep frying and consumed in forms of French fries and chips (Farinu, 2007).

In this study, a two-stage frying process was used to improve the flavor and texture of sweet potato chips. First, a basket filled with the sweet potato slices is submerged into the oil under atmospheric conditions. As soon as the potato slices are partially cooked, the fryer is evacuated (1.33 kPa) for vacuum frying. It is believed that the starch will gelatinize under atmospheric conditions, thus resulting in a better product in terms of flavor and texture.

Hypothesis:

In vacuum frying, the temperature of the chips does not reach the gelatinization temperature until most of the water is evaporated. Therefore, there is not sufficient moisture content in the product for gelatinization to occur completely. As a result, the product has a glassy texture. In the two-stage frying, the atmospheric frying prior to vacuum frying helps the starch to gelatinize. Thus, we will be able to produce a better product in terms of texture, oil content, and flavor.

The following objectives were used to examine the hypothesis.

Objectives:

1. Quantify the kinetics of quality changes such as moisture content, oil content, texture, diameter shrinkage and thickness expansion of sweet potato chips at different frying temperatures (120, 130, and 140°C) under vacuum conditions.

2. Measure the temperature of the chips (surface and center), pressure, and the frying environment during frying.

3. Determine the degree of starch gelatinization, and evaluate the microstructure for the single-stage (vacuum) fried (130°C) and two-stage fried sweet potato chips (130°C).

4. Evaluate the panelists' preference by sensory tests.

CHAPTER II

LITERATURE REVIEW

2.1. Sweet Potato

Sweet potato (*Ipomea batata L.*) is a dicotyledonous plant that has irregularly shaped oblong tubers. The most suitable temperature for its growth is around 75°F. The varieties of sweet potato change from dark orange flesh to light-colored flesh. Dark orange ones contain more beta carotene than those with light-colored ones.

Sweet potatoes are very valuable due to their nutritional content. Besides containing starch, they are rich in fiber, beta carotene, vitamin C, vitamin B6, copper, potassium, and manganese. Fried sweet potato chips are commonly consumed in Asia and the tropics.

2.2. Potato and Sweet Potato Chips

The usage of processed potatoes by percentage is table stock (26%), French fries (32%), shoestrings (12%), and dehydrated products (10%) (USDA-NAAS, 2009). Frito-Lay dominates the world market for potato chips manufacturing and uses over 3.5 million tons of the raw potato. Including the pre-formed potato chips i.e. Baked Lays®, the company's potato usage increased to 4 million tons, almost half of the world total (Vreugdenhil et. al., 2007) in 2006.

The thickness of potato chips is generally 1.27-1.78 mm and the moisture is reduced from 75-80% to 1-2% in w.b. (Miranda and Aguilera, 2006). The shelf life of potato chips depends on packaging material, storage temperature, and light exposure

(Lusas et. al., 2001). We can group potato chips as regular potato chips and processed potato chips. Regular potato chips are made from fresh potatoes, while processed potato chips are made from potato flakes which are used in baked chips.

Fried sweet potato chips are a common snack in the tropics and Asia and its consumption is on the increase in the USA. When fried, sweet potatoes undergo physicochemical changes, which affect its structural, textural, and optical properties (Moreira et al, 1999). Characterization of product quality attributes of sweet potato chips during frying will provide critical information that can be used to develop fundamental models to describe their structural changes during frying.

Odeningbo et al. (2012) evaluated quality changes during deep fat frying of five cultivars of sweet potato 'Ginseng Red', 'Beauregard', 'White Travis', 'Georgia Jet clone #2010' and 'Georgia Jet'. Samples were peeled, sliced into cylindrical shape and deep fried in canola oil at 180°C for 5 min. 'Ginseng Red' was identified as a suitable cultivar for French fries production because of its lowest oil saturation, good color, and textural properties development during frying.

Akpapunam and Abiante (1991) showed that sweet potato slices blanched in water and 1% sodium metabisulfite solution, respectively, prior to the dehydration (at 70°C for 165 min) and frying (at 190°C for 2 min) significantly improved the color and general acceptability of the chips compared to those immersed in water, only.

Brigatto-Fontes et al. (2011) found that sweet potato slices fried at 160°C in palm olein for 3.5 minutes produced the best quality chips in terms of smell, color, flavor, and texture; the final moisture content was 7.4% w.b and oil content 14.5% w.b. The samples

fried in palm stearin had the same quality characteristics than those fried in palm olein, but they were fried at 180°C, which presented moisture content and an oil content of 3.5% w.b. and 13.1% w.b, respectively.

Onigbogi et al. (2011) fried sweet potato slices in ground nut and melon seed oils and observed that chips fried with fresh melon seed was better appreciated when compared to sweet potato chips fried with ground nut oil. The color of sweet potato chip fried with second frying oil and the sweet potato chips fried with the fourth frying oil were significantly better than the other samples. The taste of sweet potato chips fried with the fourth groundnut oil was significantly better than the other samples. The crispiness of sweet potato chips fried with fresh melon seed oil and the one fried with the fourth frying oil was more acceptable than the remaining samples (P<0.05). The result obtained revealed that melon seed oil degraded the most compared to the other oils.

Taiwo and Baik (2007) studied the effects of various pre-treatments (blanching, freezing, air drying, osmotic dehydration and control) on the shrinkage and textural properties of fried sweet potatoes. Sweet potato discs were pre-treated and fried in canola oil at 170°C for 0.5–5 min, respectively. Bulk density of the fried samples decreased while porosity increased with frying time. Effect of pre-treatment was not significant on bulk density, but on product porosity. Control samples exhibited less shrinkage than the pre-treated samples. Maximum change in diameter of samples ranged between 6.7% and 10.2% depending on pre-treatment used. Maximum change in sample thickness was observed by 120 s of frying and the highest value was 18.3%. Pre-treated samples had higher difference in thickness compared to the control samples. Change in

sample volume increased with frying time reaching a maximum at 120 s after which it either decreased or leveled off. Generally, the pre-treatment improved the textural properties of fried samples in terms of hardness, springiness, chewiness, cohesiveness and, adhesiveness.

2.3. Deep-fat Frying

Deep-fat frying is a drying and cooking process of a food by contact with hot oil (Moreira et al., 1999). Frying is one of the oldest unit operations used for food preparation. Deep-fat frying is preferred in the processing of many food products because of the unique flavor-texture combination given to the product (Varela, 1988). Frying can be defined as cooking of a product by immersion in oil or fat at a temperature, which is more than the boiling point of water (Hubbard et. al., 1999). Deep-fat frying causes some changes such as starch gelatinization, crust formation, color development, protein denaturation, and Maillard reactions.

Deep-fat frying can be processed under vacuum (low pressure), high pressure, and atmospheric pressure (Moreira et al. 1999). Under atmospheric conditions, the temperature of the oil generally ranges between $160^{o}C$ and $200^{o}C$ (Moreira et. al., 1999). The high temperature above the boiling point of water results in the evaporation of water from the food through the surrounding oil. Oil replaces part of the water that evaporates during the process.

High pressure fryers are mainly preferred in frying chicken with bones because of the uniform color distribution and higher moisture content of the final product (Bouchon, 2009). Vacuum frying recently attracted the attention of industry by giving an

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opportunity to produce fruit and vegetable snacks with low oil content, desired texture, and flavor (Garayo and Moreira, 2002).

During frying, heat is transferred from the surrounding oil to the product surface by convection and from the surface of the product to the center of the product by conduction. The frying process can be accomplished by four stages: initial heating, surface boiling, falling rate, and the bubble end-point (Farkas et. al., 1994). The initial heating takes place for a few seconds. Natural convection occurs between the food and the oil. A crust formation start in the surface boiling stage and heat transfer occurs by forced convection because of the turbulence in the oil. The internal core (crumb) temperature reaches to the boiling point temperature in the falling rate stage and starch gelatinized in the crumb. When the process reaches to the bubble end-point, no bubbles occur at the surface of the product.

2.4. Vacuum Frying

Vacuum frying is a promising method for preserving the desired color, texture, and flavor of products with high sugar content. Since most vegetables and fruits degrade when processed with traditional frying, vacuum frying is an excellent alternative to high temperature processing.

Vacuum frying is applied at pressures below atmospheric pressures, preferably below 6.65 kPa. Low pressure causes a reduction in the boiling points of the water in the product (Garayo and Moreira, 2002). Vacuum frying also result is less oil degradation and less oxidation of the volatile compounds such as color, flavor, and vitamins (Shyu et. al., 1998).

Garayo and Moreira (2002) studied the effect of vacuum frying on the potato chip's oil content, color, and texture. They observed that vacuum fried potato chips had 30% less oil content compared with traditionally fried potato chips. Light yellow color and brittle texture were observed in potato chips fried under vacuum conditions. Apple slices (Shyu and Hwang, 2001) and carrot chips (Dueik et al., 2010) fried under vacuum also had less oil content than the samples fried at atmospheric conditions.

Acrylamide is considered as probably carcinogenic to humans by the International Agency for Research on Cancer. It is widely found in starch-rich foods processed at high temperatures. It is also accepted that acrylamide formation occurs as a by-product of Maillard reaction (Stadler et. al., 2002). Acrylamide content of potato chips fried under vacuum had 97% less acrylamide content than traditionally fried chips (Granda et al., 2004).

Da Silva and Moreira (2008) studied quality attributes of some fruits and vegetables such as mango chips, blue potato chips, and green beans fried under vacuum conditions. The vacuum fried products maintain more of their natural taste and color because of the application of lower temperatures and lower oxygen content of the atmospheric conditions during frying. Sensory panelists preferred vacuum fried products to conventionally fried snacks due to their natural color. The traditionally fried products looked over-cooked and had a scorched flavor.

Fan et. al. (2006) investigated the effect of several pre-treatments on the quality of vacuum fried carrot chips. Water content, oil content, and water activity of fried carrots were changed by pre-treatments such as blanching, blanching and air drying,

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blanching and osmotic dehydration, followed by freezing. However, there were no significant differences in the texture for the carrot chips.

2.5. Cooling and De-oiling Process

Most of the oil is absorbed into the porous crust region when a fried product is removed from the oil. Capillary forces are the main driving forces for the post-frying cooling oil absorption (Moreira et. al., 1999). Tortilla chips were studied to determine the oil distribution during frying and after cooling by Moreira et. al. (1997). Only 20% of the oil was absorbed by the chips, and the remaining (80%) was on the surface of the chips. In the cooling period, 64% of the total oil was absorbed, and the remaining (36%) was on the surface of the chips. As a result, it can be concluded that the cooling period is an important period, which determines the final oil content of a fried product.

When the fried product is removed from the oil, the majority of the oil stays on the surface. The surface oil is absorbed by the product during cooling until the equilibrium temperature (Moreira et. al., 1999). Therefore, it is necessary to use a de-oiling system (e.g., centrifuge) to remove the excess oil from the surface of the fried product before cooling. Since the centrifugal force acts perpendicularly to the surface of the product, the oil can be separated from the porous surface (Pandey, 2009) easily.

2.6. Product Quality Attributes

2.6.1. Oil Content

Oil content is an important quality parameter for fried foods. Potato chips are high in oil content, which is in the range of 33-38% (Moreira et. al., 1999). Oil has two roles during frying, it transfers heat to the product and provides mouth feel (texture and

taste) to the fried food (Cella et. al., 2002). Frying temperature and time, initial moisture content, pore size distribution, porosity, the geometry of the product, and pre and post-treatments are some parameters which can affect the final oil content of fried product (Saguy et. al., 1995; Moreira et. al., 1997; Bouchon and Aguilera, 2001).

Surface properties of the potatoes are the most important factor in oil absorption. Therefore, a proper coating can reduce oil absorption of a fried product (Mellema et. al., 2003). The coating technique, which is done before frying, reduces porosity and oil uptake in the product. The relationship between oil and food surface is complex due to the movement of water vapor. Water bubbles create turbulence during frying and it affects heat transfer coefficient (Singh, 1995).

Capillary forces are described as a mechanism, which play an important role in oil absorption phenomena (Moreira and Barrufet, 1998). Kawas (2000) showed that tortilla chips with small pore sizes have higher internal oil due to higher capillary forces during the cooling period.

The final oil content of potato chips can be divided into two groups: internal oil content and surface oil content. Moreira et al. (1997) observed that 80% of the total oil content is surface oil and 20% of the total oil content is internal oil content in tortilla chips. Moreira et al. (2009) proposed that surface oil content of a product at the pressurization step (during vacuum frying) has a big impact on the final oil content. Thus, a de-oiling process should be applied to remove surface oil as soon as the product is removed from the oil, before the pressurization step.

Moreira et. al. (2009) recognized that only 14% of the total oil content (TOC) is internal oil (IOC) while 86% is surface oil content (SOC) in fried potato chips. Almost 34% of the IOC and 0.7% of the SOC are absorbed during the first 20 s of frying operation. The bulk density and porosity values for the centrifuged (surface oil removed) chips were 564 kg/m^3 and 0.6, respectively, while these values were 800 kg/m^3 and 0.36 for the non-centrifuged ones (surface oil not removed).

Moreira et. al. (1998) also worked on the mechanism of oil absorption of tortilla chips. Their study showed that higher initial moisture content, smaller radius, higher interfacial tension, and lower cooling air resulted higher oil content in tortilla chips.

Monte Carlo simulation was used to model structural changes of tortilla chips during frying by Rajkumar et. al. (2003). Maximum oil absorption was predicted during the first 10 s of frying in a control tortilla chips by the model. Steam baked tortillas had a tight and rigid barrier on their surface because of starch gelatinization. Since the surface prevented water evaporation, less oil absorbed during frying.

2.6.2. True Density

True density can be defined as the weight of a material per unit of true volume (kg/m^3). True volume includes the volume of liquids in the material (Kawas, 2000). Gas pycnometer is generally used in the determination of the true density of materials. Most of the time helium is used as a gas to penetrate all open pores.

2.6.3. Bulk Density

Bulk density is the weight of a material per unit of bulk volume (kg/m^3). Bulk density does not include only the volume of liquids and solid, but also it includes the

volume of the air within the sample. It is very difficult to calculate the bulk volume for a food material because of its irregular shape in size (Kawas, 2000). Volumetric displacement of glass beads can be used to measure of the bulk volume of materials (Marousis et. al., 1990). Liquid displacement can be done with toluene (Costa et. al., 2001; Lozano et. al., 1983) or a mixture of water-ethanol (Da Silva et. al., 2008).

2.6.4. Porosity

Porosity is one of the important quality parameters for potato chips. It can be defined as a ratio of the volume fraction of total pores to the total volume of a product (Rahman, 1995).

During pre-treatment, applications changes happen in the cell membranes. Those changes in the tissues have an important role during unit operations (Bouwkamp, 1985; Taiwo et. al., 2001). The study of Taiwo and Baik (2007) showed that pre-treatments had a significant role on porosity of fried products. The porosity of air-dried and blanched sweet potato chips was much lower than the freeze-dried and osmotic dehydrated ones.

When a food product is fried, its textural and structural properties are affected by physico-chemical changes occurred in the product (Krokida et. al., 2000; Baik et. al., 2003). Shrinkage or puffing can occur in the fried products due to the changes in the porous structure of the products (Krokida et. al., 2001). The porosity of vacuum fried chips was evaluated to understand the effect of centrifuging on porosity value by Moreira et. al. (2009). Non-centrifuged potato chips showed less porosity than the centrifuged ones.

2.6.5. Diameter Shrinkage and Thickness Expansion

During frying of a food, diameter shrinkage and thickness expansion occur in the product. It means that the dimension of the changes during drying.

Mittelman et. al. (1984) understood that potato crust starts to occur when the potatoes were submerged into the hot oil. Water is uniformly evaporated from the surface of the potato slice during the first stage of frying. The crust of the potato chips becomes thicker as frying proceeds. Therefore, the crust reduces the evaporation rate of water vapor. Volume change rate is greater for processing at higher temperatures compared to processing at lower temperatures. However, the final volume shrinkage gives the highest value for potato chips fried at lower temperatures. The reason is that higher temperature makes the surface rigid faster, thus the resistance to volume change increases (Caixeta et. al., 2002) during the process.

Garayo and Moreira (2002) compared the shrinkage of vacuum fried and traditionally fried potato chips. They observed that when oil temperature increases the shrinkage of potato chips decrease due to the rapid formation of crust at higher temperatures. They realized that vacuum fried chips have numerous small bubbles and less expansion compared to atmospheric fried chips, which have less amount larger bubbles and more expansion. The reason of the formation of bubbles within the chips is gas expansion inside the pores. Kawas et. al. (2001) also measured the degree of shrinkage and expansion of tortilla chips. Tortilla chips fried at 190°C showed more shrinkage than tortilla chips fried at 160°C. Moreira et. al. (2009) did not observe any

significant differences (P<0.05) in the diameter of centrifuged and non-centrifuged potato chips.

Diameter shrinkage and thickness of sweet potato chips were studied by Taiwo et. al. (2007). They observed that sweet potato chips shrink in the radial direction whereas they expand in the axial direction.

2.6.6. Texture

Texture is a very important quality attribute for foods since it has a dominant impact on acceptability and the quality of the product (Kayacier et. al., 2003). The structural properties of food can be defined as texture (Aguilera and Stanley, 1990). Generally, it is described as a multiparameter attribute, which is related to mechanical, geometrical, and acoustic parameters (Szczesniak, 1963).

It can be evaluated by instrumental analysis and sensory evaluation (Steffe, 1996). The determination of texture by instrumental analysis is easier, more accurate, and less time consuming (Kayacier et. al., 2003). Hardness can be identified from a texture profile curve. Additionally, it can be defined as the force at maximum compression during the first bite. Soft, firm, and hard words can be used to describe hardness (Steffe, 1996). Most of the time, the Texture Analyzer (Texture Technologies Corp., New York) has been used in the determination of the texture properties of fried food material. Moreira et. al. (1997) and Kawas (2000) used the Texture Analyzer compression test to measure the texture of tortilla chips. Garayo (2001) applied a rupture test on potato chips by using the same approach used by Kawas (2000), who determined the hardness of the chips by obtaining the maximum force at compression (Steffe, 1996).

Texture development was divided into two stages in fried potato slices by Pedreschi et al. (2004). First the tissues soften; and then crust formation occurs and hardens as a function of time.

2.7. Starch Gelatinization and Glass Transition Temperature

Starch plays a key role in textural formation via gelatinization, which occurs in the presence of enough water (Thomas and Atwell, 1999). Starch is the main component of potato dry matter. Sensory properties and shelf life of potato products depend on the molecular interactions of starch with non-starch polysaccharides (Lisinska et. al., 1989). Understanding of starch gelatinization is important to optimize processing conditions.

There are several methods for measuring the starch gelatinization depending on the different properties. For example: thermal properties measured using DSC (differential scanning calorimeter) (Mechteldis et. al., 1992); loss of birefringence (Liu et. al., 1991); and changes in optical properties (Huang et. al., 1990). Morales-Sanchez et. al. (2009) developed a method to find the starch gelatinization temperature by using electrical conductivity techniques.

The effect of degree of starch gelatinization on the quality attributes of tortilla chips was studied by Kawas et al. (2001). Freeze-dried (5% of starch gelatinized) and steamed-baked (87% of starch gelatinized) tortilla chips were prepared before frying and their qualities were compared with control chips (45% of starch gelatinized). They found that the degree of starch gelatinization affected the final oil content and the oil distribution. Steam-baked chips had very low oil content compared to others. The reason is larger pores occurred in the structure of steam-baked chips. Freeze-dried chips did not

undergo starch gelatinization process prior to fry. Large number of small pores was observed in the structure of freeze-dried tortilla chips, resulting in high oil absorption occurred during frying and cooling.

Glass transition temperature (Tg) can be considered as the temperature at which an amorphous mechanism undergoes from glassy state to rubbery state. It can be useful to define food behavior and stability. It may be helpful in understanding textural formation during unit operations. Tg depends on crystallinity degree, moisture content, and temperature changes during processing.

A crispy texture is an important property for snack foods (Katz et. al., 1981). Nelson and Labuza (1993) highlighted that cereals have a crispy texture in the glassy state; however, they may lose their crispy texture in the rubbery state due to plasticization.

Kasahara et. al. (2002) determined the glass transition temperature (Tg) of French fried potatoes pre-treated in soaking solutions. They found that the Tg value was higher at the crust than in the center (crumb) of the product.

The dynamic mechanical thermal analysis (DMTA) was used to determine the Tg of baked tortilla chips by Kayacier et. al. (2002). Their study showed that the Tg increased depending on the baking temperature and time.

The Tg of starch having different amylose/amylopectin ratios was studied by a high-speed DSC (Liu et. al., 2010). They proved that the higher the amylose content `in starch the higher the Tg.

There are few studies available in the literature regarding the effect of processing variables on the quality attributes of fried sweet potatoes. The goal of this work is to improve an understanding of two-stage frying on the quality of sweet potato chips in terms of texture, color, oil content, and flavor.

CHAPTER III

MATERIALS AND METHODS

3.1. Raw material

Sweet potatoes (*Ipomea batata L.*), were provided from the same supplier at College Station, Texas. They were stored in an environmental chamber at 10^oC and 95% relative humidity. Before frying, the potatoes were kept for 3-4 days at room temperature to allow reconditioning. The variety Beauregard, a popular variety characterized by a pale reddish skin with dark orange flesh, was used in this study.

3.2. Sample preparation

Potatoes were washed, peeled, and then sliced using a mandolin slicer (Mafter model 2000, France). The thickness of a slice was 1.6 ± 0.01 mm and measured with a thickness gage (Mitutoyo Thickness Gage, Japan). A cylindrical metal cutter was used to cut a diameter of 5.08 ± 0.01 cm. The slices were rinsed in water to remove starch from the surface of slices and then blotted with paper towel before frying.

3.3. Frying Experiments

3.3.1. Vacuum frying experiments

The experiments were done by using a vacuum fryer located at the Food Engineering Laboratory, Texas A&M University, in College Station, Texas. The fryer is an aluminum vessel with a capacity of 5 liters of oil. The fryer has a basket to place the potato slices and a centrifuging mechanism to de-oil the product before the pressurization step. Figure 3-1 shows the vacuum frying system.

The vacuum fryer is a cast aluminum vessel which includes a heating element, a basket, and a centrifuging system (de-oiling unit). Six potato slices were loaded into the basket, the lid was closed, and then the vessel was depressurized. The basket was submerged into the oil when the pressure reached 1.33 kPa. After completing the frying, the basket was raised and the centrifuging (de-oiling mechanism) was applied for 40 s at 750 rpm. After that, the fryer vessel was pressurized. The fried slices were allowed to cool down at ambient temperature ($23.0\pm0.1°C$) before storing inside of desiccators for further experiments. Canola oil was used as a heating medium. Three different oil temperatures (120, 130, and 140°C) were used for 10, 20, 30, 40, 60, 80, 100, 120, 140 s frying times. The test was performed in triplicate.

3.3.2. Two- stage frying experiments

In this study, a two-stage frying process was used to improve the appearance and texture of sweet potato chips. Both atmospheric and vacuum frying was done in the vacuum frying equipment. First, a basket filled with sweet potato slices was submerged into the oil under atmospheric conditions (1st-stage). As soon as the potato slices were partially cooked (1 min), the pressure was lowered to1.33 kPa (vacuum frying stage) and the product fried for 2 more minutes. The products were fried at 130°C for different interval of times. After the frying was completed, the basket was raised and the slices were centrifuged for 40 s at 750 rpm. The vessel was pressurized after centrifuging. Fried potato slices were allowed to cool down at ambient temperature. Canola oil was used as a heating medium. The test was performed in triplicate.
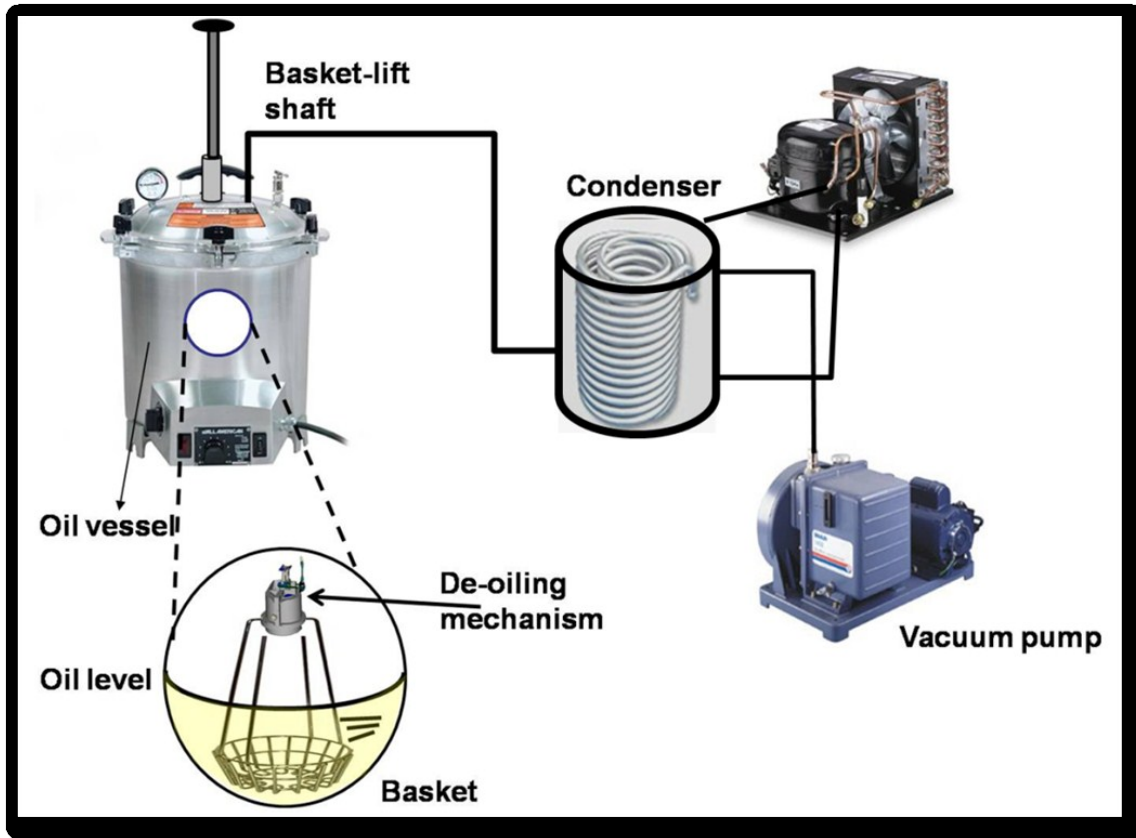
Figure 3-1. Schematic drawing of the vacuum frying system (Moreira (2008)).

3.3.3. Data collecting mechanism

Center and surface temperatures of the sweet potato chips, temperature of the headspace of the vessel, and pressure inside vessel were measured. A data collecting system (Model OMB DAQ 54 Omega Engineering Inc., Stamford, CT, USA) was used to record the changes of temperature and pressure during vacuum frying process. A pressure transducer (Model PX209-015G5V, Omega Engineering Inc., Stamford, CT, USA) was replaced inside of the vacuum fryer vessel. The data for temperature and

pressure as voltage through type-K thermocouples (Model KMQXL, Omega Engineering Inc., Stamford, CT, USA) was collected by a controller.

3.3.4. Experimental design

Two different sets of experiments were designed to test the effect of different frying temperature of the two processes – single-stage and double-stage on the quality sweet potato chips. The whole experimental design had 2 factors, where in experiments #1 to 3, factor 1 had 3 levels and factor 2 had 10 levels. For the experiment # 4, factor 1 had 2 levels (atmospheric frying and vacuum frying) and factor 2 had 1 and 6 level(s), respectively. The whole experiment was set one factor at a time. The actual design and levels for the factors are shown in Table 3-1.

Table 3-1. Experimental design for each set of experiments.

SET #	Experiment #	Factor 1 Oil Temperature [C]	Factor 2 Frying Time [s]
1	1	120	0 10 20 30 40 60 80 100 120 140
	2	130	0 10 20 30 40 60 80 100 120 140
	3	140	0 10 20 30 40 60 80 100 120 140
2	4	130	60*& 30 60*& 60 60*& 90 60*&120

*atmospheric frying for 60 s before vacuum frying

3.4. Product quality attributes (PQA)

3.4.1. Moisture content

The moisture content (MC) of sweet potato was determined by weight loss after drying 3 g of the samples in a vacuum oven for 6 hours at 70°C (method 930.04 AOAC, 1990). Three replications were done. The weight of the sample was recorded before and after drying. MC was calculated in wet basis and dry basis. The moisture content in wet basis (w.b.) was calculated as:

$$MC[w.b.] = \frac{M_{wet} - M_{dry}}{M_{wet}} \qquad [3.1]$$

where M_{wet} (g) is weight of the wet sample and M_{dry} (g) is weight of the dry sample. The moisture content in dry basis (d.b.) will be defined as:

$$MC[d.b.] = \frac{M_{wet} - M_{dry}}{M_{dry}} \qquad [3.2]$$

3.4.2. Oil content

The Soxtec System HT extraction unit (Pertorp, Inc., Silver Spring, MD, USA) with petroleum ether as the solvent (AACC 1986) was used for the determination of oil content. Dried samples (around 3 g) were ground with a grinder. The ground samples were placed on cellulose thimbles (model 2800256, Whatman, England). The cups were put into a convection oven for 15 min and then a desiccator for 20 min to allow cooling down. After that, the weight of the empty cups was recorded. First, the thimbles including the dry sample were submerged in the cups into the boiling petroleum ether (40 min). After that, the thimbles were washed with petroleum ether. Then last, the petroleum ether was evaporated from the oil. To be sure that all the petroleum ether was

evaporated from the oil, the cups were put into a convection oven (15 min at 105°C) and then in a desiccator for 20 min. The oil content (OC) of each sample in dry basis was calculated as:

$$OC[d.b.] = \frac{W_2 - W_1}{W_i}$$
[3.3]

where W_2 (g) is the final weight of cup and W_1 (g) is the initial weight of cup; and W_i (g) is the dried weight of sample i.

Internal, surface, and total oil content of chips were determined. Total oil content (TOC) was quantified as the oil content of the potato chips after frying without application of de-oiling; internal oil content (IOC) was quantified as the oil content of the potato chips after the de-oiling process; and surface oil content (SOC) was quantified as the oil content of the surface of the potato chips which was determined by subtracting the IOC from TOC. Three replications were done for oil content analysis.

3.4.3. Bulk density

The liquid displacement method with ethanol was used for measuring the bulk volume. Five potato chips were weighed, and then the volume was read with and without the sample. The bulk density (P_b) (kg/m^3) of samples was calculated by:

$$\rho_b = \frac{M_s}{V_b}$$
[3.4]

where M_s (g) is the weight of the de-oiled sample; V_b (m^3) is the bulk volume of the sample. Three replications were performed.

3.4.4. True density

The true volume is the volume which is occupied by water and solid matter. Around 1 g ground raw and fried samples (de-oiled) were used in the determination of the true volume. A compressed helium gas multi-pycnometer (Quantachrome & Trade, NY, USA) was used.

The solid volume (V_t) was determined by:

$$V_t = V_c - V_r \times \left(\frac{P_1}{P_2} - 1 \right)$$ [3.5]

where V_r (m^3) is the volume of the reference; V_c (m^3) is the volume of the cell; P_1 (Pa) is the initial pressure; and P_2 (Pa) is the final pressure.

The true density (ρ_t) in kg/m^3 was calculated by:

$$\rho_t = \frac{M_s}{V_t}$$ [3.6]

where M_s (g) is the weight of the de-oiled sample; V_t (m^3) is the true volume of the sample.

3.4.5. Porosity

Porosity was calculated by:

$$\phi = 1 - \frac{\rho_b}{\rho_t}$$ [3.7]

where ρ_b (kg/m^3) is bulk density of potato chips whereas ρ_t (kg/m^3) is true density of potato chips.

3.4.6. Diameter shrinkage and thickness expansion

A steel caliper (MG Tool Co., New York, NY, USA) was used for measuring the diameter and thickness of potato chips. Four slices and four reading were taken for each treatment. The degree of diameter shrinkage (D) was calculated by:

$$D[\%] = \left(\frac{d_o - d_t}{d_o}\right) \times 100 \qquad\qquad [3.8]$$

where d_o (m) is the initial diameter of the raw slice; d_t (m) is the diameter of fried slice for t time.

The degree of thickness expansion (L) will be calculated by:

$$L[\%] = \left(\frac{l_o - l_t}{l_o}\right) \times 100 \qquad\qquad [3.9]$$

where l_o (m) is the initial thickness of the raw slice; l_t (m) is the thickness of fried slice for t time.

3.4.7. Hardness

A rupture test was applied to determine the texture of potato chips. The TA-XT2 Texture Analyzer (Texture Technologies Corporation, Scardale, NY) was used for that experiment. A sweet potato chip was placed on an 18 mm hollow cylinder. A ball probe with a diameter of 0.254 cm was used to break the chips. The highest peak on the force x time curve was assumed as a hardness value. The speed of the probe was 0.1 mm/s. The probe passed 4 mm after the chip broke. Twenty potato chips fried at different temperatures (120, 130, and 140°C) were tested each time.

3.4.8. Degree of starch gelatinization

A Differential Scanning Calorimeter (DSC 6 – Perkin Elmer) was used to obtain the enthalpy difference of the samples.

Raw sweet potatoes (control) were washed, peeled, and fine grated. The grated sweet potato was allowed to dry for 24 h at 45°C on a convection oven. All samples, fried and control, were powdered using a mortar to 60 meshes.

About 4 mg of samples was placed into aluminum DSC pans (Model 219-0062, Perkin Elmer), and distilled water was added to give a water to sample ratio of 4:1 (Kawas and Moreira, 2001). The dry weight of the sample in each pan was determined by puncturing it after scanning and then drying it at 70°C/6 hours on a vacuum oven. The samples were scanned from 35°C to 90°C at a heating rate of 10°C/min, a cooling rate of 40°C/min, and a DSC operating range of 20 mW. The degree of gelatinization was calculated using the following equation:

$$DG[\%] = \left(\frac{\Delta H_{control} - \Delta H_{fried}}{\Delta H_{control}} \right) \times 100 \qquad \textbf{[3.10]}$$

3.4.9. Sensory test

The chips were presented to 50 individuals (randomly selected faculty, students, and staff at Texas A&M University). Panelists were asked to score the samples in terms of odor, color, texture, flavor, and overall quality. Using a nine-hedonic scale where a score of 1 represents 'dislike extremely' and a score of 9 represents 'like extremely'. Scores higher or equal to 5 were considered acceptable. Only vacuum fried and two-

stage fried potato chips were evaluated. The samples were served to each panelist in a white plate. The containers were coded with a random number to identify each sweet potato chip.

3.5. Statistical analysis

The data were analyzed using SPSS software (version 20 for Windows, 2011). Different treatments (single-stage and two-stage fried sweet potatoes) were evaluated. Differences between variables (product quality attributes and sensory evaluation) were tested for significance ($p < 0.05$) by Chi-Square statistics and analysis of variance (ANOVA).

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Temperature and pressure history during vacuum frying process of sweet potato chips

Figures 4-1, 4-2a, and 4-3 show the temperature history at the center of the sweet potato chip (PC), surface of the chip, and the headspace (HS), as well as the pressure changes (P) during vacuum frying at three different temperatures (120, 130, and 140°C).

There are four periods during vacuum frying such as depressurization (DP), frying (FR), pressurization (PR), and cooling (CL). The sweet potato slices were placed into the basket, the closed, and the vessel evacuated to 1.33 kPa during the depressurization period which takes around 110 seconds. The second step is frying, which takes place for 6 minutes at 120, 130, and 140°C oil temperatures. During the frying period, heat is transferred from the oil to the surface of the product by convection and then from the surface to the center of the slice by conduction. Moisture evaporated and oil absorbed by the sweet potato slice. The last step, the pressurization, consists of holding the chips in the headspace of the frying vessel until the system recover to atmospheric pressure after the vacuum is broken. After the recovery, the basket is removed from the frying vessel and waited for cool down to the ambient temperature. During cooling, the pressure changes inside the pores of the sweet potato chips. The

changes in the pressure create a driving force for the absorption of the surface oil into the pores.

4.1.1. Temperature history at the center of the chip (PC)

The thermocouple (0.254 mm diameter) was attached into the center of a sweet potato slice (2.60 mm thicker) to measure the temperature history during vacuum frying process at 120, 130, and 140°C (Figures 4-1, 4-2a, and 4-3).

The center temperature of the chip for all three oil temperatures had a sudden increase and decrease during the depressurization step (DP). The temperature at the center of the chip increased during the first 80s because of the heat irradiating from the oil at the headspace (~80°C) of the vacuum frying vessel.

During the frying period, the temperature at the center of the chip increased to ~ 70-80°C, reaching a plateau which is known as the evaporation period. The time to reach the equilibrium temperature was longer for the lower oil temperature (120°C). An interesting finding was that the evaporation temperature of water was between 70 and 80°C depending on the frying temperature (Figure 4-2b). This evaporation temperature is well above the water evaporation temperature at the system pressure of 1.33 kPa (11.2°C). This behavior was also noted by Pandey (2009). It is believed that the high evaporation temperature is related to a difference in pressure between the system and the center of the potato chip, in which the pressure should be higher than 1.33 kPa in order for water to evaporate at those temperatures. For the remaining time of immersion in oil, the temperature at the center of the chip increased until it reached equilibrium with the frying medium; this period was also longer for the lower frying temperatures.

The center temperature of the chip started to decrease to ambient temperature during pressurization (PR) and cooling (CL). During pressurization, the temperature decline was slower due to high headspace temperature. During cooling, the center of the chip decreased fast and reached the room temperature in about 200 s.

4.1.2. Temperature history at the surface of the chip (PS)

Figures 4-1, 4-2a, and 4-3 show the temperature history at the surface of the chip for all frying temperatures (120, 130, and 140°C). It was very important to pay attention the position of the thermocouple not to measure the oil temperature instead of the surface temperature of the chip.

The surface temperature history shows very similar behavior to the center temperature history. The surface temperature of the chip was rapidly increased to ~100°C after submerging into the oil. After that, the temperature increased slowly until reaching the same temperature to the oil temperature (120, 130, and 140°C). Since the surface was in contacted with the oil directly, the surface temperature reached the plateau faster than the center temperature. Thus, water in the surface of the chip decreased faster than water in the core of the sweet potato chip. The temperatures of surface and center of the chip showed very similar behavior during pressurization (PR) and cooling (CL) periods. However, the surface temperature decreased faster than the temperature at the center of the chip.

4.1.3. Temperature history at the headspace of vacuum fryer (HS)

The headspace temperature had an effect on the temperature histories of the center and the surface of the sweet potato chips (Figures 4-1, 4-2a, and 4-3).

The thermocouple measured the ambient temperatures until the lid was placed on the top of the vessel. The temperature increased rapidly to ~60°C due to the radiating heat from the oil after the lid was closed tightly. In the depressurization period, the headspace temperature was constant at around 50°C. After submerging the basket into the oil, the headspace temperature increased up to 75, 78, and 80°C for 120, 130, and 140°C oil temperatures, respectively, due to the evaporation of the water from chips to the headspace. The headspace temperature remained almost constant until the basked was lifted from the oil. Then, the headspace temperature increased to 102, 108, and 116°C for 120, 130, and 140°C, respectively. During the first 100s of the pressurization step, the temperature decreased to about 90°C, which stayed constant until the lid was removed.

4.1.4. Pressure history inside the vacuum fryer (P)

Figures 4-1, 4-2a, and 4-3 show the pressure history inside the vessel at different frying temperatures. It is essential to record the pressure history during vacuum frying to understand the mechanism of oil absorption and show the frying conditions inside the vacuum fryer.

The basket filled with the sweet potato slices was submerged into the oil when the desired pressure was achieved inside the vessel. The pressure was lowered from 96.5±0.22 kPa to 2.29±0.002 kPa. The pressure increased after submerging of the slices due to the water evaporation from the slice to the headspace of the vessel. The pressure inside the fryer returned to the lowest values thanks to the vacuum pump. After vacuum

was broken, the pressure inside the vessel recovered to the ambient pressures during the

pressurization period.
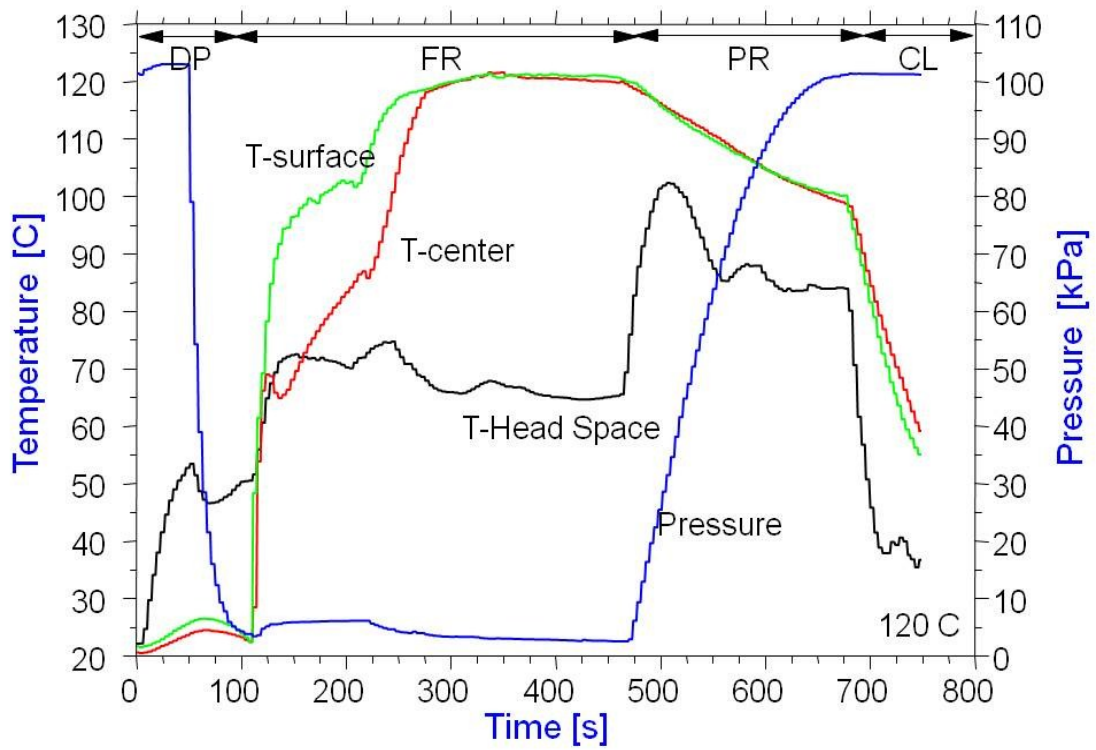
Figure 4-1. Temperature history at the center of the sweet potato chip (PC), at the surface of the chip, and of the headspace (HS), as well as the pressure changes (P) during vacuum frying at 120°C.
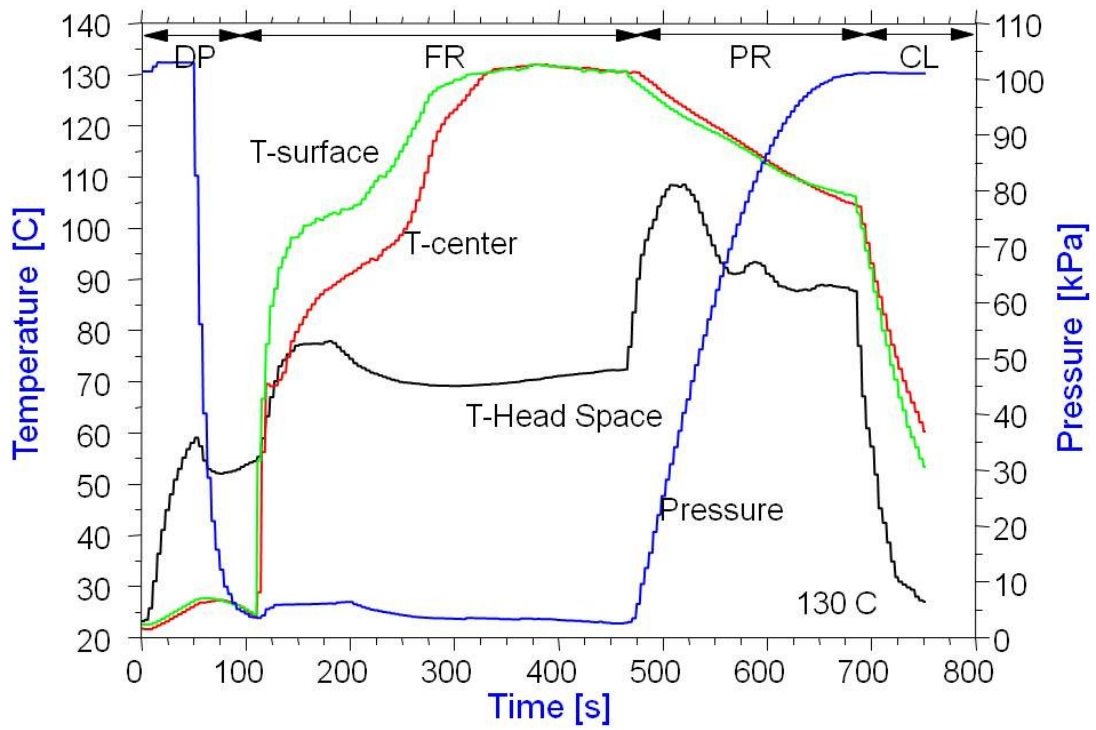
Figure 4-2a. Temperature history at the center of the sweet potato chip (PC), at the surface of the chip, and of the headspace (HS), as well as the pressure changes (P) during vacuum frying at 130°C.
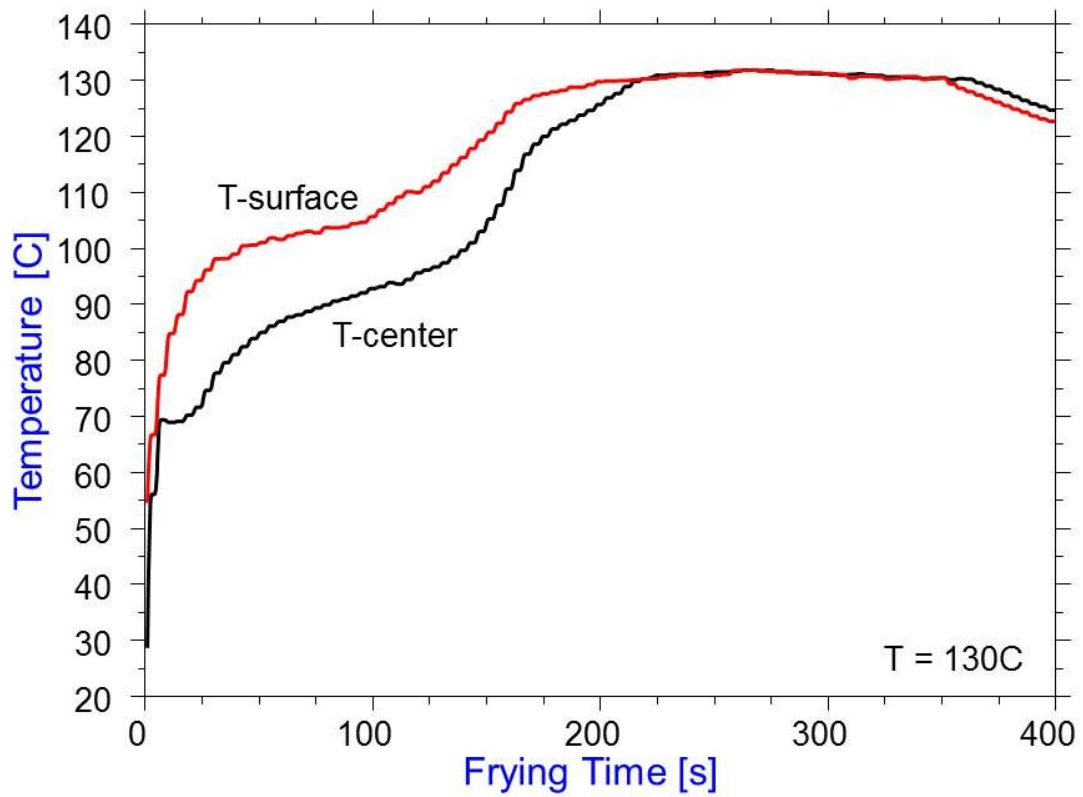
Figure 4-2b. Temperature history at the center and surface of the sweet potato chip during vacuum frying at 130°C.
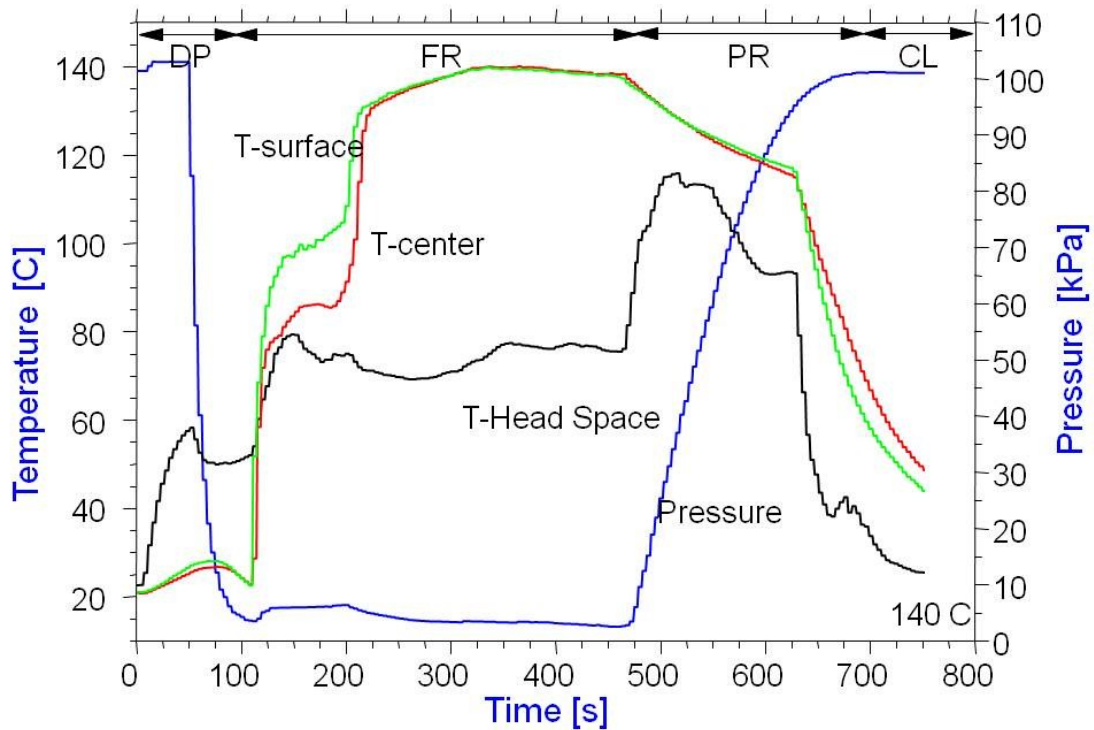
Figure 4-3. Temperature history at the center of the sweet potato chip (PC), at the surface of the chip, and of the headspace (HS), as well as the pressure changes (P) during vacuum frying at 140°C.

4.2. Effect of frying time and oil temperature on product quality attributes (PQA) of sweet potato chips

4.2.1. Effect of frying time and oil temperature on moisture loss of sweet potato chips during a single-stage and two-stage frying.

4.2.1.1 Single-stage processing

Figure 4-4 shows the moisture loss of sweet potato slices fried under vacuum conditions at different oil temperatures (120, 130, and 140°C). The curves show a typical drying behavior for food products as reported by Garayo and Moreira (2002), Shyu and

Hwang, (2001), and Gamble et. al. (1987). There are three periods observed in a typical drying. The first period is warm-up period in which the food product gets heat from its surroundings until reaching to evaporation temperature. The second period is the constant-rate period, which is defined as a constant state of evaporation per unit of area of the surface surrounded by a heating medium. The last period is the falling-rate period, which continues until reaching the equilibrium moisture content.

Food cooks faster by vacuum frying compared with any other drying methods since the boiling point of water is lower (11.2°C at 1.33 kPa). When the basket is submerged into the oil, water evaporates from the sweet potato slices. The moisture removal rate was very rapid for the first 40-50 seconds of the frying. After that, the moisture removal rate slows down until almost all the moisture evaporated.

Oil temperature affects the moisture losses of sweet potato slices during frying. The moisture of the slices was evaporated faster at 130 and 140°C than the moisture of the ones fried at 120°C. For the higher temperatures (130 and 140°C), moisture content of slices reached their equilibrium value after 80 seconds of frying. For the lower temperature (120°C), the slices reached the equilibrium value after 100 seconds of frying.
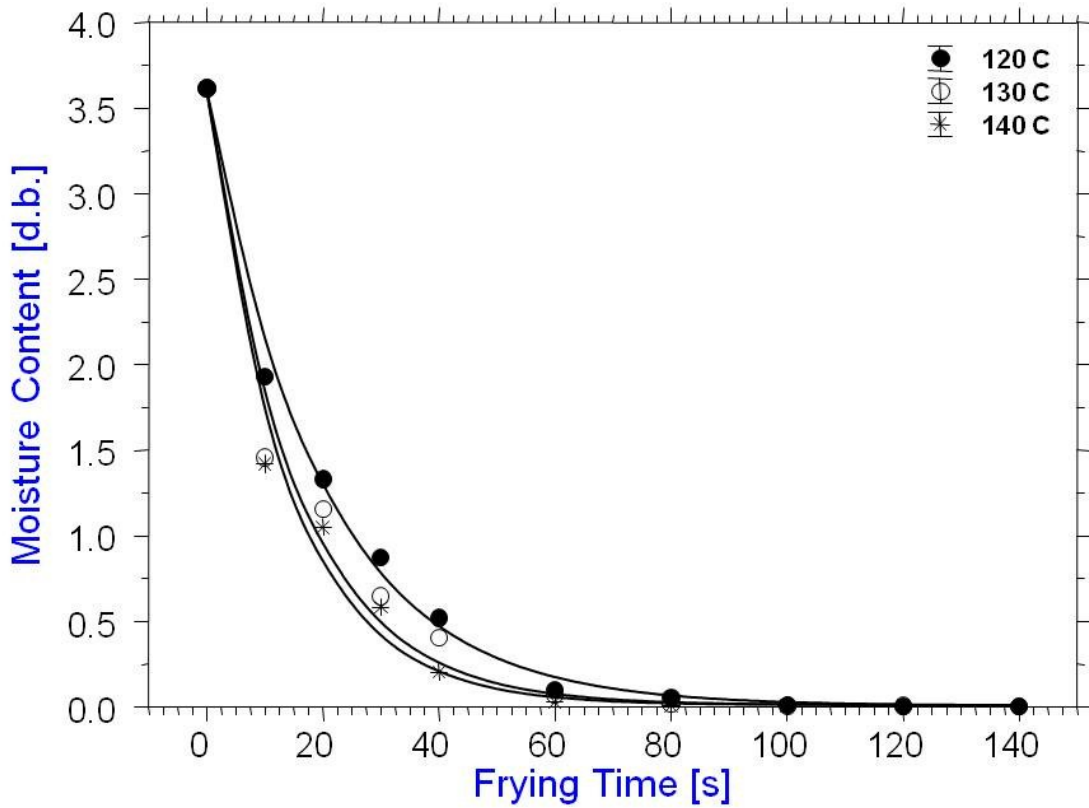
Figure 4-4. Moisture loss of sweet potato chips during only vacuum frying at three different oil temperatures.

Moisture loss during frying was modeled as a diffusion process. The chips were assumed as an infinity plate for the calculation of the diffusion coefficient (D_e) (Broker et. al., 1992):

$$MC_{db} = (M_0 - M_e)exp\left(\frac{\pi^2 D_e\, t}{4a^2}\right) + M_e \qquad \text{[4.1]}$$

where MC_{db} is the moisture content in dry basis (g/g solid), M_0 is the initial moisture content of the product (g/g solid), M_e is the equilibrium moisture content of the final product (g/g solid), a is half of the thickness of the sweet potato slice (m), t is the frying time (s).

Table 4-1 shows the diffusion coefficient values for sweet potato chips fried at 120, 130, and 140°C. The diffusion coefficient was higher at higher oil temperatures. The reason is that more heat transfer occurred at higher temperatures and the moisture evaporated faster from the wet sweet potato chips.

Table 4-1. Diffusion coefficient values for sweet potato chips fried under single-stage process at 120, 130, and 140°C.

T_{oil} [°C]	M_0 [g/g solid]	M_e [g/g solid]	D_e [m^2/s]	R^2
120	3.618	0.007	$1.325*10^{-8}$	0.981
130	3.618	0.006	$1.729*10^{-8}$	0.959
140	3.618	0.005	$1.878*10^{-8}$	0.972

The effect of the frying medium temperatures on the diffusion coefficient was modeled by using an Arrhenius equation:

$$D_e(T) = A \exp\left[-\frac{E_a}{RT}\right] \qquad [4.2]$$

where A is the pre-exponential factor, E_a is the activation energy, T is the absolute temperature (K), and R is the universal gas constant. Equation 4-2 was inearized as:

$$\ln D_e = \ln(A) - \frac{E_a}{RT} \qquad [4.3]$$

Figure 4-5 shows the experimental data fitted by Eq.[4.3] used to find the values of A and E_a. A value was found as $1.887*10^{-5}$ s^{-1} and E_a as 23632 kJ/kmol for the temperatures range of 120 to 140°C.
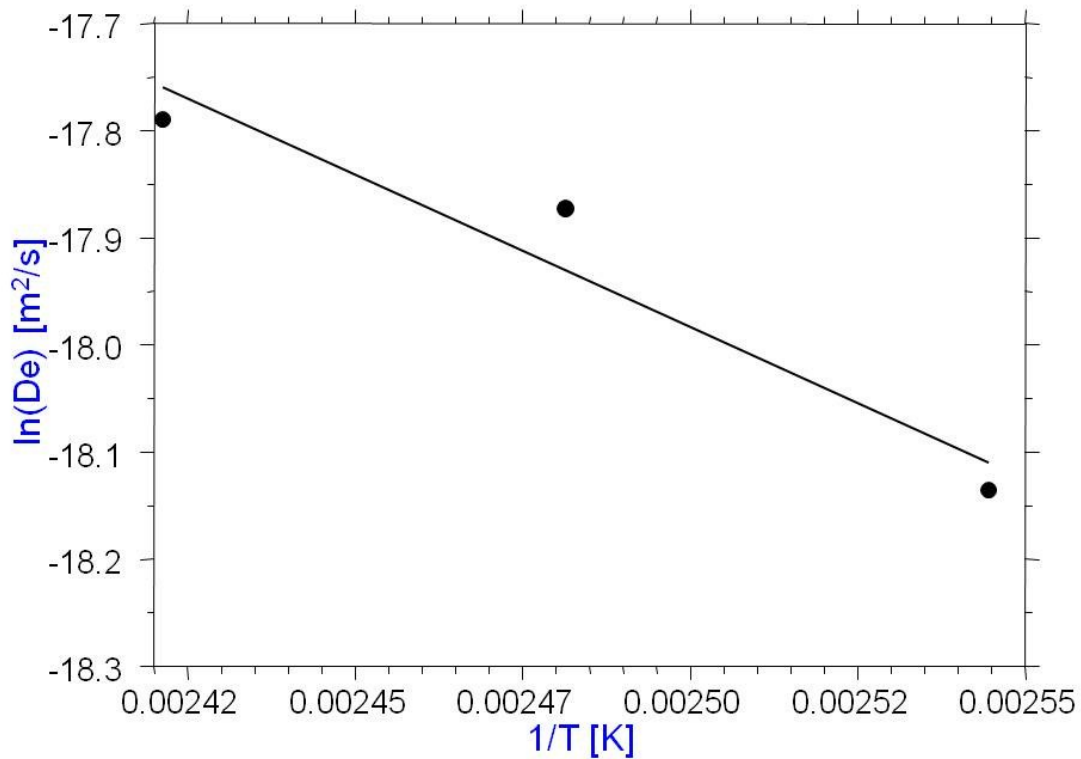
Figure 4-5. Changes on the moisture diffusion coefficient (D_e) depending on the frying oil temperatures.

4.2.1.2 Two-stage frying

Table 4-2 shows the moisture content of two-stage fried sweet potato chips. The pre-treatment time (atmospheric frying) was the same for all two-stage fried chips, 1 minute. However, vacuum frying times changed from 0.5 minute to 2 minutes. Vacuum frying times of 0.5 and 1 minute were not enough to obtain crispy chips. A crispy product was obtained for the single-stage process at the end of 100 seconds and for the two-stage frying at the end of 150 seconds (1 min. atm. + 1.5 min. vac.). Removal of the excess water from the wet slice took more time when using the two-stage frying method.

Table 4-2. Moisture content values of two-stage fried sweet potato chips at 130°C.

T_{oil} [°C]	Time [min.]	MC [g/g solid]	STD [g/g solid]
130	1(atm.)+0.5 (vac.)	0.419	0.001
130	1(atm.)+1(vac.)	0.130	0.003
130	1(atm.)+1.5(vac.)	0.016	0.001
130	1(atm.)+2(vac.)	0.008	0.001

Toil= oil temperature , MC= moisture content, STD = standard deviation,
atm= atmospheric fried, vac.= vacuum fried.

4.2.2. Effect of frying time and oil temperature on oil content of sweet potato chips during during frying

4.2.2.1. Internal oil content of sweet potato chips during single-stage frying

Figure 4-6 shows the internal oil content (IOC) of sweet potato chips fried under vacuum conditions at three different temperatures (120, 130, and 140°C). The internal content was determined after de-oiling the sweet potato chips. The internal oil content values of the single-stage fried sweet potatoes were 0.178±0.007, 0.178±0.011, and 0.172±0.002 g/g solid for oil temperatures of 120, 130, and 140°C, respectively.

The IOC accounted for 48-55% of the total oil content (TOC) and 45-52% of the TOC was occupied by surface oil content (SOC). The internal oil content of the sweet potato chips was the lowest at highest temperature (140°C) due to, maybe, the oil viscosity, which is lower at higher temperatures, thus making the removing of surface oil easier during centrifuging than for the lower temperatures. Figure 4-9 to 4-11 show the

internal, total, and surface oil content of sweet potato chips fried under vacuum conditions at 120, 130, and 140°C.

Figure 4-6. Effect of different frying time and temperatures (120, 130, and 140°C) on internal oil content (IOC) of sweet potato chips fried under vacuum.

The internal oil content of the sweet potato chips was modeled using the fractional conversion kinetic model (Chen et. al., 2002):

$$OR = \frac{OC(t) - OC_e}{OC_o - OC_e} = A \times \exp(-k \times t) \qquad \textbf{[4.4]}$$

where OR is the oil ratio, OC_0 is the initial oil content (g/g solid), OC_e is the equilibrium oil content (g/g solid), t is the frying time (s), A and k are the regression coefficients. Table 4-3 shows the values used for the calculation of internal oil content as a function of frying time.

Table 4-3. Regression coefficients (A and k) at different frying temperatures.

T_{oil} [°C]	OC_0 [g/g solid]	OC_e [g/g solid]	A [g/g solid]	k [1/s]	R^2
120	0.087	0.181	1.352	0.0264	0.975
130	0.091	0.176	1.559	0.0396	0.952
140	0.099	0.173	1.855	0.0555	0.922

4.2.2.2. *Total and surface oil content of sweet potato chips during single-stage frying.*

Figure 4-7 shows the total oil content of the sweet potato chips fried under vacuum. The total oil content of the chips increased with frying time and reached a plateau by the end of frying. The total oil contents of vacuum fried sweet potato chips were 0.348±0.001, 0.354±0.009, and 0.358±0.002 g/g solid for oil temperatures of 120, 130, and 140°C, respectively. The higher the frying oil temperature, the higher the total oil absorbed by sweet potato slices. Most of the total oil was absorbed between 60-80 seconds of frying. The equilibrium total oil value was obtained faster at higher oil temperatures.
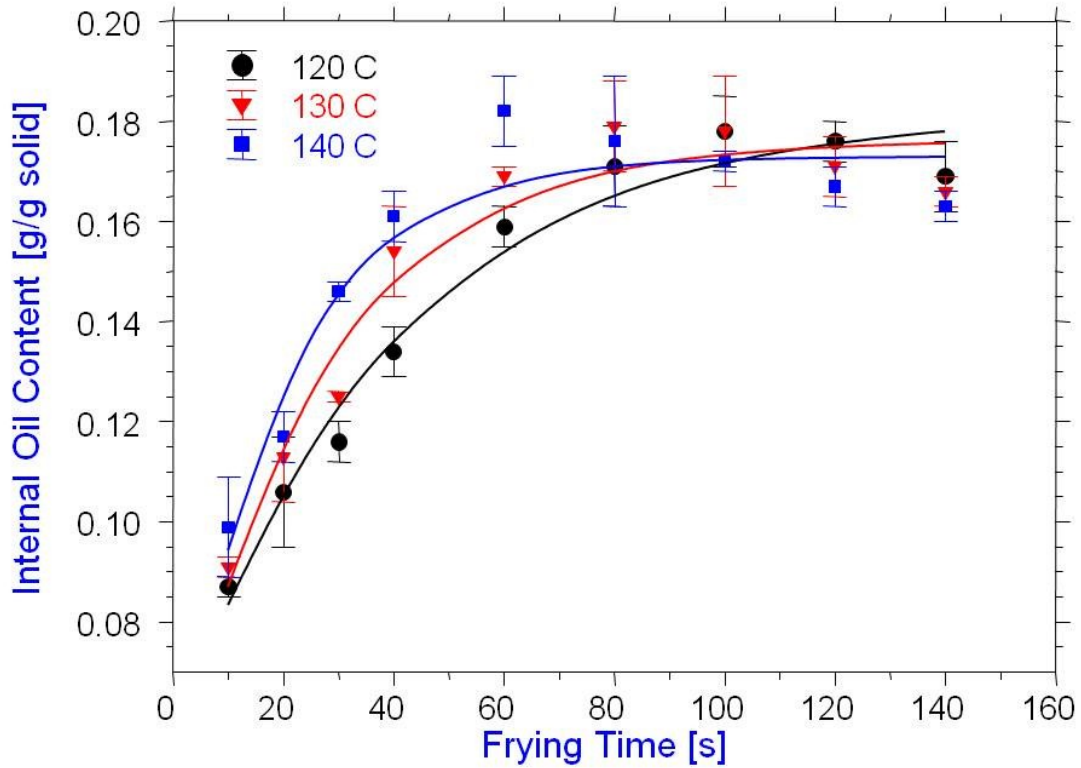
Figure 4-7. Effect of different frying time and temperatures (120, 130, and 140°C) on total oil content (TOC) of sweet potato chips fried under vacuum.

Another model use to describe TOC dynamics is the Gompertz function. It is a type of mathematical model for a time series, where absorption is slowest at the start of a time period. The right-hand or future value asymptote of the function is approached much more gradually by the curve than the left-hand or lower valued asymptote:

$$OC(t) = OC_o + B \times \exp\{-\exp[-C(t-D)]\} \qquad \text{[4.5]}$$

where OC_o is initial oil content (g/g-solid); B (g/g-slid) is equal to (OC_o-OC_e) where OCe is the maximum OC value at the end of frying; C is the relative oil absorption rate

(g/g-solid/h); and D is the time at which the absorption rate is maximum (s). Table 4-4

shows the values used for the calculation of total oil content in fucntion of time.

Table 4-4. Regression coefficients ($B, C, and D$) at different frying temperatures.

T_{oil} [°C]	OC_o [g/g solid]	B [g/g solid]	C [g/g solid/h]	D [s]	R^2
120	0.1613	0.1759	0.07843	48.01	0.992
130	0.1813	0.1551	0.1083	41.94	0.985
140	0.2046	0.1524	0.1405	43.37	0.998

Figure 4-8 shows surface oil content of sweet potato chips fried at different

temperature under vacuum. The difference between TOC and IOC gave the SOC of the

chips. The surface oil content values were 0.179, 0.188, and 0.195 g/g solid for 120, 130,

and 140°C, respectively. The surface oil of the chips was removed by the de-oiling

process (centrifuging) to decrease the total oil content of the final product.

Figures 4-9 to 4-11 shows the different oil content histories for potato chips fried
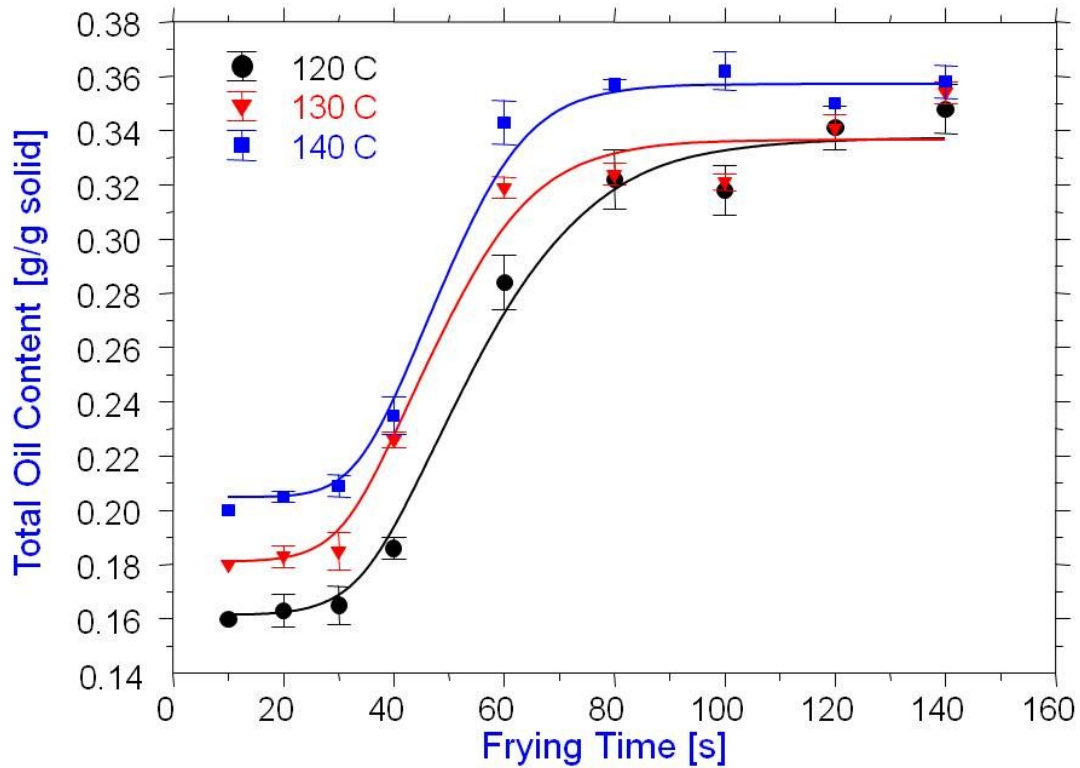
at different temperatures.
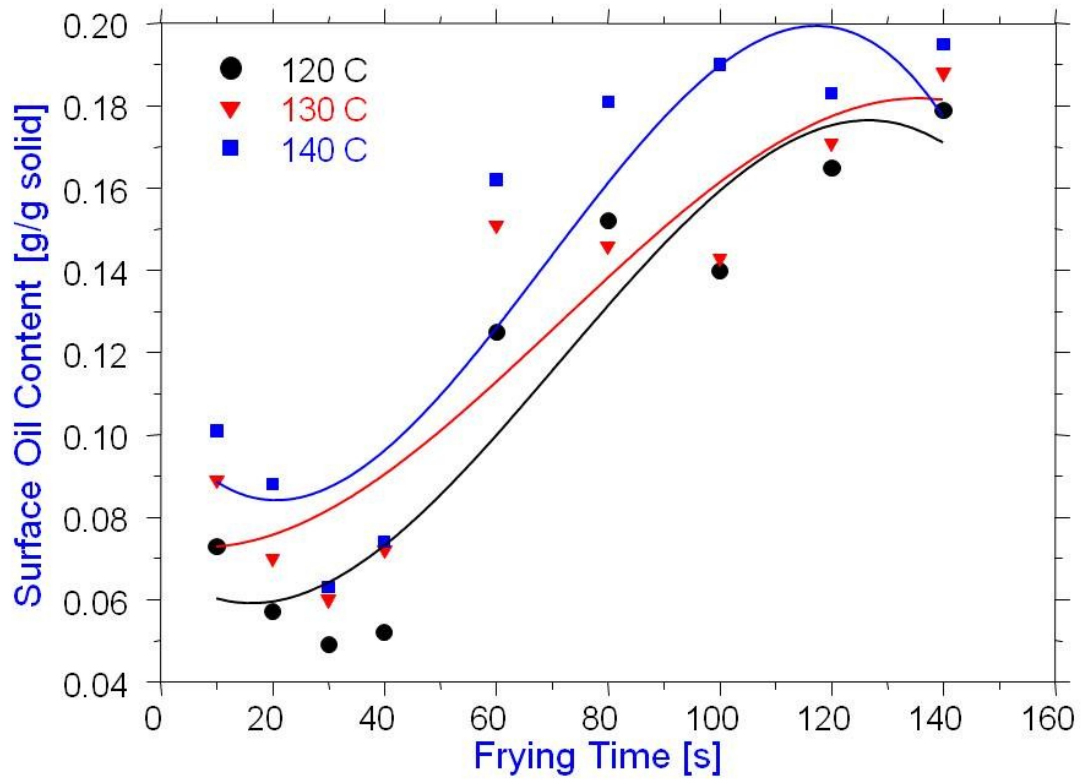
Figure 4-8. Effect of different frying time and temperatures (120, 130, and 140°C) on surface oil content (SOC) of sweet potato chips fried under vacuum.
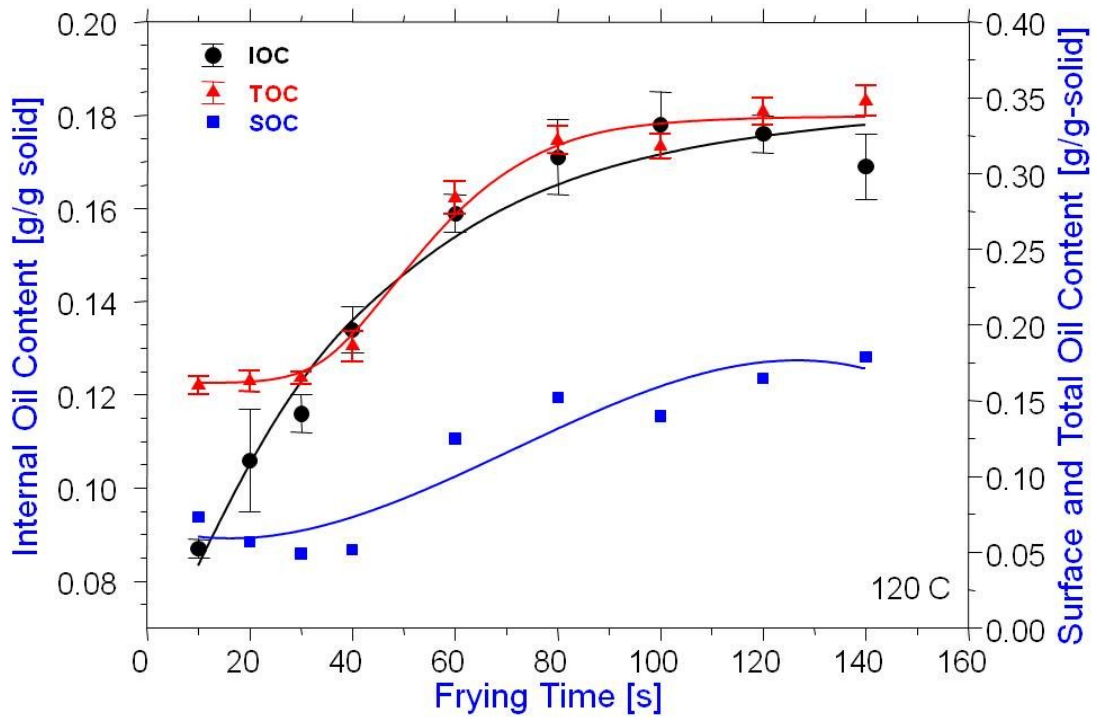
Figure 4-9. Internal, total, and surface oil content of sweet potato chips fried under vacuum at 120°C.
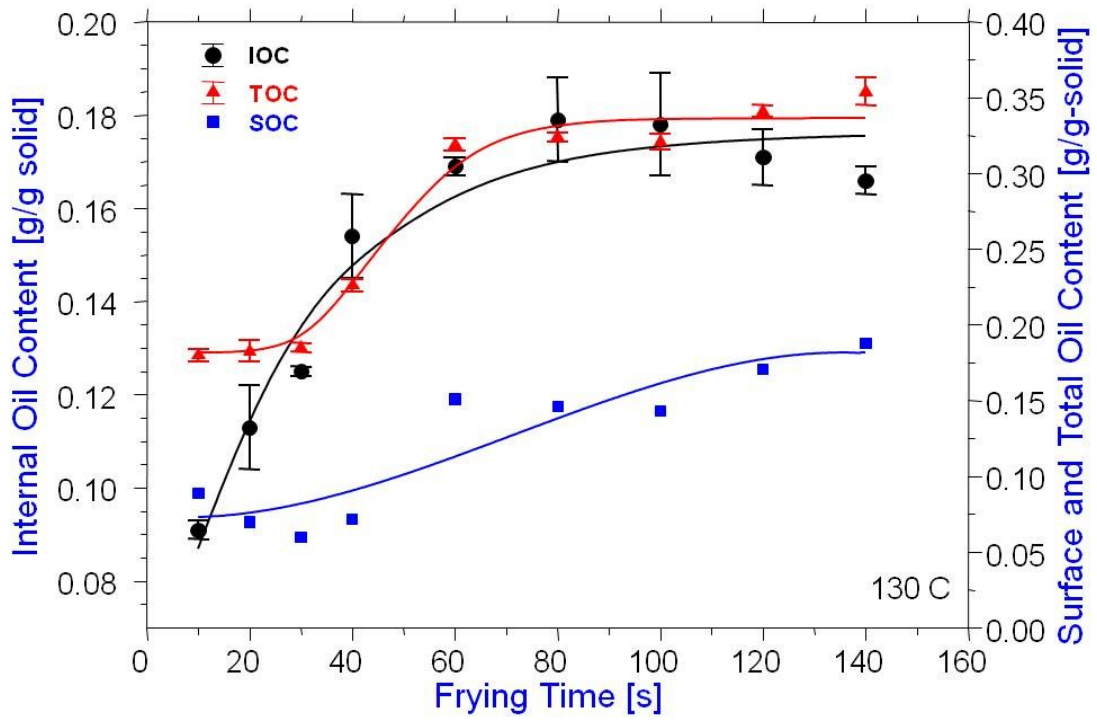
Figure 4-10. Internal, total, and surface oil content of sweet potato chips fried under

vacuum at 130°C.
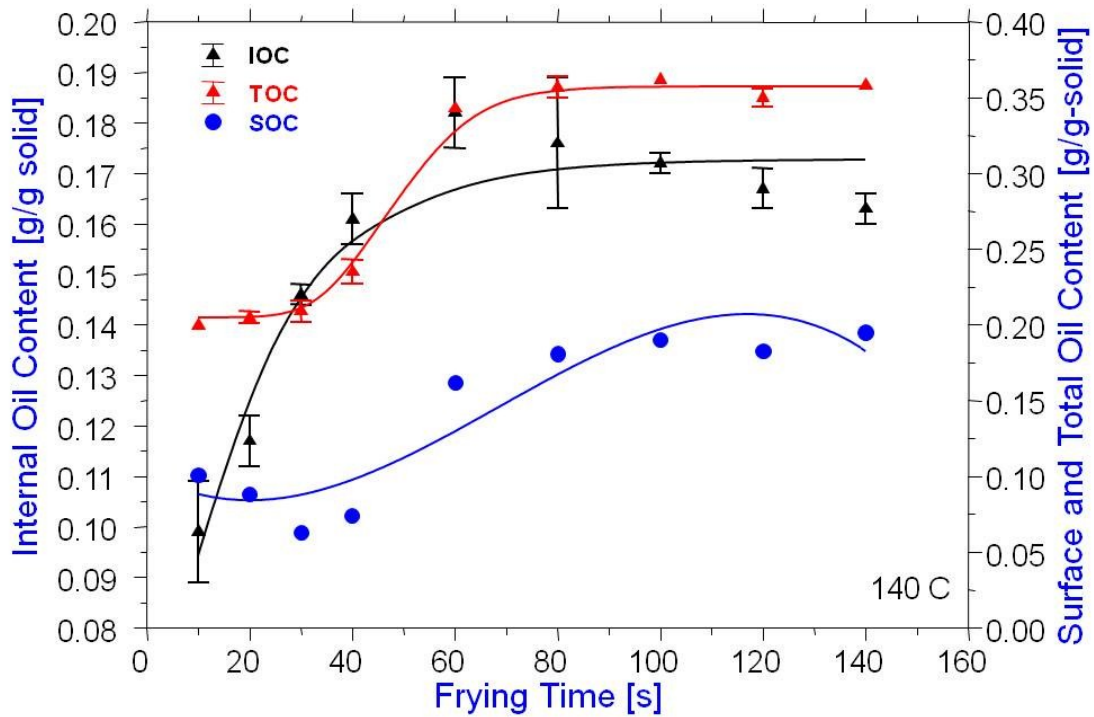
Figure 4-11. Internal, total, and surface oil content of sweet potato chips fried under vacuum at 140°C.

4.2.2.3 Internal oil content of sweet potato chips during two-stage frying

Table 4-5 shows the oil distribution of two-stage fried sweet potato chips. The total oil content of two-stage fried sweet potato chips showed similar behavior to the single-stage fried ones. The TOC of the pre-treated chips increased during frying from 0.157±0.003 g/g solid to 0.427±0.005 g/g solid. It was observed that the two-stage fried chips did not have a smooth surface, which may have resulted in high total oil content due to increase in the surface area (blisters).

The IOC of the two-stage fried chips were 0.116±0.006, 0.141±0.003, 0.153±0.008, and 0.140±0.002 g/g solid for   1 (atm.)+0.5 (vac.), 1 (atm.)+1 (vac.), 1

(atm.)+1.5 (vac.), 1 (atm.)+2 (vac.), respectively. The IOC of the two-stage fried sweet potato chips was lower than the IOC of the single-stage fried ones. The reason might be the gelatinization of starch by the atmospheric frying pre-treatment. Gelatinized starched made a barrier at the surface of the chips and lowered the oil penetration to the core of the chips.

The values for the SOC of dual-stage fried potatoes increased gradually from 0.041 g/g solid to 0.287 g/g solid. The de-oiling system for the two-stage frying removed more surface oil compared to the one-stage frying. The SOC of pre-treated chips was higher than the SOC of vacuum fried chips.

For the final product [1 (atm.) +1.5 (vac.)] of two-stage frying, the IOC was 40% of the TOC, while the SOC was 60% of the TOC of sweet potato chips.

Table 4-5. Effect of different frying vacuum frying times on the oil distribution of two-stage fried sweet potato chips at 130°C.

Time [min.]	TOC [g/g solid]	STD [g/g solid]	IOC [g/g solid]	STD [g/g solid]	SOC [g/g solid]
1 (atm.)+0.5 (vac.)	0.157	0.003	0.116	0.006	0.041
1 (atm.)+1 (vac.)	0.296	0.008	0.141	0.003	0.155
1 (atm.)+1.5 (vac.)	0.382	0.005	0.153	0.008	0.228
1 (atm.)+2 (vac.)	0.427	0.005	0.140	0.002	0.287

Toil=oil temperature, TOC= total oil content, IOC=internal oil content, SOC= surface oil content, STD.=   standard deviation

4.2.3 Effect of frying time and oil temperature on the bulk density, true density, and porosity of sweet potato chips during frying

4.2.3.1 Single-stage frying

Figures 4-12 to 4-14 show the kinetics of bulk density, true density, and porosity of vacuum fried sweet potato chips at three different frying temperatures (120, 130, and 140°C). Bulk and true density values were calculated for the samples containing no oil to understand the actual pore space inside the sweet potato chips.

The final values of bulk density, true density, and porosity did not show significant difference (P>0.05) between three different frying temperatures. The porosity of the chips was calculated by bulk density and true density values. The bulk density decreased from 1138 ± 2 kg/m^3 to 668 ± 13 kg/m^3 (120°C), to 653 ± 15 kg/m^3 (130°C) to 645 ± 12 kg/m^3 (140°C), while the true density increased from 1098 ± 8 kg/m^3 to 1392 ± 8 kg/m^3 (mean value for all frying temperatures). Porosity increased during frying due to the decrease in bulk density of the chips, from 0.02 to 0.55 ± 0.01 for all frying temperatures. The chips fried at 140°C reached the final values of bulk density, true density, and porosity faster than the chips fried at 120 and 130°C.
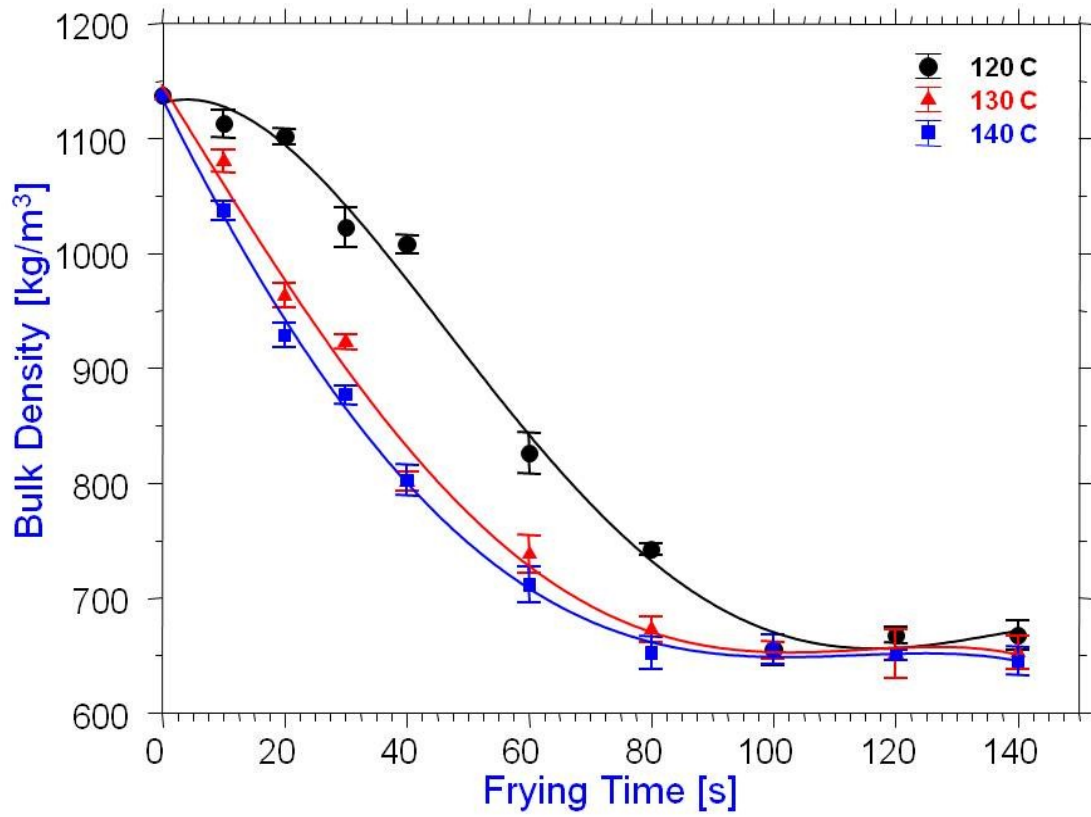
Figure 4-12. Effect of different frying time and temperatures (120, 130, and 140°C) on bulk density of sweet potato chips fried under vacuum.
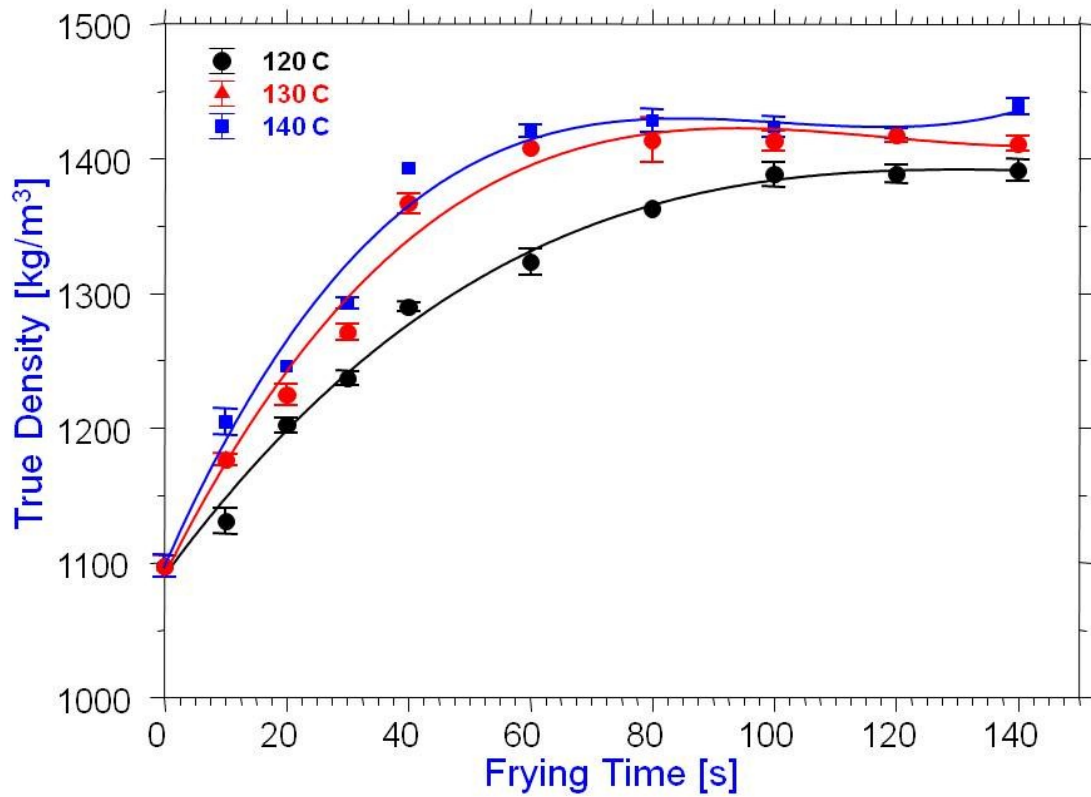
Figure 4-13. Effect of different frying time and temperatures (120, 130, and 140°C) on

true density of sweet potato chips fried under vacuum.
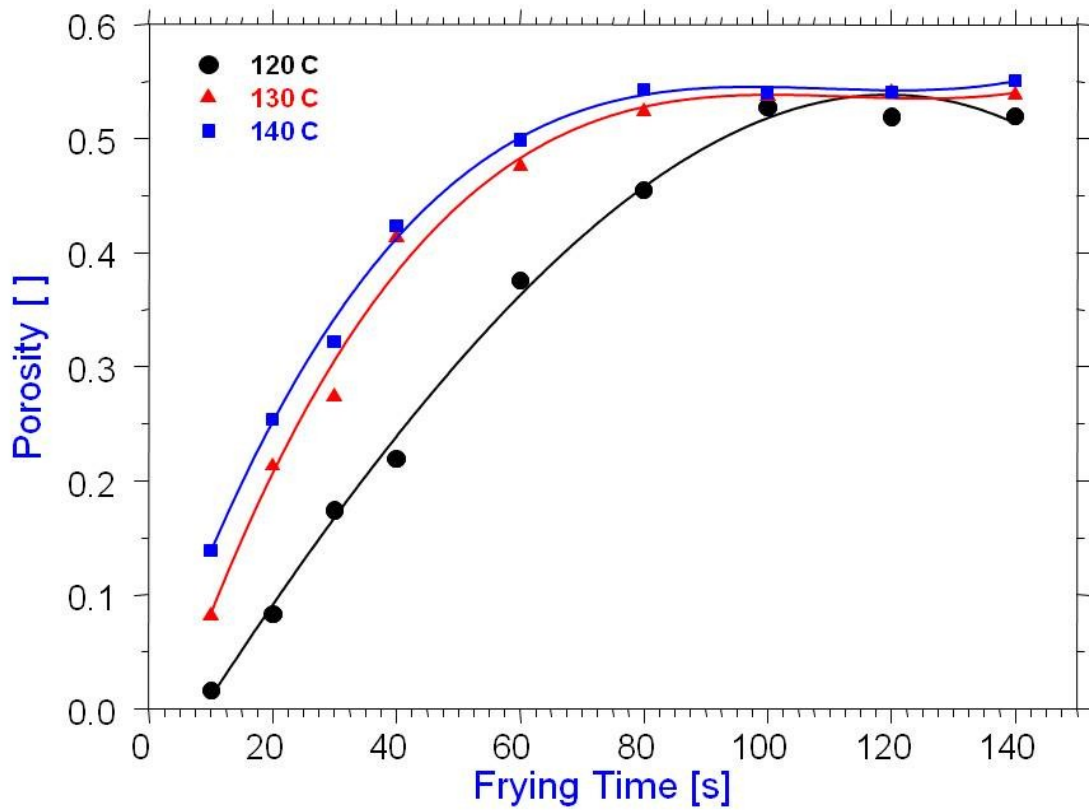
Figure 4-14. Effect of different frying time and temperatures (120, 130, and 140°C) on porosity of sweet potato chips fried under vacuum.

4.2.3.2 Two-stage vacuum frying

Table 4-6 shows the values of bulk density, true density, and porosity for the two-stage fried sweet potato chips at 130°C. The bulk density values were 654.99±13.37, 654.46±7.74, and 655.31±13.29 kg/m^3 for single-stage fried chips for 100 seconds at 120, 130, and 140°C. Dual-stage fried chips had higher bulk density than the one-stage fried ones. On the other hand, the true density values were higher for the two-stage fried chips.

Table 4-6. Bulk density (ρ_b), true density (ρ_t), and porosity (Ø) values for the two-stage fried sweet potato chips at 130°C.

Time [min.]	ρ_b [kg/m³]	STD [kg/m³]	ρ_t [kg/m³]	STD [kg/m³]	Ø [ ]
1 (atm.)+0.5 (vac.)	763.70	14.98	1308.20	6.80	0.42
1 (atm.)+1 (vac.)	512.60	3.17	1429.90	5.49	0.64
1 (atm.)+1.5 (vac.)	364.49	8.80	1444.32	11.75	0.75
1 (atm.)+2 (vac.)	366.75	5.15	1416.89	8.91	0.74

4.2.4 Effect of frying time and oil temperature on diameter shrinkage and thickness expansion of sweet potato chips during frying

4.2.4.1 Single-stage frying

Equations 3-8 and 3-9 were used to determine diameter shrinkage and thickness expansion at different temperatures and frying times.

Figure 4-15 and Figure 4-16 show the diameter shrinkage and thickness expansion for the vacuum fried sweet potato chips. Oil temperature did not affect significantly (P<0.05) the diameter shrinkage of the chips during vacuum frying. For the highest temperature (140°C), the chips reached the final diameter value faster than those fried at lower temperatures (120 and 130°C). The reason for that is the last formation of crust at high temperature. The diameter shrinkage curves for all three temperatures (120, 130, and 140°C) showed a rapid increase followed for a rapid decrease in the diameter shrinkage values at around 80 s of frying and remaining constant until the end of frying.

The final values for the diameter were 10.67±0.33% (120°C), 12.08±1.02% (130°C), and 11.69±0.63% (140°C). Sweet potato chips shrank faster due to rapid water evaporation at the first stage of frying. After that, the changes in the diameter values were decreased due to the rigidity of the crust formation.

The thickness of the sweet potato chips was suddenly reduced to negative values for the early times of frying and then it showed increasing in a slow manner for the three different temperatures (Figure 4-16). After 140 seconds of frying, the chips could not reach their initial thickness value of 1.6 mm. The minimum values in thickness expansion were -57.53±1.51% (at 40 s), -58.56±0.73% (40 s), and -55.63±0.37% (30s) for 120, 130, and 140°C. Chips fried at high frying temperatures reached the constant thickness value faster than those fried at lower temperature.
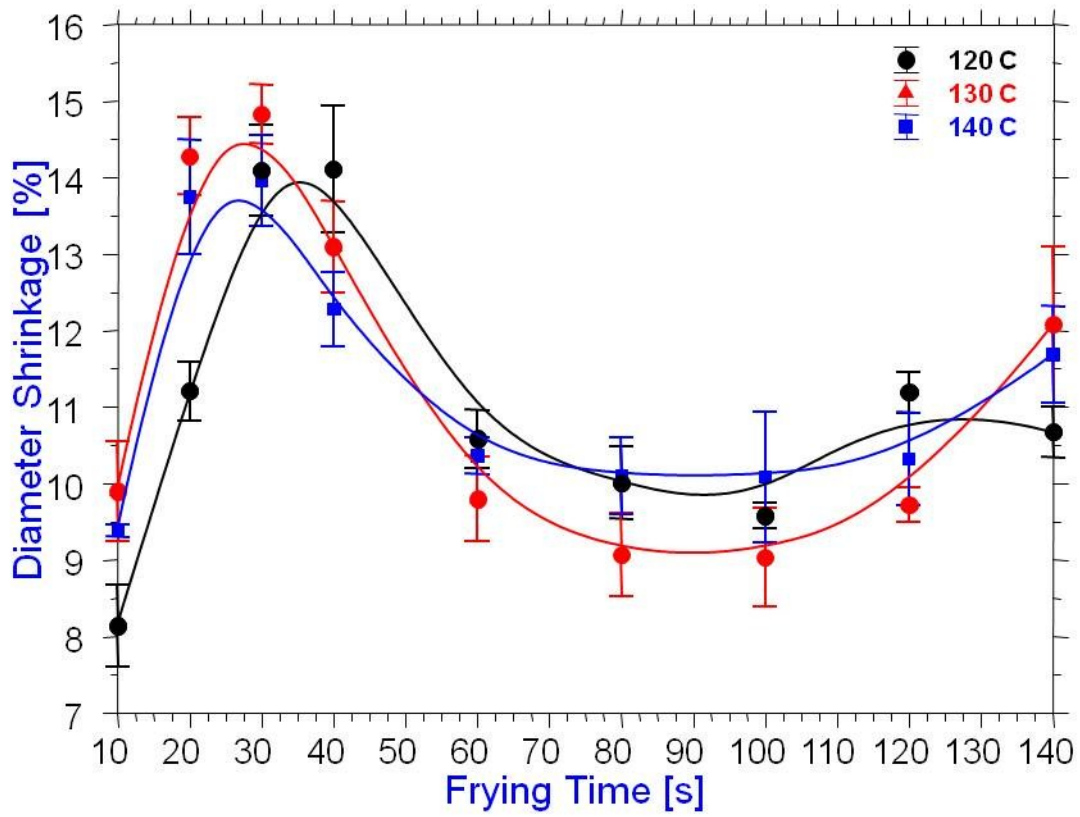
Figure 4-15. Diameter shrinkage of vacuum fried sweet potato chips at different oil temperatures.
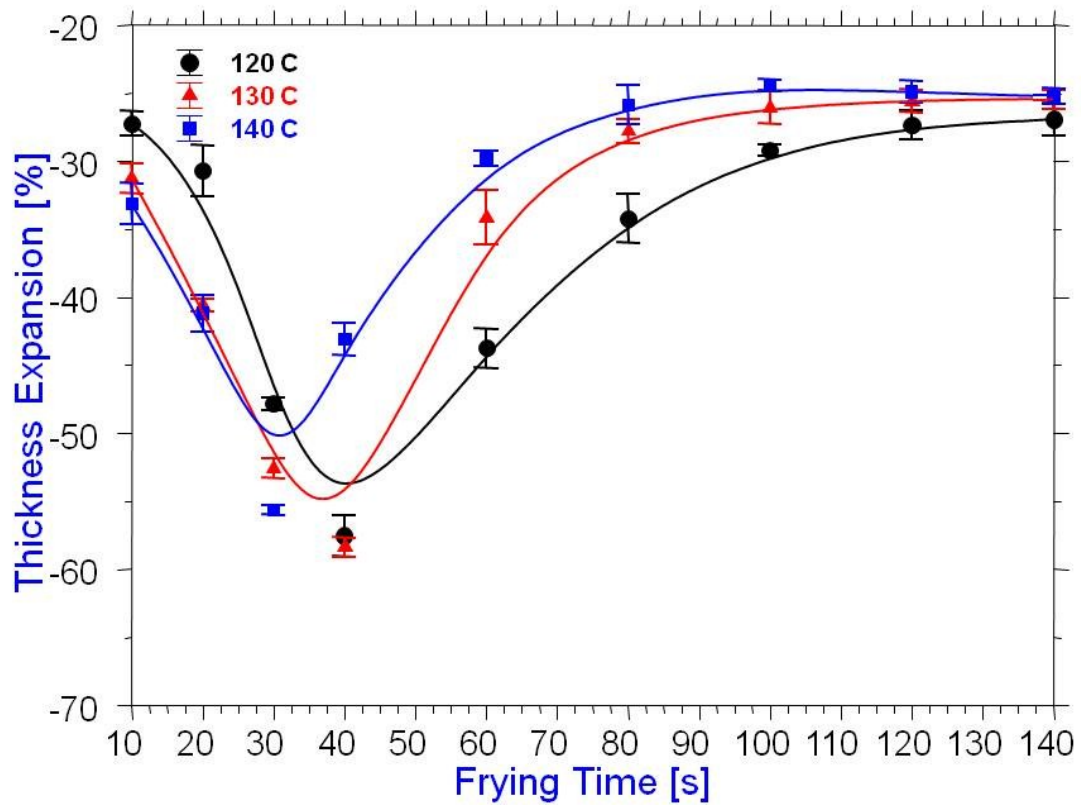
Figure 4-16. Thickness expansion of vacuum fried sweet potato chips at different oil temperatures.

4.2.4.2 Two-stage frying

Table 4-7 shows the diameter shrinkage for the two-stage fried sweet potato chips at different vacuum frying times (at 130°C). The diameter shrinkage values were measured as 15.74±0.78%, 14.50±0.59%, 13.16±0.71%, and 12.65±0.44% for the dual stage frying. The diameter shrinkage decreased as vacuum frying time increased. The diameter shrinkage values for the vacuum fried sweet potato chips were 9.58±0.17% (at 120°C), 9.04±0.64% (130°C), and 10.09±0.86 (140°C). The diameter shrinkage percentage was higher for two-stage fried chips compared to vacuum fried ones.

Table 4-7. Diameter shrinkage for the two-stage fried sweet potato chips at 130°C.

Frying time	D [%]	STD [%]
1 min.+30 sec.	15.74	0.78
1 min. +1 min.	14.50	0.59
1 min.+1.5 min.	13.16	0.71
1 min.+2 min.	12.65	0.44

The thickness expansion of the two-stage fried chisp is shown in Table 4-8. The thickness expansion rate of the chips processed by the two-stage frying increased during frying from -45.26±2.46% to 50.97±1.39%. The final product (1 minute atmospheric + 1.5 minutes vacuum fried) of the dual stage frying had higher thickness than the initial thickness (1.60 mm) of the raw slice. Atmospheric frying treatment prior to vacuum frying let the surface starch to gelatinize. After that, the saturated vapor could not escape

from the surface of the chips. Thus, bubble and increased thickness formation (on the surface) occurred during the process.

Table 4-8. Thickness expansion of two-stage fried sweet potato chips at 130°C.

Frying time	L [%]	STD [%]
1 min.+30 sec.	-45.26	2.46
1 min. +1 min.	24.22	1.94
1 min.+1.5 min.	26.04	2.30
1 min.+2 min.	50.97	1.39

4.2.5 Effect of frying time and oil temperature on texture of sweet potato chips during single-stage and two-stage frying

Texture analysis was conducted for the single-stage and two-stage fried sweet potato chips. The single-stage was applied for the chips fried for 100 seconds at 120, 130, and 140°C under vacuum conditions; while the two-stage was applied for the chips fried for 1 minute atmospheric + 1.5 minutes vacuum conditions at 130°C. The 100 s for the single-stage fried chips was chosen based on the final product moisture content for the three temperatures selected in this study.

Figure 4-17 shows the forces applied to break the sweet potato chips. For the single-stage fried chips, the applied forces were 2.15±0.09 N, 2.01±0.11 N, and 2.36±0.20 N for 120, 130, and 140°C, respectively; and 2.61±0.23 N force was applied to the two-stage fried chips. There is a significant difference ($P<0.05$) between the

hardness value of the samples. It was harder to break the two-stage fried sweet potato chips than the single-stage fried ones ($P<0.05$). The result was not surprising since we observed that these chips were thicker and full of blisters. The single-stage fried chips had a smooth surface, whereas the two-stage chips had a rough surface as a result of many blisters that were formed during the atmospheric frying pre-treatment. The gelatinized starch in the chips behaves as a barrier, which prevents the saturated vapor from escaping during atmospheric frying; thus, few but large bubbles are formed in the chips surface (Kawas et. al., 2001).
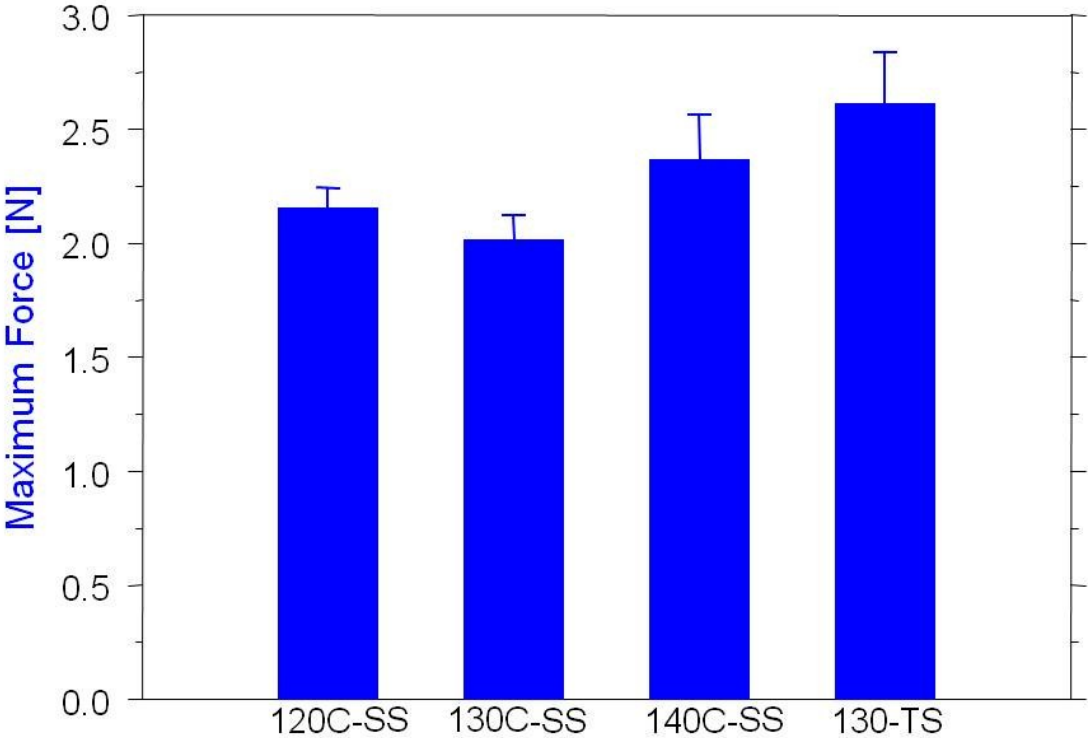
Figure 4-17. Maximum force values for single-stage and two-stage fried sweet potato chips at different temperatures.

4.2.6 Effect of frying time and oil temperature on color of sweet potato chips during single-stage and two-stage frying

Figures 4-18 to 4-20 show the differences in the color parameters (L^*, a^*, and b^*) for the vacuum fried chips at three different temperatures (120, 130, and 140°C for 100 seconds) and the two-stage fried (1 minute atmospheric + 1.5 minutes vacuum fried) ones at 130°C.

The L^*-value ranges from 0 to 100 (from black to white) points to lightness. The L^*- values were 49.02±0.46, 48.08±0.38, 47.05±0.59, and 55.70±1.12 for the vacuum fried at 120, 130, and 140°C, and the two-stage fried chips, respectively. The frying temperature showed a significant differences ($P<0.05$) for L^* value of the chips. The atmospheric frying pre-treatment improved the color of the sweet potato chips in terms of lightness.

The a^*-value denotes the green-red chromaticity. The a^*-values obtained were 16.04±0.14, 16.35±0.64, 15.48±0.29, and 17.03±0.10 for the vacuum fried at 120, 130, and 140°C, and the two-stage fried chips, respectively. The changes at the a^*-value did not follow a clear trend for either frying temperature or frying method.

When the frying temperature was increased under the single-stage conditions, the b^*-value (blue-yellow chromaticity) decreased from 26.81±0.24 (120°C) to 25.48±0.45 (140°C). For the two-stage frying, the b^*-value was 29.73±0.55, higher than chips fried in the single-stage process. Thus, the atmospheric frying pre-treatment increased the yellowness of the sweet potato chips, which is a more desirable quality for consumers. The frying temperature had a significant ($P<0.05$) on b^*-value of the sweet potato chips.
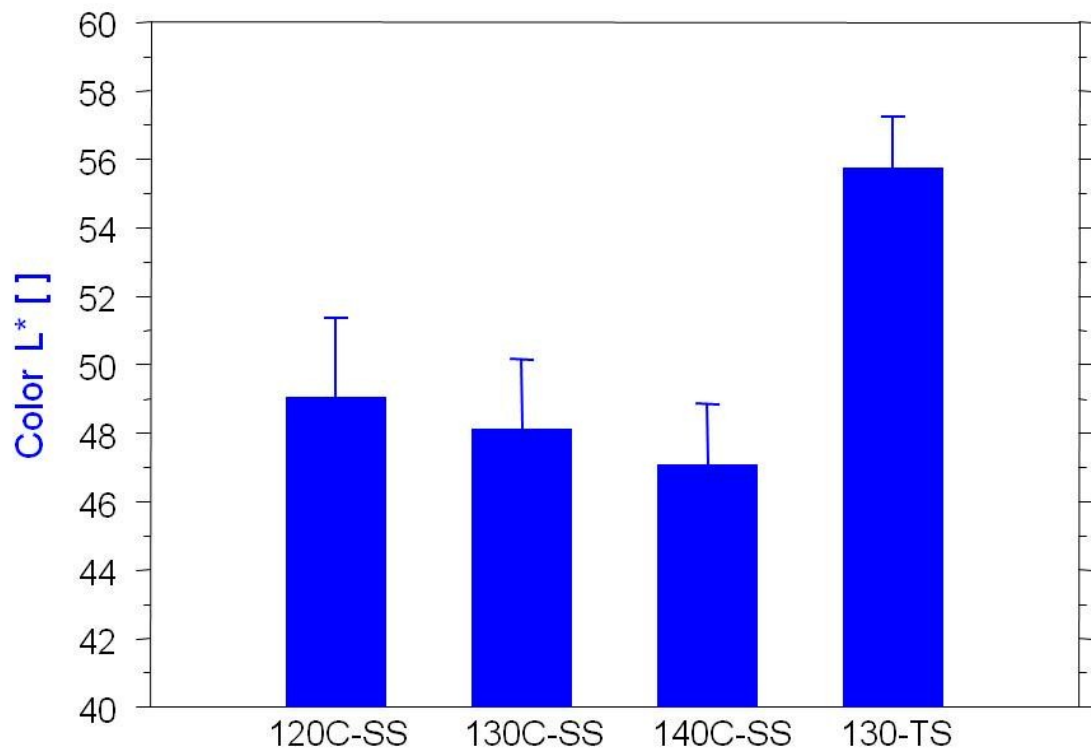
Figure 4-18. Effect of frying type (singele-stage and two-stage) and temperature on *L*-value (lightness) of sweet potato chips (SS: single-stage; TS: two-stage).
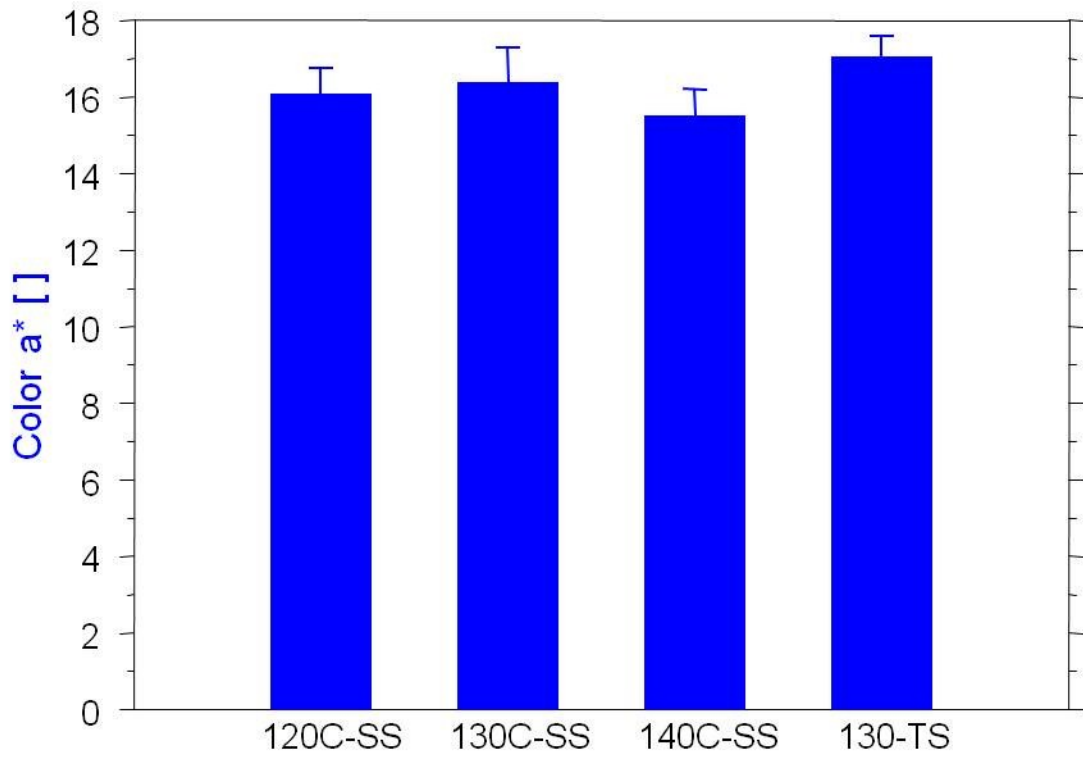
Figure 4-19. Effect of frying type (singele-stage and two-stage) and temperature on *a**-value (green-red chromaticity) of sweet potato chips (SS: single-stage; TS: two-stage).
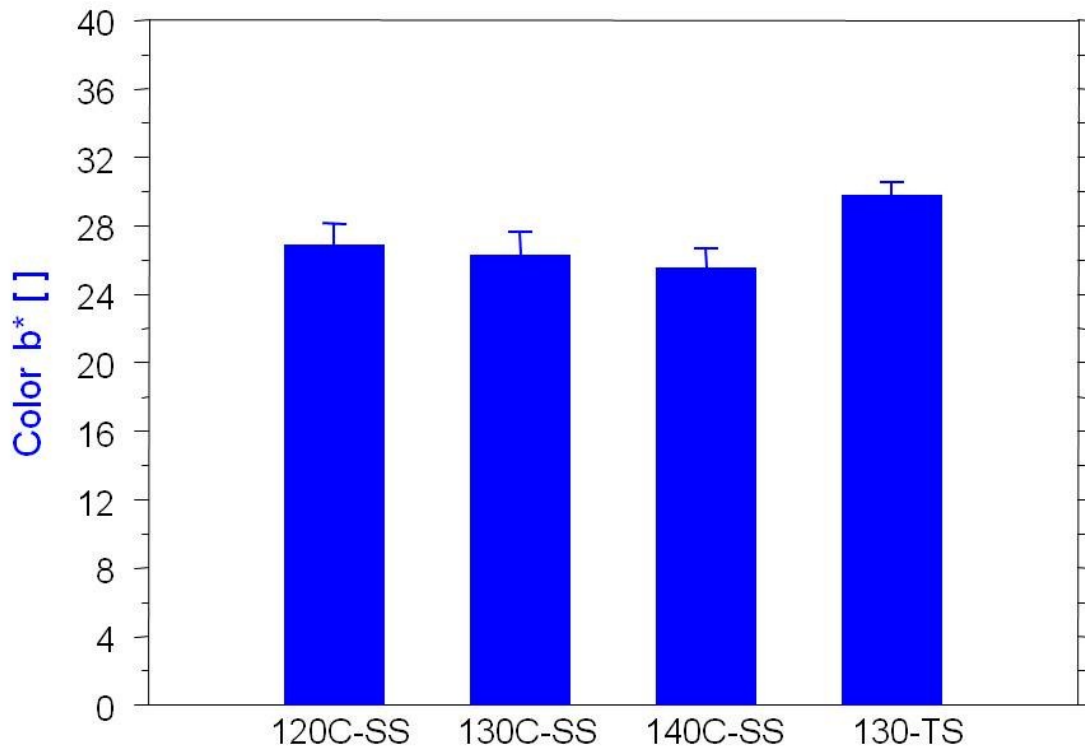
Figure 4-20. Effect of frying type (singele-stage and two-stage) and temperature on *b**-value (blue-yellow chromaticity) of sweet potato chips (SS: single-stage; TS: two-stage).

4.2.7 Effect of frying time and oil temperature on sensory evaluation of sweet potato chips during single-stage and two-stage frying

Sensory test was done with four groups of sweet potato chips: single-stage chips fried at 120, 130, and 140°C for 100 seconds, and two-stage fried chips at 130°C for 2.5 minutes (1 minute atmospheric + 1.5 minutes vacuum fried). The panelists evaluated each sweet potato chip individually without comparing with each other. Their scores higher than or equal to 5 were consired acceptable, based on the nine- point scale hedonic scale.

Figure 4-21 shows the results for the sensory test. All the scores for these four groups and four categories were above 5, meaning that the single-stage and the two-stage fried chips were acceptable to the panelists. The highest score in color was 7.22±1.24 for the two-stage fried sweet potato chips. The two highest scores for odor were 7.36±1.13 and 7.16±1.17 for the single-stage fried chips at 140°C and the two-stage fried chips, respectively. The two highest scores for texture given by the panelists were 7.57±1.16 for the two-stage fried chips and 6.67±1.60 for the one-stage fried ones at 140°C. In terms of flavor, the highest scores were 7.24±1.46 and 6.80±1.52 for the two-stage fried chips and the one-stage fried ones at 130°C. For the overall quality, the two-stage fried chips obtained the highest score, 7.40±1.21 followed by 6.78±1.18 for one-stage fried chips at 140°C. According to the Chi-Square results, there is a statistically significant difference among the samples in terms of texture scores ($P<0.05$). The results indicate that there were statistically significant differences ($P<0.05$) between the texture of the 120°C fried chips and the two-stage fried ones; the chips fried in the single-stage at 130°C and two-stage fried; the single-stage fried chips at 140°C and two-stage fried ones; and the ones fried at 140°C and 120°C in the single-stage process. Color, flavor, odor scores of the panelists did not show significant differences ($P>0.05$) among the treatments.

In summary, the two-stage fried sweet potato chips obtained the highest scores in terms of color, texture, flavor, and overall quality. The panelists commented that they liked the airy texture and yellow color produced with the two-stage process. Even though for some of the panelists it was the first time they tried sweet potato chips, they

liked the chips very much. The chips were not seasoned; therefore they had a bland flavor, which could explain why the scores were not higher, especially for the flavor and overall quality categories. Some of the panelists commented that it would be great if we could add some salt to the sweet potato chips.

4.2.8 Effect of frying time and oil temperature on starch gelatinization of sweet potato chips during single-stage and two-stage frying

The degree of gelatinization of the sweet potato chips fried under vacuum at 130ºC for 100 seconds was compared to the two-stage fried (1 minute atmospheric + 1.5 minutes vacuum fried at 130°C) ones. A Differential Scanning Calorimeter (DSC 6 – Perkin Elmer) was used to obtain the enthalpy difference of the samples.

The degree of gelatinization (Equation 3-10) was 72.1±0.3% for single-stage vacuum fried chips and 87.4±2.8% for the two-stage fried ones. Hence, the atmospheric frying pre-treatment improved the starch gelatinization. During vacuum frying, the temperature of the chips does not reach the gelatinization temperature until most of the water is evaporated. Therefore, there is not sufficient moisture content in the product for gelatinization to occur completely. As a result, the product has a glassy texture. In the two-stage frying, the atmospheric frying prior to vacuum frying helps the starch to gelatinize thus producing a better product in terms of texture, oil content, and flavor.
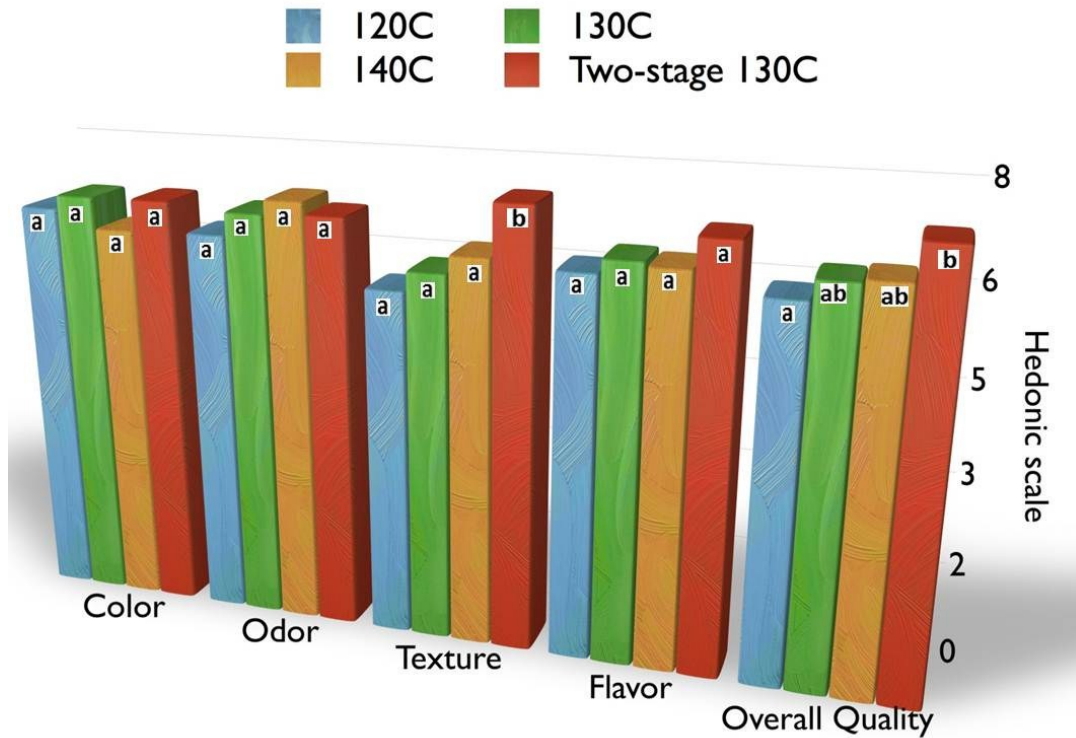
Figure 4-21. Effect of frying type (singele-stage and two-stage) and temperature on sensory preference of the panelists.

4.2.9 Sweet potato chips microstructure produced under different treatments.

The microstructure of raw sweet potato slices and sweet potato chips, fried in single-stage vacuum (130ºC), two-stage (130ºC), and traditional frying (165ºC), was studied by means of Scanning ElectronMicroscopy (SEM). Images were taken at different magnifications (x100, x300, x500, x1000) to visualize more details on each sample. The SEM images are shown from Figure 4-22 through Figure 4-25. Figure 4-22 shows the fresh sweet potato cells; the intact cells of fresh potato tissue are almost in perfect contact with each other. This image shows the actual structure and the contents

of the plant cells where numerous starch granules of size ranging from 5-15 μm in length were observed.

Figure 4-23 shows the microstructure of atmospheric pressure fried sweet potato chips. The cell structure can barely be recognized and there is no trace of starch granules with preserved shape. The walls collapsed and the starch granules disappeared and form a whole mass filling the whole interior of the cell

Figure 4-24 illustrates the microstructure of the vacuum fried sweet potato chips. The cells look compacted, there are less starch granules and they are dispersed between the creases of the structure; some of the cells walls collapsed and the components of the plant cell start to lose their individual characteristics.

Figure 4-25 shows the microstructure of the chips processed by the two-stage frying. The images only shows the wrinkled surface of the collapse cell with some trace of material that probably erupted from starch granules. The brightness of this image is evidence of oil presence in the sample. The chips fried by the two-stage process showed similar structure than those fried under atmospheric conditions (Fig. 4-23), indicating that 1 minute of vacuum frying is enough to cause gelatinization of starch to produce a product with completely different microstructure from the vacuum fried ones.

The results obtained in this study are supported by several researchers who have explained that when starch is heated in water (as in frying), the granules go through the gelatinization process, which includes hydration, swelling, and rupture of the structure (Liu and Shi, 2006). Moreover, Bouchon and Aguilera (2001) reported that, during frying, cells shrink and their walls become wrinkled and convoluted around dehydrated

gelled starch, but are not ruptured During frying, the cells of the potato become dehydrated as water is released from the intercellular spaces in the form of steam. It has been postulated that cells shrink and their walls become wrinkled and convoluted around dehydrated gelled starch but are not ruptured.

In summary, microstructure during frying is constantly changing since it is affected by the heat transfer and moisture loss. Cells retain their shape while the inside material changes during the heat and mass processes that occur during frying. Also, there are changes on the surface of the cell related to shrinkage.
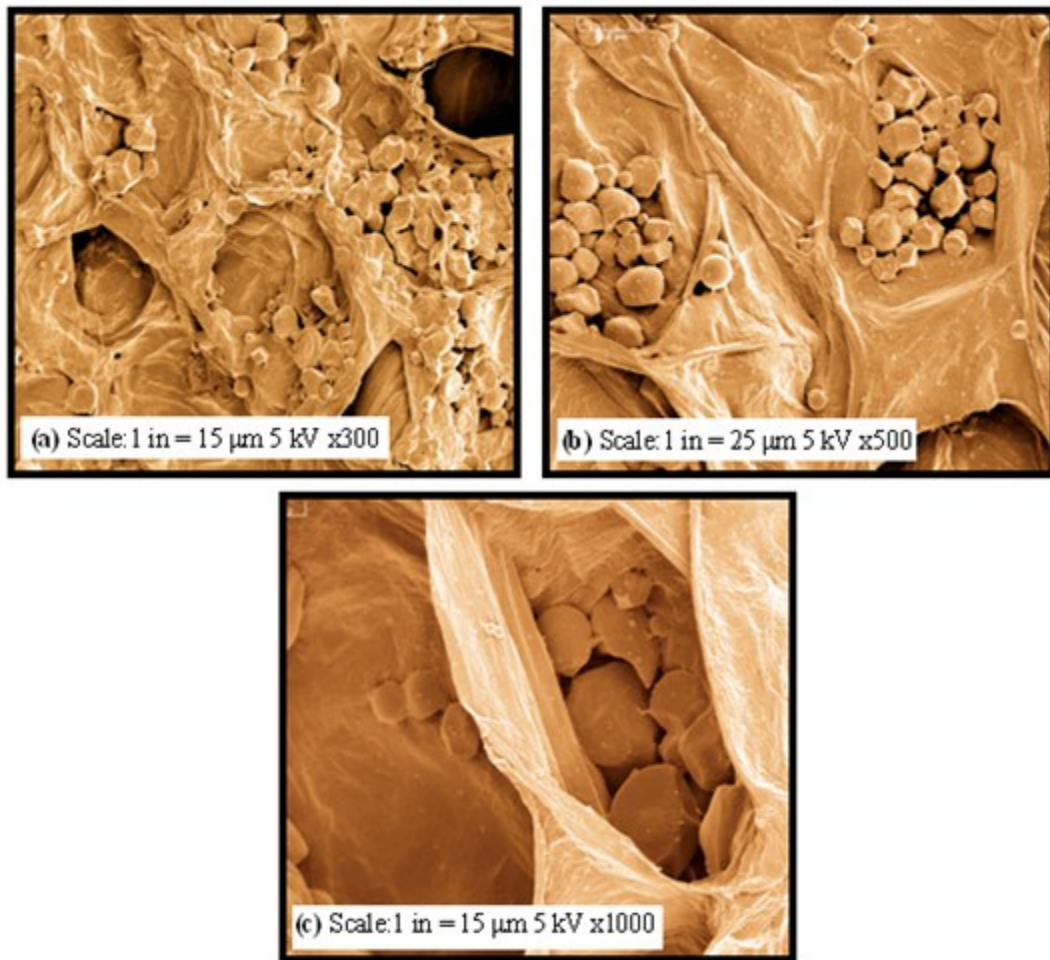
Figure 4-22. SEM image of the cross-section of a raw sweet potato slice at different magnifications.
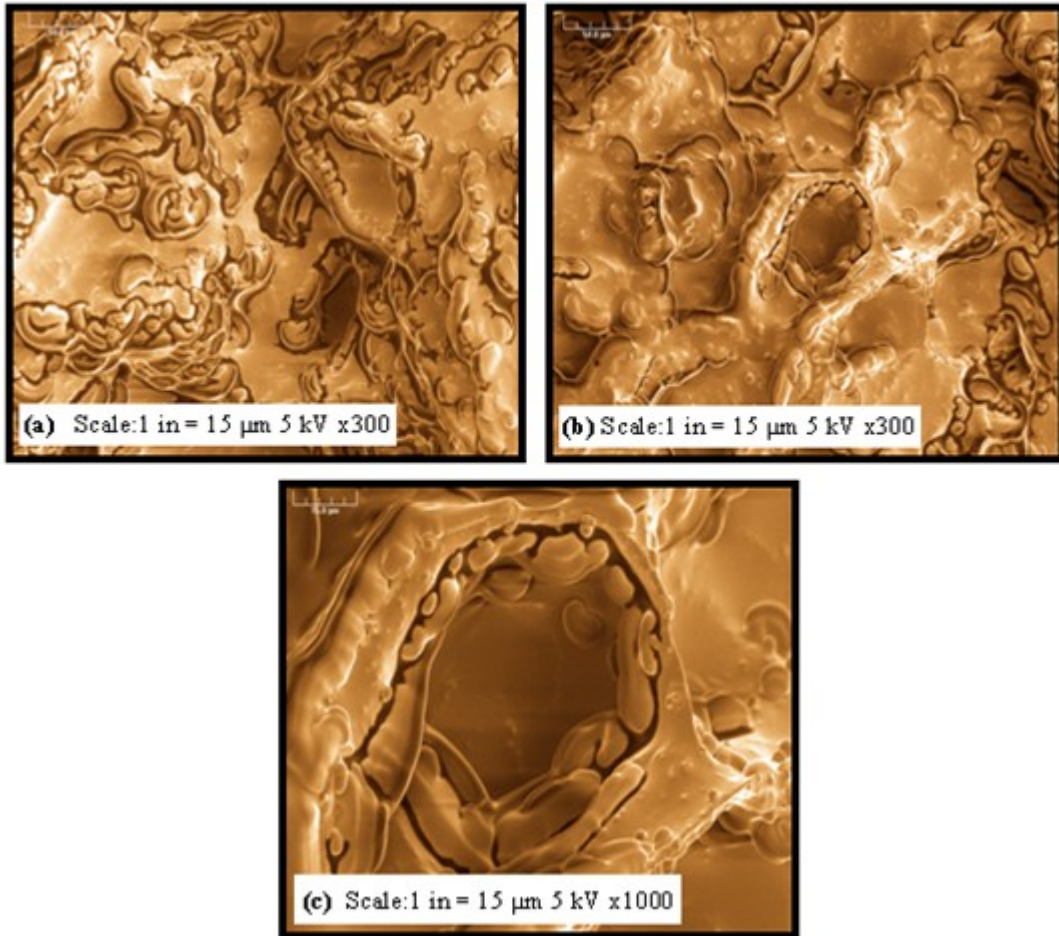
Figure 4-23. SEM image of the cross-section of a sweet potato chips fried for 120s at 165°C under atmopheric pressure.
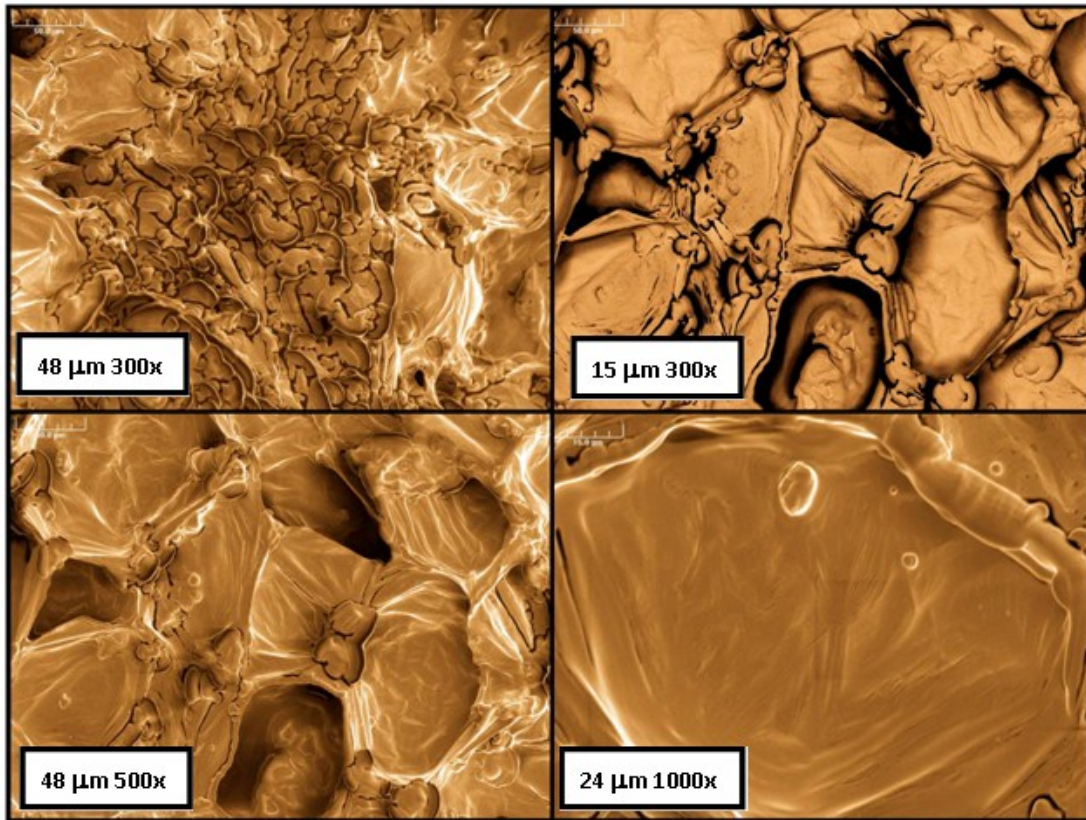
Figure 4-24. SEM image of the cross-section of a sweet potato chips fried for 100 s at 130°C under vacuum pressure (~1.33 kPa).
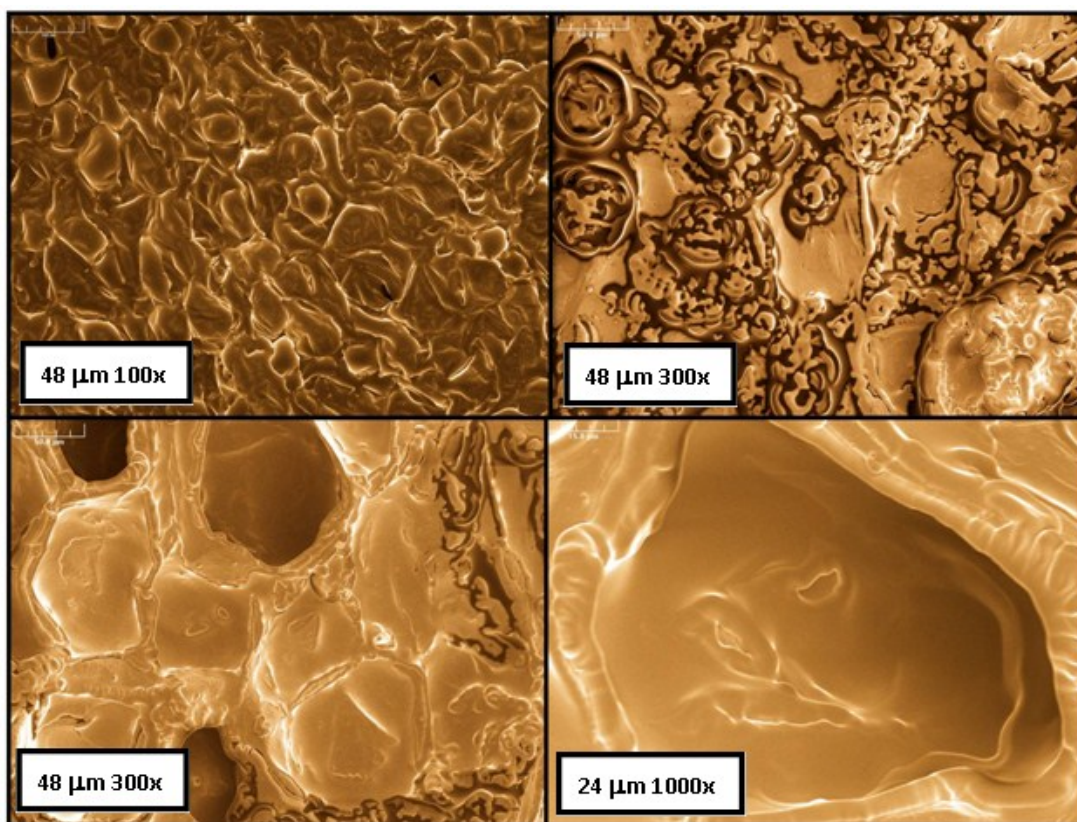
Figure 4-25. SEM image of the cross-section of a sweet potato chips fried for 60s under atmospheric conditions and 120 s under vacuum pressure (~1.33 kPa) at 130°C.

4.2.10 Summary of the PQA of the sweet potato chips produced under single-stage and two-stage frying

Figure 4.26 shows the pictures of the sweet potato chips prepared at different conditions. In general, the color of the chips looks very similar. The chips prepared by the single-stage process showed a dark orange color and a surface with very few blisters, regardless of the frying temperature used. The two-stage fried chips were a little lighter in color, more yellowish, and had a rough surface with many bubbles.

Table 4.9 shows that the two-stage fried chips were more porous than the chips fried by vacuum only. The bulk density and porosity of the two-stage fried chips were 82% lower and 25% higher, respectively, than the chips fried under vacuum. This tells us that the vacuum fried chips were more compact than the two-stage fried samples. The two-stage samples were more porous, which resulted in a better color and flavor. As a result, the two-stage fried chips shrunk more in the diameter and expanded more in the thickness than the sample fried under vacuum only.

The total oil content of the two-stage fried chips was higher than the product fried under vacuum. However, the internal oil content was lower for the two-stage fried samples. This suggests that the structures of these chips were very different and the de-oiling process could remove the surface oil easier from the chips fried under the two-stage process.

Figure 4-26. The effect of frying temperature and frying method on the appearance of sweet potato chips.

Table 4-9. Comparison between single-stage and two stage fried sweet potato chips at 130°C.

Attributes	Single-Stage Frying (100 s VF*)	Dual-Stage Frying (60 s ATF* + 120 s VF)
Moisture content [g/g-solid]	0.01±0.00	0.01±0.00
TOC [g/g-solid]	0.32±0.01	0.43±0.00
IOC [g/g-solid]	0.18±0.01	0.14±0.00
Shrinkage [%]	9.04+0.64	12.65±0.44
Expansion [%]	-26.03±1.22	50.97±1.37
Color-b [ ]	26.17±0.40	29.73±0.55
Texture [N]	2.01±0.11	2.61±0.27
Bulk density [kg/m^3]	652.50±14.83	366.75±5.15
Porosity	0.54	0.74
Degree of gelatinization [%]	72.1+0.3	87.4±2.8

*VF = vacuum frying; ATF = atmospheric frying

Figure 4.27 compares the effect of lifting or not the basket when changing the vessel pressures from atmospheric to vacuum on the quality attributes of sweet potato chips. The first thing we noticed is that the chips produced by lifting the basket had more bubbles at their surfaces. The oil content for these samples were higher than the chips produced without lifting the basket, i.e., the total and internal oil content were 43% and 17% higher, respectively. The time the basked was lifted during pressure changes may have caused some cooling effect thus increasing the chips internal oil content. Therefore,

not lifting the basket between the treatments should be the best choice to produce healthier and high-quality sweet potato chips.
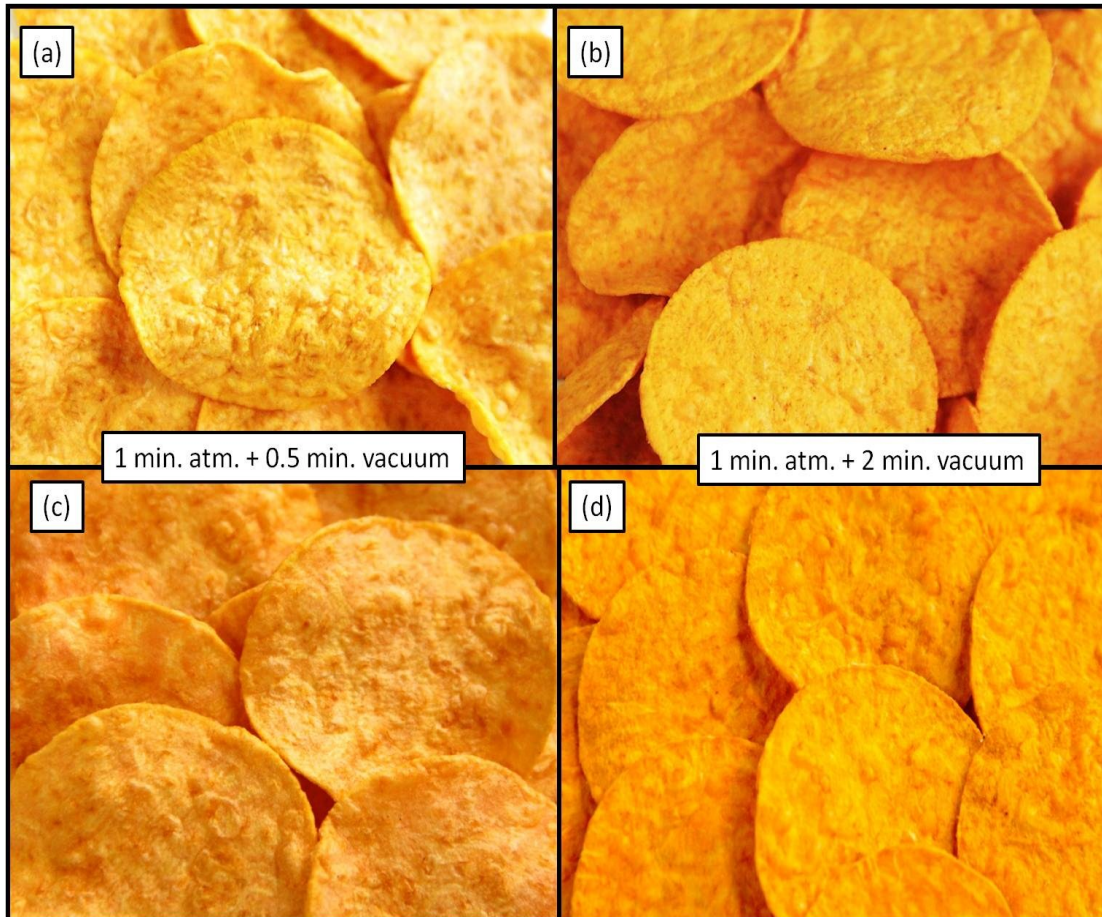
Figure 4-27. The effect of not lifting (a, b) and lifting (c, d) the basket from the oil when changing pressures from atmospheric to vacuum on the appearance of sweet potato chips.

In Figure 4.28 we can clearly see that sweet potato chips do not fry well under atmospheric frying conditions. The color, appearance, and flavor were unacceptable

compared to the other treatment used in the study. Vacuum frying not just makes a better product it enhances the color of the chips and makes them more appealing to the consumers. The oil content of the atmospheric pressure fried chips were 0.426 ± 006 g/g-solid, about 60% higher than the chips fried by the two-stage process.
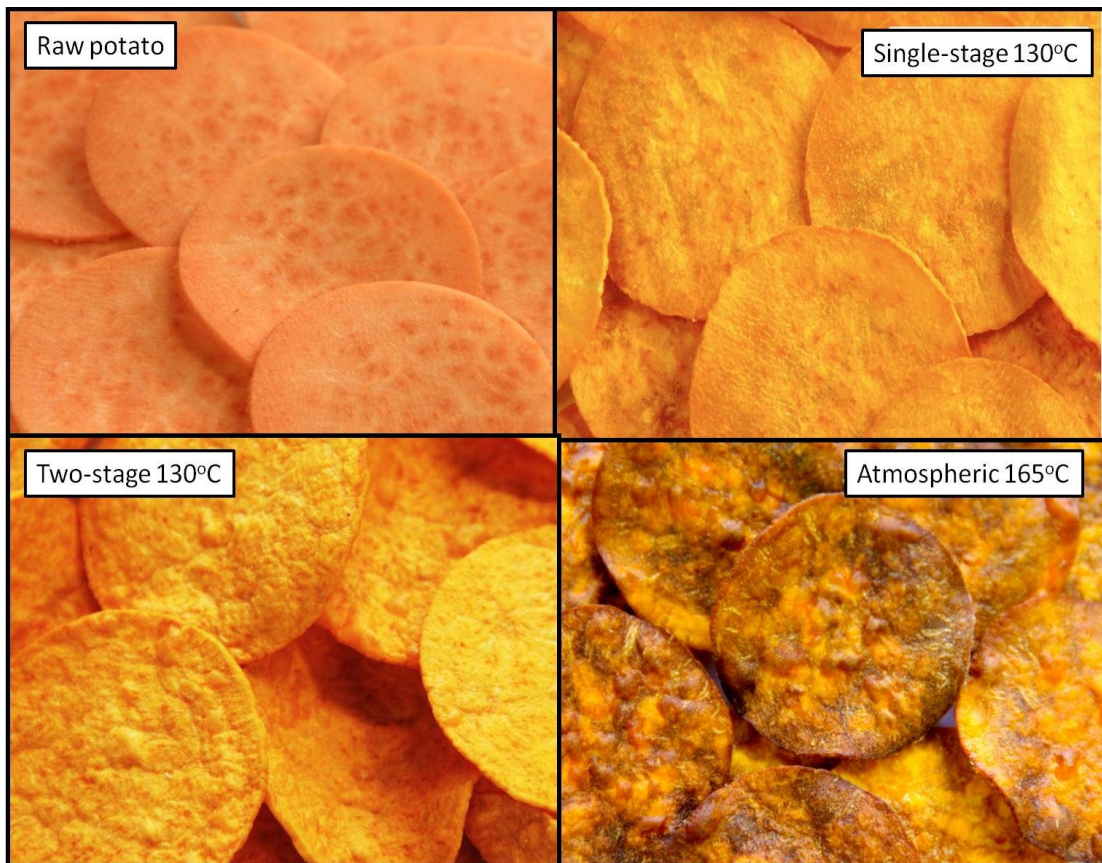
Figure 4-28. Comparison among raw potato slices and chips fried in a single-stage, two-stage, and atmospheric processes.

CHAPTER V

RECOMMENDATIONS FOR FURTHER STUDY

- Determine the raw material (sweet potato) quality parameters for different varieties to obtain the highest quality sweet potato chips.

- Perform a sensory test to compare sweet potato chips by using different sweet potato varieties.

- Measure the amount of phenolics of each sweet potato tuber, from tuber to tuber even though the potatoes are obtained from the same field and harvested at the same.

- Determine which factors create differences in the final oil content of the chips even though the initial moisture content and dry matter amount are the same from the tubers.

- Perform different pre-treatment applications to compare product quality attributes in terms of color, texture, oil content, and starch gelatinization.

- Determine the product quality attributes for vacuum fried sweet potato chips at lower temperatures such as 70, 80, and 100°C.

- Evaluate consumer perception by sensory analysis for sweet potato chips centrifuged at different centrifuge speeds.

- Measure acrylamide amount for single-stage and two-stage fried sweet potato chips.

- Develop a mathematical model for vacuum fried sweet potato chips by using the data obtained in this study.

- Conduct a sensory test to understand how addition of seasonings makes changes in panelists' scores.

- Measure all the thermal properties of sweet potato chips, like thermal conductivity specific heat, and thermal diffusivity.

CHAPTER VI

CONCLUSIONS

Vacuum frying process for sweet potato chips was studied at different temperatures (120, 130, and 140°C) and 1.33 kPa. The kinetics of oil absorption and oil distribution in sweet potato chips (total, internal, and surface oil content) was studied so that effectiveness of the de-oiling system could be established. An analysis of product quality attributes (PQA) such as moisture content, oil content, microstructure, diameter shrinkage, and thickness expansion, as well as, color, texture, bulk density, true density, and porosity of chips fried at different temperatures (120, 130, and 140°C) was performed to evaluate the effect of process temperature on the product.

A two-stage frying process (atmosphere frying prior to vacuum frying) was compared to the vacuum frying process in terms of color, oil content, texture, diameter shrinkage, thickness expansion, porosity, gelatinization, sensory evaluation, and microstructure.

The main results and conclusions obtained from this study are:

- During vacuum frying at 1.33 kPa for the range of temperature studied, the evaporation temperature of water is between 80 and 90°C, suggesting that the pressure inside the sweet potato chip is higher than the one of the vacuum system.

- Moisture loss of sweet potato chips during vacuum frying is faster at higher temperatures and is successfully modeled with a modified equation for moisture diffusion in a flat plate.

- The moisture diffusion coefficient has a directly proportional relation with the frying temperature which can be modeled with an Arrhenius type equation.

- Sweet potato chips fried at higher temperatures have higher total oil content than those fried at lower temperatures; however, final internal oil content is lower at higher temperatures, which means than the de-oiling system is more efficient at the highest temperatures.

- Use of the de-oiling system, before pressurization, removed up to 52% of the surface oil content of potato chips, proving that is a necessary device to produce high-quality and healthier snacks.

- Sweet potato chips reduce in diameter by about 10%, and expand thickness by 25% at the end of frying. Fluctuations in diameter values were more pronounced at the lowest temperature.

- Porosity of sweet potato chips increases during frying due decrease in bulk density and increase in true density, which are caused by water loss.

- Sweet potato chips were harder at higher temperature, indicating that the chips fried at high temperature are more difficult to break.

- Sweet potato chips were darker and more orange in color (lower a* and b*) when fried at high temperature.

- The microstructure of vacuum-fried sweet potato chips differs from that of the traditionally-fried chips. Shrinkage of the cells and collapse of the wall, as well as, disruption of starch granules occur as during the process. The two-stage fried chips showed a microstructure similar to the atmospheric pressure fried ones.

- During the two-stage frying, more starch gelatinized compared with single-stage frying. Atmospheric frying pre-treatment helped starch to gelatinize.

- Sweet potato chips were harder to break when processed with the dual-stage frying method and they did not have a glassy appearance.

- The color of the chips processed on the two-stage process was lighter than those processed by the single-stage frying process.

- The bulk density and porosity of the two-stage fried chips were 82% lower and 25% higher, respectively, than the chips fried under vacuum. This tells us that the vacuum fried chips were more compacted than the two-stage fried samples. The two-stage samples were more porous, which resulted in a better color and flavor.

- Blisters were observed on the surface of the two-stage fried chips. The occurrences of blisters were not observed on the surface of single-stage frying ones.

- Vacuum fried and two-stage fried sweet potato chips obtained scores above 5 (acceptable) in every category offered to the panelists in terms of color,

flavor, odor, texture, and overall quality. However, the two-stage fried sample received better scores and more acceptance from the panelists.

- The total oil content of the dual stage fried chips had more oil content than the vacuum fried ones. The two-stage fried chips stayed longer in the oil and had more surface area (because of blisters) compared with single-stage.

- The internal oil content of vacuum fried chips was higher than the internal oil content of two-stage fried ones. The reason was the penetration of the oil towards the inside of the chips. Starch on the surface of the chips was gelatinized, thus made a barrier for oil entrance.

- Thickness expansion was higher for two-stage fried chips than for the vacuum fried ones.

- Diameter shrinkage was more for the dual stage fried chips than the single-stage fried samples.

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